Professional Practice in Earth Sciences

Mike Cambridge *Editor*

The Hydraulic Transport and Storage of Extractive Waste

Guidelines to European Practice

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with contributions by

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Preface

The preparation of this book, which was initially promoted by the UK Health and Safety Executive, has been undertaken in parallel with the development of an EU Standard prEN 16907-7—Earthworks—Part VII: Hydraulic placement of extractive wastes. The principal author, together with members of the drafting and peer review groups, has actively participated in the development of this Standard, which has subsequently been supported both actively and passively by the European mining sector.

Thanks to all who have made the development of this book possible.

Ashford, Kent, UK
August 2017

Mike Cambridge

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Contents

Definitions

Confining embankment: an engineered dam constructed from both natural and processed geotechnical materials to retain the fine-grained materials (tailings) and process water derived from a mineral-processing plant, and natural runoff, in safety.

Decant: an engineered structure designed to facilitate recycling of process water and, as appropriate, to discharge natural runoff.

Extractive waste - Waste resulting from the prospecting, extraction, treatment and storage of mineral resources and the working of quarries, but excluding waste which is generated by the prospecting, extraction and treatment of mineral resources and the working of quarries, but which does not directly result from those operations; waste resulting from the off-shore prospecting, extraction and treatment of mineral resources; and excluding injection of water and re-injection of pumped groundwater as defined in the first and second indents of Article 11(3)(j) of Directive 2000/60/EC, to the extent authorised by that Article. [Directive 2006/21/EC]

Emergency spillway: an engineered structure designed to pass in safety an extreme flood event without endangering the stability of the confining embankment.

Mine waste facility: an engineered structure which, together with all necessary appurtenant works, is designed to retain or confine in safety the extractive waste resulting from industrial processing of naturally occurring soil, ore or rock and to store and recycle, where appropriate, process and flood waters.

Tailings - The waste solids or slurries that remain after the treatment of minerals by separation processes (e.g. crushing, grinding, size-sorting, flotation and other physico-chemical techniques) to remove the valuable minerals from the less valuable rock [Directive 2006/21/EC]

Tailings dam (see also Tailings Management Facility [TMF], Tailings Storage Facility [TSF] and Mine Waste Facility [MWF]): an engineered structure, together with all necessary appurtenant works, for ensuring stability, tailings, water and environmental management, and designed to retain or confine the tailings resulting from ore processing and for recycling the process water.

Abbreviations

ABA	Acid Base Accounting
ALARP	As Low As Reasonably Practical
ANCOLD	Australian National Committee on Large Dams
AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
BAT	Best Available Techniques
BFS	Bankable Feasibility Study
BRE	Building Research Establishment
BREF	BAT Reference Document
CDA	Canadian Dam Association
CIRIA	Construction Industry Research and Information Association
CMP	Construction Management Plan
CN	Cyanide
CP	Competent Person
CQA	Construction Quality Assurance
DFS	Definitive Feasibility Study
EN	European Standard
ESIA	Environmental and Social Impact Assessment
EU	European Union
EPCM	Engineering, Procurement, Construction Management
EWD	Extractive Waste Directive (see also MWD)
FBA	Furnace Bottom Ash
GARD	Global Acid Rock Drainage
GPS	Global Positioning System
HDPE	High Density Polyethylene
ICARD	International Conferences on Acid Rock Drainage
ICE	Institution of Civil Engineers
ICOLD	International Commission On Large Dams
IFC	International Finance Corporation
IIE	Independent Inspecting Engineer

IMPEL	EU network for the Implementation and Enforcement of Environmental Law
INAP	International Network for Acid Prevention
ISO	International Organisation for Standardisation
IPPC	Integrated Pollution Prevention and Control
MCE	Maximum Credible Earthquake
mOD	Metres to Ordnance Datum
MTWR	Management of Tailings and Waste Rock
MWD	Mine Waste Directive (see also EWD)
MWF	Mine Waste Facility (see also TMF)
NP	Neutralisation Potential
NAF	Non-Acid Forming
NAGpH	Net Acid Generation
NAPP	Net Acid Producing Potential
NRD	Neutral Rock Drainage
O&M	Operation and Maintenance (see also OMS, OSM)
OMS	Operation, Maintenance and Surveillance
OBE	Operating Base Earthquake
OSM	Operation, Supervision and Maintenance
PAF	Potentially Acid Forming
PAH	Polycyclic Aromatic Hydrocarbons
PFA	Pulverised Fuel Ash
PAG	Potentially Acid Generating (see also PAF)
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PS	Performance Standards
SEED	Safety Evaluation of Existing Dams
SFM	Soil Forming Material
TMF	Tailings Management Facility (see also MWF)
TSF	Tailings Storage Facility (see also MWF)
UC	Uncertain

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Chapter 1
Preamble

Mike Cambridge

At 9.15 am on 21st October 1966 the active waste tip at Merthyr Vale Colliery in South Wales, UK, failed, the resulting slide debris engulfing Pantglas Junior School and several houses in the mining village of Aberfan. The death toll resulting from the disaster was 144, of whom 109 were schoolchildren, more than half the pupils at the school. In addition, five of their teachers were killed in this tragic event. The UK government immediately appointed a Tribunal of Inquiry under the Tribunals of Inquiry (Evidence) Act 1921, which reported in July 1967. Its report (Davies 1967) was fiercely critical of the Owner/Operator, having uncovered numerous ignored warnings in addition to other serious failings.

Summary—Edmund Davies (chairman), ***Report of the Tribunal appointed to inquire into the Disaster at Aberfan on October 21st 1966*****, HL 316, HC 553 (London: HMSO, 1967), pp. 131–132.**

Findings

I. Blame for the disaster rests upon the [Owner][1]
II. There was a total absence of tipping policy and this was the basic cause of the disaster.
IV. The legal liability of the [Owner/Operator] to pay compensation for the personal injuries (fatal or otherwise) and damage to property is incontestable and uncontested.

[1]Here "Owner" and "Owner/Operator" have been substituted for the "National Coal Board" for clarity.

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Lessons

V. Action needs to be taken to safeguard the future condition of the tips[2] ….
VII. All tips should be regarded as potentially dangerous.
VIII. Tips should be treated as civil engineering structures.

Recommendations

XI. The [Owner/Operator] should continue to have prime responsibility in respect of all tips in its ownership.
XII. A standard Code of Practice should be prepared for consideration … with a view to its being issued publicly and applied to all tips ….
XIII. [A Regulator], strengthened by the addition of qualified civil engineers and armed with additional statutory powers, should be made responsible for ensuring the discharge by [all Owner/Operators] of their duties in relation to tip stability and control.[3]
XIV. A local authority should have access to plans for tipping and reports on existing tips and, if not satisfied with them, should have a right of appeal ….
XV. Men engaged in the daily management and control of tips should be trained for their responsibilities.
XVI. Managers and surveyors should as soon as possible be made aware of the rudiments of soil mechanics and ground-water conditions. The statutory qualifications for managers and surveyors should be amended to include awareness of the rudiments of soil mechanics and hydrogeology, in addition to the geology ….

[2]In this context a tip is a MWF defined as "consisting of refuse accumulated or deposited wholly or mainly in solution or suspension and if any part of the tip (other than any wall or other structure retaining or confining it but including any liquid in it) is more than 4 m above the level of any part of the neighbouring land within 50 m of the perimeter of the tip; or the volume of the tip (other than any wall or other structure retaining or confining it but including any liquid in it) exceeds 10,000 m^3:" (HMSO 1971).

[3]Reference the subsequent UK Legislation: Mines and Quarries (Tips) Act 1969 Mines and Quarries (Tips) Regulations 1971

Chapter 2
Introduction

Mike Cambridge and Gavin Ferguson

All tips should be regarded as potentially dangerous.
Tips should be treated as civilengineering structures.
—Davies, Aberfan Tribunal, 1967

These guidelines have been prepared in parallel with the development of the European Standard on Earthworks (prEN 16907) which includes, under CENTC396, Working Group 6 (WG6), a section on the hydraulic transport and storage of extractive waste (Cambridge 2015). The content of this book has been influenced by the well-publicised need for guidance to all stakeholders on both technical and regulatory aspects of the permitting, design and construction of extractive waste facilities in Europe. The Directive on the management of waste from the extractive industries (Extractive Waste Directive [EWD] (2006/21/EC) imposes a duty to ensure competent design, operation and closure of such facilities. Though some guidance on a limited number of related technical elements has been subsequently published, the relevance of these contributions has been diminished by the lack of an integrated approach to geotechnical and geochemical issues. It has therefore been evident, both to regulatory bodies and operators alike, that a unified and comprehensive document providing guidance to all stakeholders was required at an early stage if the future of mining within the EU was to be assured and future untoward incidents avoided.

These guidelines seek to address all technical stages of the development of a hydraulic fill project in the context of the EWD, with an emphasis on waste and facility characterisation and on the risk-based assessments which underwrite them. They are intended for use by all stakeholders involved in those European industries which involve the generation, transport and storage of fine particulate waste products requiring long-term confinement in a safe, stable and environmentally acceptable location.

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2.1 Background

The report entitled "Lessons from historical dam incidents" (CIRIA 2011), indicates that "the number of casualties arising from a breached dam can be greater than from most other kinds of technological disasters" and a breach in an extractive waste facility may have similar consequences. However, the impact can be compounded by the release of potentially-contaminating materials in addition to the contained water, posing a threat to both humans and to the environment. Maintaining the safety of mine waste facilities in the EU has been of increasing importance both to Regulators and to the public following a number of high-profile incidents in the period immediately preceding the enactment of the EWD. Safety management is particularly important given that extractive waste facilities within Europe may pose a higher risk than in other parts of the world since they are more likely to be located upstream of heavily-populated and industrialised areas. Thus, although the probability of the failure of such facilities is generally low, the consequences may be significant and any local impact receive extensive and adverse publicity to the detriment of the extractive industries Europe-wide. As most mine waste facilities (MWFs) containing significant volumes of water (>10,000 m^3) constitute a low-probability/high-consequence hazard similar to that for water supply reservoirs, careful management of these risks is essential. The perception is that MWFs breach and fail regularly but this statistic is not substantiated, as indicated in Table 2.1 which lists the catastrophic failures of both MWFs and water reservoirs leading to loss of life in Europe since 1945. Much can be learned from these disasters as well as from those which have occurred outside the EU.

Incidents such as those at Baia Mare and Aznalcollar in particular, though not leading to fatalities (Cambridge 2005), resulted in major negative environmental impacts and significant adverse public reactions. These incidents were the subject of detailed investigation and study, and resulted not only in the improved regulation of such structures but in other associated initiatives within the EU. These guidelines

Table 2.1 European dam disasters causing loss of life (CIRIA 2011; Blight et al. 2003)

Year	Dam	Country	Dam type	Failure mode	Deaths
1959	Vega de Tera	Spain	Reservoir	Structural failure	144
1959	Malpasset	France	Reservoir	Foundation failure	421
1961	Babii Yar	Ukraine	Reservoir	Overtopping failure	145
1963	Vaiont	Italy	Reservoir	Catchment landslide	2600
1965	Stava	Italy	MWF	Overtopping failure	285
1991	Belci	Romania	Reservoir	Overtopping failure	25
1996	Sgurigard	Bulgaria	MWF	Overtopping failure	107
2010	Kolontar	Hungary	MWF	Foundation failure	10

The Aberfan incident, though resulting in the loss of 144 lives, did not involve the failure of an impounding (dam) structure (Bishop 1973)

The well-publicised failures of Aznalcollar in Spain and Baia Mare in Romania did not result in loss of life seek to draw together combined experience from Europe, from good international practice and from the lessons learnt from recent untoward incidents related to the storage of extractive waste. Given the broad scope of this subject, the book has sought to present the state of the art in Europe and the content is, therefore, for the most part limited to extractive waste facilities in the EU, with useful examples of international practice included for illustrative purposes where appropriate.

2.2 Objectives

These guidelines are principally intended for use in respect of those European industries which involve the generation, transport and storage of fine particulate waste products requiring long-term confinement in a safe, stable and environmentally acceptable location. The extractive industries, which are ubiquitous throughout Europe and cover a wide range of both metalliferous and non-metalliferous materials, constitute the principal driver for the guidance. However, it is recognised that this document may prove of assistance to a wide range of practitioners in diverse industries, both within and outside the EU, for which the geotechnical and geochemical technical guidance described is applicable. The principal objective is to address the technical stages of the development of a hydraulic fill project in the detail summarised in Fig. 2.1, the emphasis being on the

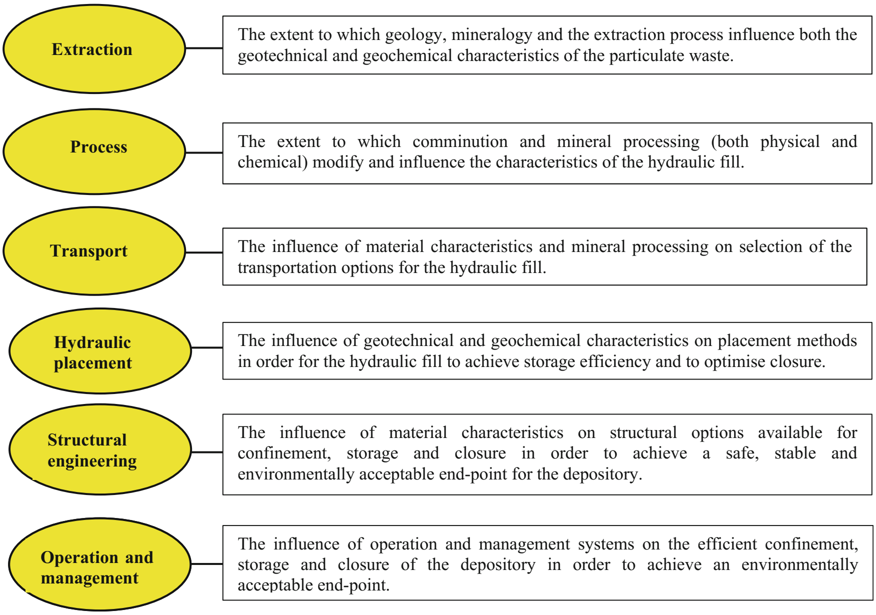

Fig. 2.1 Scope of the guidelines

key characterisation elements for which guidance is deemed to be required for both regulatory and technical compliance.

The objectives of these guidelines are the provision of technical guidance and recommendations on good practice applicable to:

- all stakeholders engaged in the deposition of mineral wastes using hydraulic placement techniques with respect to geotechnical and geochemical aspects of the investigation, engineering design, construction and operation of a mine waste facility and all subsequent monitoring activities;
- those extractive industries involving the production of fine particulate wastes which, in the course of industrial processing, require to be stored in a safe, stable and environmentally acceptable location;
- practitioners in non-extractive industries in fields where similar techniques may be applicable and for which no other European guidance exists.

For the purposes of these guidelines, "stakeholders" include governmental and non-governmental agencies involved in the planning, approval, certification and regulation of an extractive waste facility, together with owners, developers, operators and the diverse range of associated industrial, consulting engineering and environmental companies.

In addition, the aims of the book are:

- to improve design, construction, operation and inspection practices at mining projects throughout Europe;
- to provide technical interpretation and clarity for both regulators and developers with particular respect to compliance with the EWD and the EU Inspection Guidelines (EC 2012);
- to provide guidance with respect to the development of hydraulic fill projects under the multi-agency approach taken in the EU during permitting.

Though the technical contents do not address mine waste rock dumps it is recognised that design elements such as waste and facility characterisation, together with some of the technical, operating and inspection procedures, are of direct relevance to coarse mine waste facilities and may be considered appropriate subject to context.

The guidelines do not cover landfill, dredging or the hydraulic filling aspects related to grouting.

2.3 Scope

These guidelines are generic in content given that the range of extractive operations, the principal driver for this document, is broad. Further, the precise characteristics of each mineral waste and its depositional properties will depend on the geology and the extractive and mineral processing techniques adopted, as well as on the type and location of the disposal facility. Considerable discussion of processing techniques and of the characteristics of waste depositories is provided as these have a significant impact on the choice of deposition system and the ultimate geotechnical properties of the waste material. In addition, the book details specific geotechnical investigations and laboratory techniques which are not covered in other BS, DIN or EN documents.

The contents of the guidelines and the associated disciplines addressed are summarised in Table 2.2 and the principal processes and activities involved in a typical mining project and the on-going operations described are illustrated in Fig. 2.2.

Table 2.2 Contents by chapter and discipline

Activity	Chapter	Topics	Disciplines
Hydraulic placement projects	3	The project The hydraulic fill The facility The legislative background	Project management Legislation and regulation
Material characterisation	4	Effect of geology, mineralogy and extraction processes Impact of comminution and mineral processing Transportation and deposition	Geology Geotechnics Geochemistry Process chemistry Metallurgy Hydraulics/fluid dynamics
Engineering design process	5	Risk basis Site selection and characterisation Environmental setting Facility design and engineering Emergency planning Closure and rehabilitation	Geotechnics/geochemistry Structural engineering Hydraulics/hydrology Seismo-tectonics Environmental management
Facility design options	6	Risk mitigation Confining structure Hydraulic disposal and deposition Closure and rehabilitation	Structural engineering Geotechnics Geochemistry Hydraulic engineering Environmental management
Quality control	7	Construction quality control Disposal quality control Inspection and monitoring Instrumentation	Construction management Geotechnical characterisation Geochemical characterisation Environmental monitoring
Special applications	8	Industrial minerals Quarry waste Mine hydraulic fill Power station fly ash	As per Chaps. 3–7

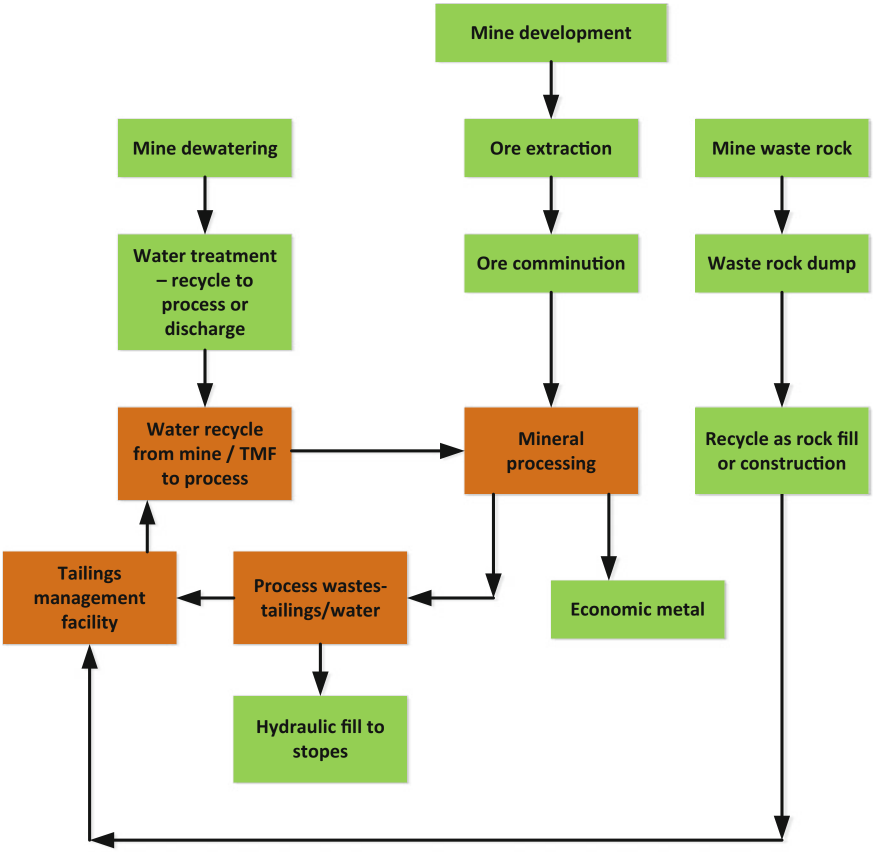

Fig. 2.2 Typical hydraulic fill flowsheet for a mining project

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CIRIA Evidence Report (2011) Lessons from historical dam incidents. UK Environment Agency, CIRIA
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European Standard Earthworks—prEN (2017) 16907 Parts 1–6

Chapter 3
Hydraulic Fill—Sources, Placement and Regulatory Issues

Mike Cambridge, Gavin Ferguson, Nick Coppin and Ciaran Molloy

This section outlines the derivation and sources of hydraulic fill and the subsequent placement of extractive wastes in surface depositories, together with the industrial background and technical context for such projects within Europe. The range of extractive wastes addressed in this volume is exemplified by Table 3.1 as defined in the EU sampling guidance (EC 2012).

The format and contents of the guidelines as they relate to all stages of the MWF project, and in particular to the design and implementation process explained in this Section, are illustrated in Fig. 3.1.

3.1 Hydraulic Fill

The principal materials targeted by EU legislation are the extractive wastes and, in particular, the finer particulate wastes which are transported and deposited in slurry form (hydraulic fills). Hydraulic fills are generally produced by industrial processing of a naturally-occurring soil, ore or rock in order to extract the economic material (Fig. 3.2). The processing of both metalliferous and non-metalliferous extractive materials involves crushing and grinding, and a range of gravitational and chemical separation processes. The resulting waste products are discharged, generally as a slurry comprised of a mixture of particles and water, and deposited into a confining area where sedimentation takes place. These extractive wastes (tailings) may range in size from fine gravels (particle size < 10 mm) to clay-sized particles (particle size < 2 μm), the latter comprising either rock flour or true clays dependent on the mineralogy and the extractive process. The characteristics of the tailings, and therefore of the hydraulic fill, may vary considerably depending on the final elements of the processing circuit and the degree to which the slurry is thickened. The transport medium between process plant and disposal area may comprise conveyors, open channels and pipelines,

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Table 3.1 Potential extractive wastes

Extractive operation	Overburden	Waste rock	Extractive waste	Environmental aspects
Aggregates Construction materials Dimension stones	Tipped in dumps Backfilled into voids	Tipped in dumps Backfilled into voids	Tipped in dumps Deposited as a slurry in lagoons	Dust from exposed tips Contaminated seepages Occasional ARD Tip and slope failures Failure of containment structures
Industrial minerals Salt & potash	Tipped in dumps Backfilled into voids Construction use	Tipped in dumps Backfilled into voids Construction use	Tipped in dumps Deposited as a slurry in lagoons or extractive waste management facilities Underground backfill Deep-well disposal	Dust from exposed tips Contaminated seepages Leaching of process chemicals Tip and slope failures Failure of containment structures Salinity of runoff
Metal mining	Tipped in dumps Backfilled into voids Construction use	Tipped in dumps Backfilled into voids Underground backfill Construction use	Deposited in extractive waste management facilities	Dust from exposed tips Contaminated seepages Leaching of process chemicals Tip and slope failures Failure of containment structures ARD of both waste rock and tailings
Energy minerals Coal & lignite	Tipped in dumps Backfilled into voids Construction use	Tipped in dumps Backfilled into voids Construction use	Tipped in dumps Deposited as a slurry in lagoons or extractive waste management facilities Underground backfill	Dust from exposed tips Contaminated seepages Leaching of process chemicals Tip and slope failures Failure of containment structures ARD of both waste rock and silts

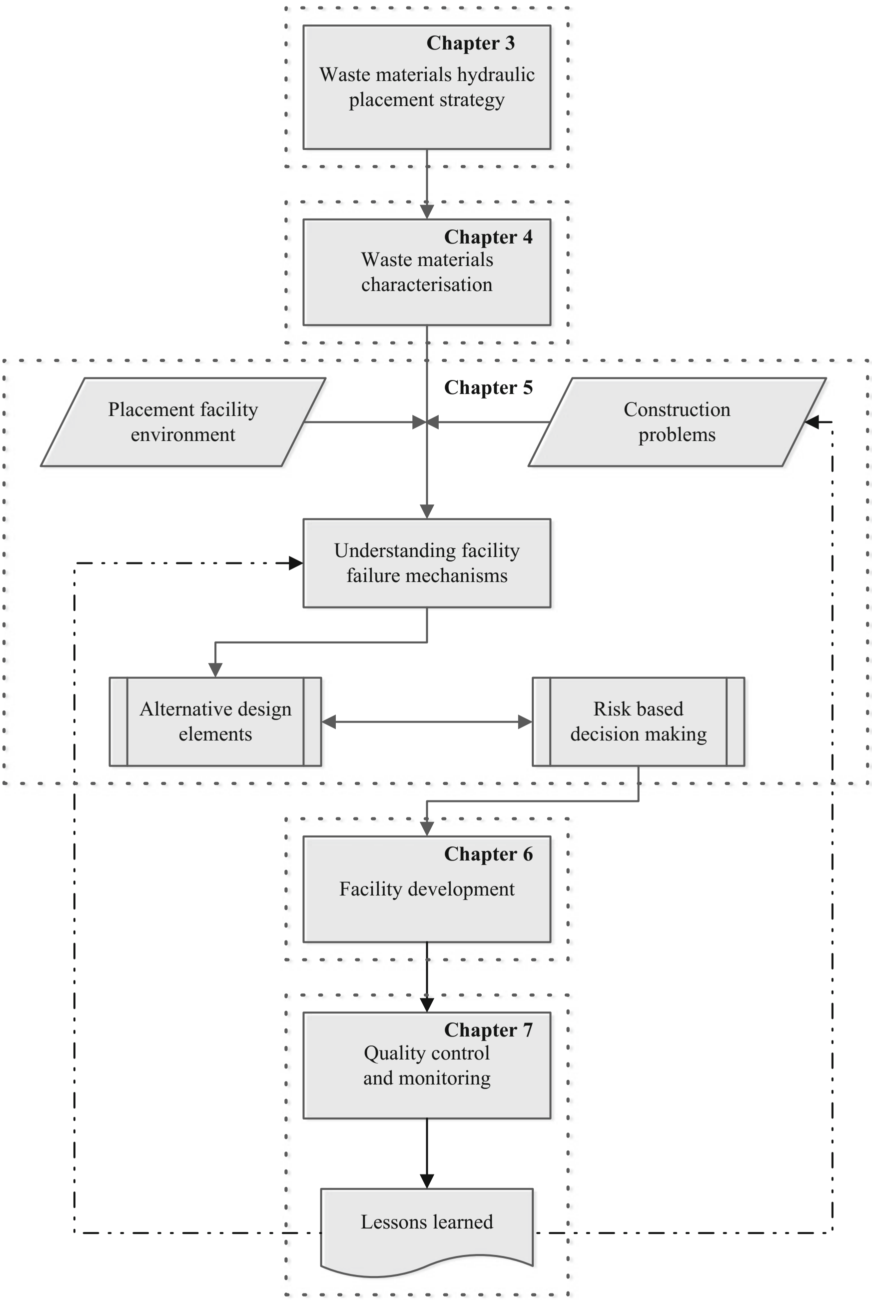

Fig. 3.1 The framework developed in the guidelines (Ferguson 2015)

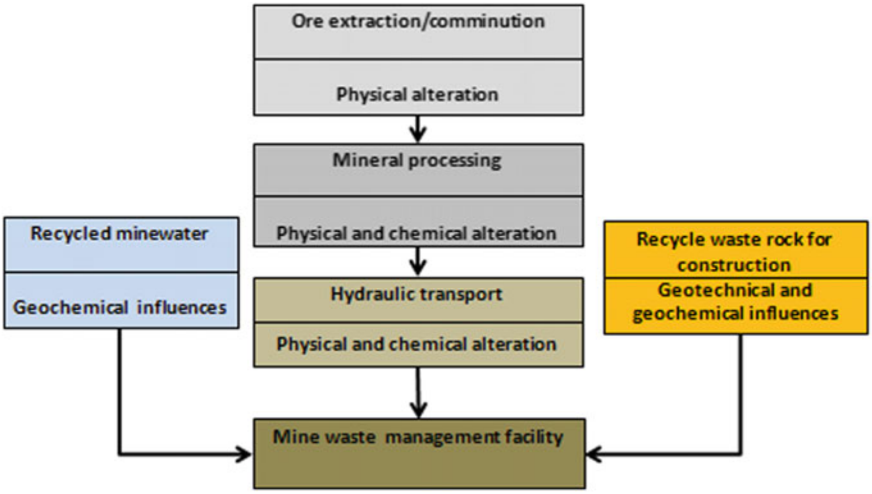

Fig. 3.2 Physical and chemical influences on hydraulic fill

and the pulp density[1] vary from less than 10% to more than 70% (a common target for thickened tailings disposal). The material comprising the hydraulic fill may consist of geotechnically-competent particles which will not be subject to material change during the course of the placement and closure process. Alternatively, the material may comprise elements which readily degrade, resulting in physical and geochemical changes during both deposition and placement. Further, the hydraulic fill may include elements which are not chemically stable, also resulting in the breakdown of the particles and a reduction in grain size.

3.2 Historical Perspective

"Engineers ignore history at their peril." - Cambridge 2005

Mining has been undertaken in Europe for more the 3500 years. Archaeological evidence from locations such as Cyprus, southern Greece, Portugal, Spain and the south–west of England has produced artefacts from the bronze age, proving the continuity of industrial-scale mining up to the present day. The extraction process resulted in significant quantities of waste being produced, much of which remains evident in the landscape throughout Europe today. The history of mining and the parallel development of pan-European industrial society resulted not only in an important heritage but in the development of a wide range of extractive and processing technologies for mineral production and disposal of the waste products.

[1]See Appendix B1 for definitions of pulp density and other mass and volume relationships.

Mining history provides important lessons for future design, operation and closure of mine waste facilities in Europe.

Archaeological research into industrial-scale mining across Europe indicates that early trading in both precious and base metals, extending from the eastern Mediterranean to Cornwall and Ireland, existed in pre-Roman times. Numerous sites display evidence of all phases from extraction to disposal, albeit on a localised level, indicating continuous mineral extraction over the following 1500 years. The level of mineral output does not appear to have risen dramatically across Europe until the 16th and 17th centuries, when a significant increase in the number of mines operating is noted. The consequent rise in the production and hydraulic disposal of residues at this time led to major impacts on river and estuarine systems, the preferred repositories for the waste, and on the environment across Europe. Dramatic evidence of such impacts is documented in archives from Cornwall in the south–west of England. Mineral extraction in the Carnon Valley, a major source of the world's tonnage of tin and copper in the late 19th century, had by 1660 led to significant volumes of tailings being deposited in the local river and significant changes in its geomorphology and ecology (Cambridge 2004). The volumes of extractive waste so deposited restricted the waterways, preventing trading vessels from reaching the local port of Bissoe some 6 km upstream of Devoran at the head of Restronguet Creek (Hamilton-Jenkin 1963). The topography and ecology of this deep-water inlet were subsequently affected by the next two hundred years of hydraulic disposal of mine residues, such changes in river systems being reflected across other European mining areas.

The industrial revolution led to a further surge in the development of new mines and a dramatic increase in the production of metal and waste products, exemplified again by the Carnon catchment, an area of some 4 km^2, where it is estimated that more than 200 mines were operating from surface to depths in excess of 2500 feet. These mines collectively produced approximately 1 million cubic feet of tailings and other solid wastes on a daily basis, most of which was deposited into the river system. Throughout this period there was in general little attempt in Europe to contain the extractive wastes arising from mineral processing and ore production. Where a mine had access to the sea, marine disposal was undertaken, as at Lavrion in southern Greece, and in valley systems disposal into rivers was considered to be most cost-effective. On-land disposal appears to have been limited to those mines working at elevated levels on upland areas where there was no easy access to a major river conduit, and on these sites rudimentary tailings dams were constructed.

During the latter part of the 19th century, mines in Europe were challenged by the low cost of metal production in America, Australia and, ultimately, Africa. At mines outside Europe, often located in remote and underdeveloped regions, maintaining a robust water supply for processing was potentially a major economic issue. Discharging hydraulic fill to waste was not an option, and means of recycling industrial water became an economic necessity which required hydraulic disposal into predefined areas, enabling sedimentation of solids and the return of water to the processing plant. During the 1950s and the 1960s changes in planning requirements and funding arrangements, together with a growing awareness of environmental issues, led to increasing formalisation of mine waste disposal arrangements and a decreasing tolerance of marine disposal[2] with an emphasis on design and construction of MWFs by many mining corporations in accordance with good practice. The need for such sound design and construction practices was reinforced by a number of major failures of mine waste facilities during this period (Cambridge 2005; Blight et al. 2003).

The extractive industries are currently major contributors to the world economy and will continue to be so, particularly in developing countries where economic growth is dependent upon a sound supply of primary materials. The global mining industry has made major technical improvements in design and construction techniques for mine waste facilities and there has been a parallel increase in regulation culminating, in the EU, in the EWD and associated environmental legislation (Cambridge 2003).

3.3 Facility Description

The mineral processing of an extractive resource results in both coarse and fine residues. The fine wastes, the subject of this book, comprise a sandy silty particulate material with variable clay content, and are generally discharged from the process plant in slurry form. Such materials, regardless of their consistency, need to be placed in a secure containment facility and, in most cases, would not be stable without being suitably confined. The efficiency of the refining process and the site water balance generally necessitates that the greater part of the water contained within the slurry be recycled and re-used. A containment facility in Europe would normally include capacity for both the extractive waste and for process water storage and recycling. The primary purpose of a MWF is therefore the storage of hydraulic fill in a controlled manner for an infinite amount of time (Bjelkevik 2005). Its secondary function is the provision of suitable capacity to store surplus process waters and any runoff from precipitation on the mine site and potentially from the upstream catchment. The siting and type of the MWF will be dependent on the volumes involved, on the suitability and accessibility of the terrain, on local geology and climate and on the characteristics of the waste material to be deposited. The containment facility invariably involves some form of confining structure or dam constructed from local borrow materials or the waste product, and sometimes from a combination of both.

The design of the confining structure is initially a function of the geographic and topographic setting of the MWF, the type of ore body and the life of the mine, and requires the adaptation of the site and waste characterisation data to develop the most cost-effective and environmentally appropriate storage facility in the locality of the mineral extraction operations. The terrain and climate will determine the configuration of the depository, i.e. the adoption of a valley, side-valley or paddock-type facility as defined in Sect. 6.1. The final selection will be subject to

[2]It is noted that marine disposal continued into the 1990s in parts of Europe, such as at the Bay of Portman in Spain where some 70 million tonnes had been deposited at cessation of operations.

preliminary screening for efficiency of waste storage-to-wall volume ratio and to geological, hydrological, seismological and environmental suitability, together with review of the risks posed to any populated areas downstream and to those potentially affected by the development of the mine waste facility.

The initial site screening and basic risk assessment will enable the configuration of the confining embankment and the deposition mode to be selected. However, of overriding importance is the understanding that the facility will invariably require to be stage-raised and that the structure may need to be extended beyond its original capacity in order to suit future project expansion. Of critical importance during this stage of project development is the necessity both for Regulators and other non-technical specialist stakeholders to appreciate the differences between a mine waste confining structure and an embankment dam for a water supply reservoir. Water supply embankments generally comprise a single "simple" cross-section and are built in a single stage, albeit over a period of several years (McLeod 2003). In comparison, the confining embankment for a MWF is invariably stage-constructed, requiring a number of construction phases over the life of the mine and may, in addition, comprise a complex cross-section with numerous design changes as the mine develops or mineralogy, production or economics dictate. An overview of the principal technical details for the main components of a mine waste facility and of the confining embankment are described below, noting that this may comprise either a simple or a complex cross-section in which a number of construction methods are combined in order to achieve the most cost-effective dam construction. In maintaining long-term safety, disposal efficiency and suitability for closure it is common for the methodology adopted for raising the embankments and for hydraulic placement to need modification, and for the waste characteristics to change during the life of the depository. These factors must be taken into account during the design and operation process.

3.4 Containment Structures

All sectors of the extractive industry are likely to produce a residue which, during beneficiation, will be physically and sometimes chemically altered by comminution and by the concentration processes employed. These residues, generally comprising fine particulate materials (solids) mixed with process water, are discharged from the plant as a hydraulic fill. These extractive wastes, regardless of their consistency and general characteristics, need to be placed in a secure containment facility, an MWF, unless they are to be immediately recycled. Such surface MWFs tend to be referred to as "silt lagoons" by the aggregates and industrial minerals sectors, as "ash lagoons" by the energy sector and as "tailings management facilities" (TMFs) by the metal mining industry. In most cases the resulting waste product would not be stable unless confined within an engineered impoundment area, i.e. a reservoir or lagoon developed behind a containing embankment or other structural wall. As the terminology implies, the industrial processes, both refining and placement, generally involve significant volumes of water as a transportation medium. This water, by virtue of its contact with the waste, becomes defined as industrial or process water, and its use and re-use constitutes an integral part of the hydraulic filling process. The efficiency and economics of the industrial process, environmental requirements and the site water balance will normally necessitate that water used to transport the solid fraction be recycled and re-used in subsequent mineral processing. The containment facility normally includes provision not only for the storage of the hydraulically transported fill but also for the effective sedimentation of the particulate waste and the decanting and return of the excess water to the refining plant for re-use.

The effective storage of the hydraulic fill and the efficient recycling of the resulting industrial water require the appropriate design, operation and management of the mineral processing and residue storage system to achieve safe, stable and sustainable containment in the engineered facility. A facility designed for the storage of the extractive waste arising from mineral processing on a site is required to be purpose-built and, as indicated, is often stage-constructed throughout the operating life of the project. Such waste facilities need to be designed and constructed in accordance with statutory requirements and with good practice in order to store the wastes safely. The design and construction of a facility needs to be monitored by the designer, certified by a Competent Person (CP) or Independent Inspecting Engineer (IIE) appointed by the owner and, in the case of higher-risk facilities, inspected from time to time by, or on behalf of, the Regulator. Further, all subsequent modifications need to be properly designed and implemented and, again, for higher risk facilities, approved by the Regulator. The importance of documenting the design and construction process cannot be over-emphasised.

The options for transport from the refining plant and for placement and disposal in such a facility are numerous, but the principal drivers are the long-term goals of safety, stability and efficient deposition to an agreed sustainable end-point and are common to all such projects where good practice is applied. Unfortunately, examples of poor design, poor construction, poor management and incorrect operation are exemplified by failures such as those at Samarco, Mount Polley, Merriespruit, Mufulira, Buffalo Creek, Baia Mare, Aznacollar and Kolontar amongst others. Further, these incidents also show the potential dangers to both life and to the environment from design imperfections and poor operation. The principal objective is therefore to deposit the solids and mineral wastes by hydraulic placement in a custom-built and properly-designed storage facility. The depository for such materials may vary in area from less than 10,000 m^2 to several square kilometres and in height from a few metres for an aggregate silt lagoon to more than one-hundred metres for a TMF required for a large and complex polymetallic mining operation. Typical sections through MWFs for a complex metalliferous mining project and for an aggregate quarry silt lagoon are shown in Figs. 3.3 and 3.4 and provide an indication of the key features of such depositories. It is noted that, depending on the setting, not all of the features shown may be required.

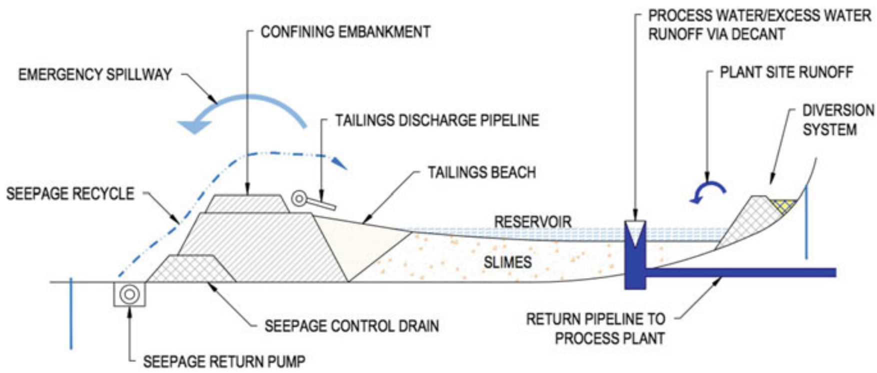

Fig. 3.3 Typical section through a tailings management facility (Cambridge 2012a, b)

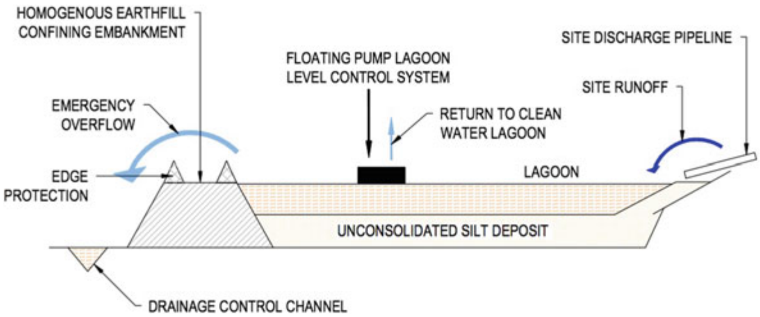

Fig. 3.4 Typical section through a silt or ash lagoon (Cambridge 2012a, b)

The purpose of the MWF is therefore twofold:

- to provide a cost-effective and environmentally appropriate means of storing the waste and of recycling the process water;
- to provide safe storage of the waste such that at closure the facility will remain geotechnically and geochemically stable, effectively in perpetuity.

3.5 Tailings Continuum

The particulate residue resulting from mineral processing is usually pumped or fed under gravity in slurry form from the beneficiation plant to the storage depository. The consistency of the slurry will vary from project to project dependent on the geological origin of the economic material, its geotechnical characteristics, the industrial processes, the configuration of the storage basin and the geographical setting. The slurry may take the form of a thin pulp with solids concentrations as low as 5%, as for many silt lagoons, or achieve 70% solids and be deposited as thickened tailings.

The properties of a hydraulic fill such as that derived from a mineral processing plant are determined not only by the geotechnical properties of the waste but also by the water content of the slurry. The latter will determine the dominant transport and disposal system, and the state of the hydraulic fill has been described as a physical continuum (Davis 2011) in which deposition management is expressed in terms of both process water content and of hazard potential (Fig. 3.5). This figure has been annotated to show the following:

(i) with *decreasing* water content

(a) the risks associated with tailings confinement decrease due to the improvement in stability;
(b) the mine waste becomes increasingly expensive to transport, i.e. as a wet cake the tailings are no longer pumpable and other transport methods are required;
(c) the process and water storage costs increase and thus operating margins are reduced.

(ii) with *increasing* water content

(a) the risks associated with tailings confinement increase, i.e. the hazard potential to the environment rises accordingly;
(b) the costs of closure and of meeting long-term liabilities increase.

The stability and environmental implications and, in particular, the high closure costs associated with storing hydraulic fill with an elevated water content, have led to the increasing adoption of dewatering techniques over the last 30 years. Figure 3.6, taken from an evaluation of global trends in dewatered tailings practice, provides a summary of the relative number of dewatered facilities on a global scale (Davis et al. 2010), showing the dominance of thickening in the disposal process since 1970. However, in spite of the obvious benefits of dewatering tailings it has

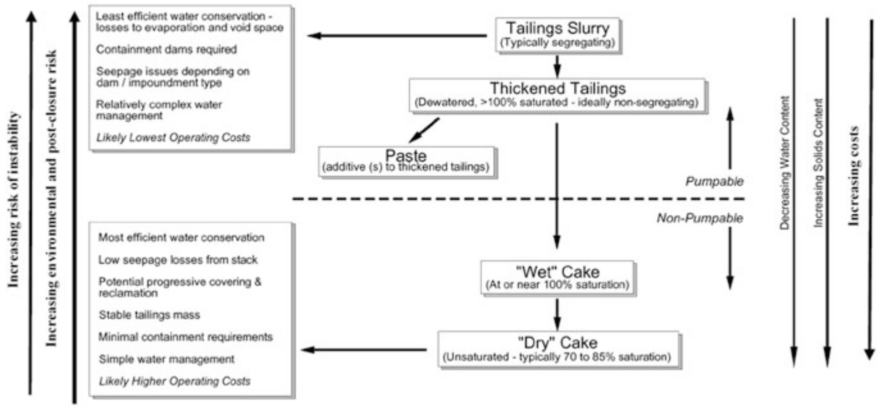

Fig. 3.5 The Tailings Continuum (Davis 2011)

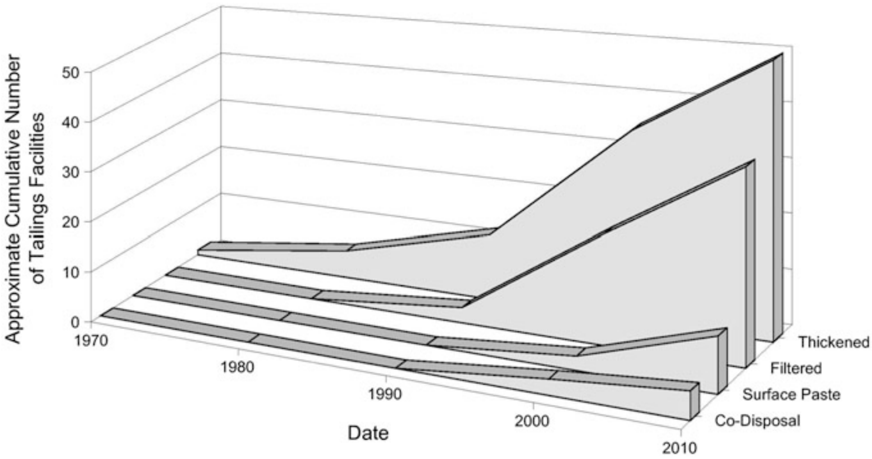

Fig. 3.6 Trends in use of dewatered tailings in mining (Davis et al. 2010)

been recognised in parallel that filtered or thickened tailings are not necessarily applicable at all disposal sites, and the minerals industry continues to rely on hydraulically-placed tailings and thus on their containment in a MWF. It has further been recognised that dewatered tailings still require some form of containment structure in most climatic conditions for reasons of environmental management and post-closure stability. Ultimately, defining the most cost-effective tailings continuum for any mine waste project is site-specific and requires rigorous assessment of mining, processing and disposal costs to suit the prevailing economic climate and to achieve environmental good practice and regulatory compliance.

3.6 General Disposal Objectives

The objectives of the disposal process are the transportation and placement of the materials by the most cost-effective and environmentally sound method. The aim is to ensure that the deposited materials achieve both geotechnical and geochemical stability in the longer-term, and the disposal system must be engineered to achieve this end-point. The adoption of inappropriate disposal techniques will reduce long-term stability and may negatively affect the environmental performance of the facility, as well as reducing the efficacy of closure and rehabilitation planning, thus increasing both operational and post-closure costs.

The key operational and environmental parameters during the hydraulic disposal of mineral wastes are geotechnical and geochemical stability. These parameters are interrelated, with geotechnics being used to drive the transportation and placement system. However, there are implications for the geotechnical characteristics of both the deposited waste and the confining embankment materials, resulting from both short- and long-term chemical changes brought about by both mineral processing and surface exposure to atmospheric conditions. The design of the storage facility must therefore consider hydraulic fill as a continuum (physical and chemical) with the key objective of managing both geotechnical and geochemical stability. Each MWF for the storage of hydraulic fill should achieve this objective, and a wide range of engineered systems is available to suit the site setting and the characteristics of the materials to be deposited.

The mine water balance and the environmental setting of the MWF are the principal drivers in determining the optimum configuration for the facility and, in particular, may dictate the method of transport and deposition of hydraulic fill. In arid or polar regions, environments where water is limited, recovery of transport water from the tailings product may need to be maximised at the process plant to avoid high evaporative or other losses from the depository and the reliance on scarce raw water supplies. The use of deep-bed thickeners and belt or vacuum filters, together with the construction of separate process water storage facilities, may therefore be necessary on such sites in order to reduce the pulp density of the extractive waste being transported and increase water use efficiency. In water-rich environments there is greater flexibility for transporting the hydraulic fill at lower pulp densities and of discharging the extractive waste on to a beach, enabling the MWF to operate as a large-diameter natural thickener. However, the adoption of a transport system for the hydraulic fill at high or low pulp density may be determined by other factors such as pumping costs, water storage capacity and environmental controls on water releases during flood periods. In all cases a principal objective is generally that residual water released from the deposited tailings be returned (decanted) to the process plant for re-use. As the water content within the hydraulic fill reduces, so the physical characteristics of the slurry change, affecting both size and capacity of the waterway used for transport as well as the rating of any pumps and the type of disposal system adopted. Figure 3.7 illustrates the relationship between water content of the hydraulic fill and pulp density, which will dictate to a greater extent the potential transport method to be considered, i.e. open channels, gravity pipelines and high pressure pipelines, as well as the type of pumping system necessary, i.e. centrifugal or positive displacement. Though conveyors and other forms of mechanical transport are available, their use is generally restricted for hydraulic fills.

Typical physical characteristics for the range of hydraulic fill properties deposited within a surface MWF, together with optimum conveyance systems, are summarised within Table 3.2. However, selection of the most appropriate transport and deposition system must be made on the basis of regional seismicity and geochemical characterisation of the extractive waste as well as of the permit and closure requirements. An additional objective is the need for the waste facility to comply with all environmental requirements at all stages of operation. This objective can only be achieved in a cost-effective manner by ensuring full characterisation of all process products both in the solid and the liquid phases. Further, the characterisation must consider both short- and long-term conditions to ensure that the facility uses the most appropriate combination of geotechnical and

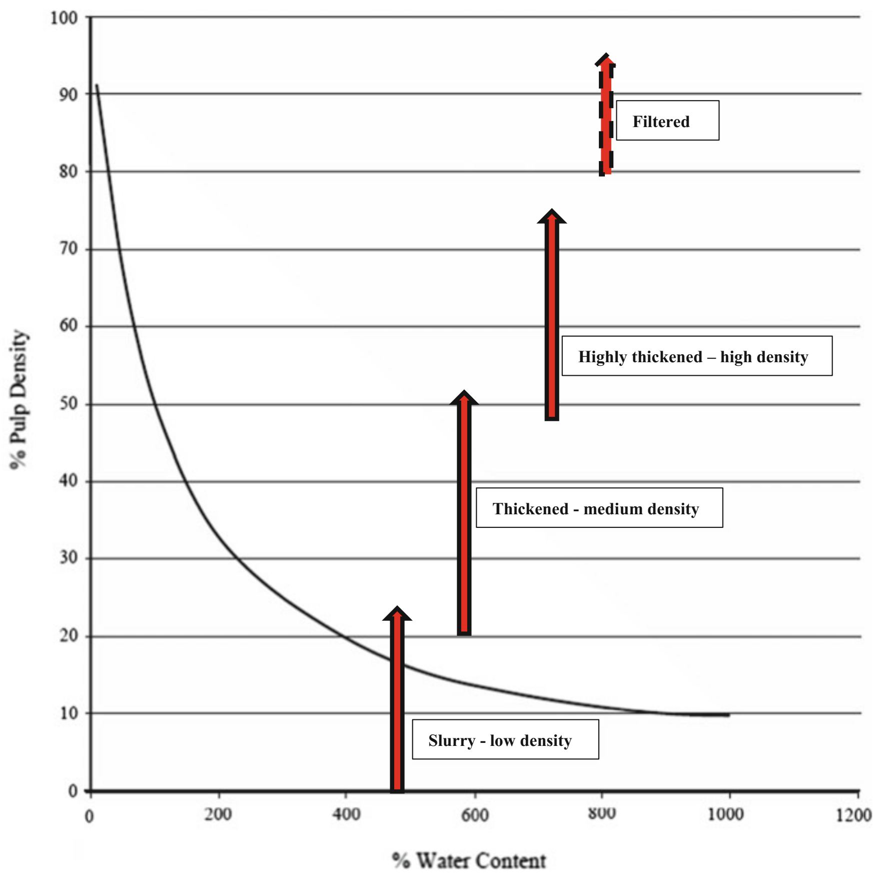

Fig. 3.7 Relationship between water content and pulp density

geochemical techniques to meet the requisite environmental standards from start-up to closure and beyond. It is noted that experience indicates that a well-engineered and well-operated mine waste facility with an efficient disposal and water recycle system is generally also fully compliant with environmental criteria.

3.7 Legislative and Regulatory Requirements

A review of the operational and permitted mine sites in Europe indicated that most MWFs were covered by some form of legislation (Cambridge 2008) before the imposition of the EWD. The majority of EU countries have national regulatory bodies for water supply reservoirs which require designs to be in full accordance with internationally accepted criteria for embankment dams, both for stability and

Table 3.2 Tailings continuum facility: characteristics and transport options

Parameter	Slurry Low density	Thickened Medium density	Highly thickened High density	Filtered (cake)
Dewatering	Process thickening only	Process thickening and cycloning	Deep bed cone thickeners	Filters (vacuum or pressure)
Typical pulp density	<20%	20–50%	50–70%	>70%
Pumping facility	Gravity low pressure pumps	Centrifugal pump	Positive displacement pumps	Trucks or conveyers
Hydraulic transport	Open channel, launders, pipelines	Low–to-medium pressure pipelines	Medium-to-high pressure pipelines	
Hydraulic placement	Single or multiple spigots Floating pipelines	Single or multiple spigots Embankment cyclone or spray-bar feed	Single or multiple spigots	Waste dump Wet stack
Deposition mode	Sub-aerial Deltaic beaches	Sub-aerial Beach deposits	Sub-aerial Sheet flow	Conventional earthworks
Supernatant pond	Large, often uncontrolled, pond	Rotational deposition control	Minimal bleed water and slope runoff only	Slope runoff only
Decanting requirements	Provide majority of plant requirements	Provide majority of plant requirements	Additional industrial water storage facility required	Additional industrial water storage facility required
Beach slopes	Dependent on beach length	1% subject to beach length	Up to 5%	N/a
Management input	Low	Medium-to-high	Medium-to-high	High
Risk (physical)	High	Medium	Low	Low
Costs	Low	Medium	High	High

hydrological control (Appendix A). Such regulations generally require the confining structures and associated waterways to comply with national or international criteria such as those produced by ICOLD, and many are subject to ongoing national embankment inspection routines. Many MWFs, whether designed and constructed in the recent past, i.e. during the last twenty years or earlier, have been governed by national legislation relating to water dams. This legislation, though not entirely appropriate, has resulted in an ongoing programme of control of design and construction processes and, in some instances, of the operational phase as well. Specific regulations recognising the differences between water dams and the confining structures for an extractive waste facility existed in only a limited number of countries, and across the EU there were no specific monitoring requirements for MWFs as distinct from water supply reservoirs. This resulted in a large number of waste facilities which met international standards of design and construction despite the varied legislative provisions, and an almost similarly-sized group whose day-to-day operations received at least some level of independent scrutiny.

In May 2008, the EU Directive EC/2006/21 on the management of waste from the extractive industries (EWD) came into force, and was transposed into national legislation by all EU Member States by 2009. This Directive is intended to regulate all mine waste materials emanating from the metal, energy, industrial minerals and aggregates sectors with the exclusion of oil and peat, and to ensure that suitable regulations exist in all EU Member States. The primary aim was to prevent a repetition of major incidents such as the overtopping of the Baia Mare tailings impoundments in Romania in 2000 (EC 2009) and the failure at Aznalcóllar in Spain in 1998 (Polimon and Rodriguez-Ortiz 2013).

During the development of the Directive it was recognised by the European Commission that there was a body of existing national regulation across the EU which was deemed to be competent when dealing with extractive waste. The EWD was therefore intended to provide regulation where it did not exist and to be complementary to existing national regulations where considered to be applicable. The following section addresses the principal EU regulatory requirements pertaining to a MWF and, in addition, references key EU Directives and International Standards of significance in brief. References to a range of national standards and guidelines are included in Appendix A.

3.7.1 The Legislative Context

European legislation is based mainly on a number of Directives from the European Parliament/Council, together with relevant guidance or reference documents. These Directives do not constitute law in themselves but rather provide a legal framework which must be incorporated into the national laws and regulations of EU Member States. It is therefore incumbent on each State to frame appropriate laws in accordance with its own legal and regulatory system by enacting new, or by adapting existing, legislation. Member States may maintain or adopt stricter measures than those contained in a Directive, but may not reduce their stringency or weaken them.

Key principles underwriting the transposition legislation relevant to extractive waste are summarised below:

- European environmental protection legislation is to a greater extent based on the principle of Best Available Techniques (BAT) rather than on strict standards and prescriptions. Compliance therefore requires a risk-based approach to determining impact. This approach is, in theory, flexible, recognising that technology and mitigation techniques, as well as the understanding of environmental, social and health and safety risks, may evolve with time.

- EU Directives also refer to the Competent Authority responsible for the regulation of a particular function, which differ between Member States according to institutional and governmental systems. Member States thus have discretion on how the requirements are regulated and enforced, provided that a regulatory authority with appropriate powers and competences is established.
- EU Directives recognise transboundary issues and the legal requirement to involve any Member States which may be affected by a development across an adjacent state boundary.

Whilst it was intended that basic legislative requirements be consistent across Europe, Member States can and do differ significantly in their approach to, and in their institutional capacity for, monitoring and enforcement. A responsible owner or operator of a MWF will need to ensure compliance through internal corporate policies, systems and resources, at the same time ensuring that all elements of the national permitting process are met and that all monitoring meets the requirements of the relevant Competent Authority. Failure by a corporate entity to ensure compliance with national legislation risks undermining its international reputation and investor confidence. It is not the intention in these guidelines to detail the specific regulatory requirements for each European country or to focus on any particular legislative system except where used for illustrative purposes. The following summary describes the overarching requirements set out in relevant EU Directives and, since Member States differ in how such legislation is implemented, regulated and enforced, diligent research is required for each specific project and location in order to ensure compliance on a specific extractive waste project.

It is noted that, even in apparently well-regulated countries and with responsible owners and operators, serious incidents still occur, such as the recent failures at Mount Polley in Canada in 2014 and at Bento Rodrigues, Samarco, Brazil in 2015. These incidents show that, though the hazard potential may be recognised at the design stage, risk mitigation remains dependent on sound engineering together with the adoption of good operating practice and a diligent approach to management and control.

The best practice guidance in this book is intended to reduce the risks of such incidents occurring in Europe.

3.7.2 Relevant EU Directives

In response to major incidents with widespread transboundary environmental and social consequences involving mine waste facilities in Europe (and elsewhere) the EU developed a framework for the safe management of waste from the extractive industries. The intention was to ensure the long-term stability of disposal facilities and to prevent or minimise air, water and soil pollution arising from acute or chronic migration of waste or its derivatives.

The three principal instruments are:

- Directive 2006/21/EC on the management of waste from the extractive industries—the Extractive Waste Directive (EWD).
- A Best Available Techniques reference document (BREF) for the management of tailings and waste rock in mining activities—the Management of Tailings and Waste Rock (MTWR) BREF.
- An amendment of the Seveso-II Directive (now the Seveso-III Directive 2012/18/EU) on the control of major accident hazards involving dangerous substances, to include in its scope the mineral processing of ores and tailings ponds or dams used in connection with such mineral processing.

Additional Directives directly relevant to the site selection, design, operation, management and closure of tailings and similar waste disposal are:

- EIA Directive 2014/52/EU—the assessment of the effects of certain public and private projects on the environment
- Environmental Liability Directive 2004/35/EC, based on the "polluter pays" principle, 2004
- European Commission of 18 December 2014 amending Decision 2000/532/EC on the list of waste pursuant to Directive 2008/98/EC of the European Parliament and of the Council, 2014
- European Commission of 3 May 2000 replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste
- European Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste
- European Commission Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, the EU Water Framework Directive.

Additional legislation and international standards of potential relevance which will apply to the disposal of hydraulic fill and mineral wastes are:

- national legislation, often based on European Directives such as protection of air and water resources, of biodiversity and of land, as well as of health and safety.
- international "standards" such as the Equator Principles and the International Finance Corporation (IFC) Performance Standards (IFC-PSs) (IFC 2013) to which they refer, and the World Bank/IFC's Environment, Health and Safety (EHS) Guidelines (IFC 2012). These are intended to provide performance levels and measures which apply to World Bank- or IFC-financed projects, mainly for countries where domestic legislation and regulation is not adequate.

Though these have no statutory or regulatory status, the Performance Standards and EHS Guidelines are often considered to be de facto international standards. It is noted that similar requirements may also apply for projects financed by EBRD and other international financial institutions.

3.7.3 Extractive Waste Directive

The Extractive Waste Directive was transposed into national legislation by all EU Member States in 2009 and was intended to regulate all mine waste materials emanating from the metal, energy, industrial minerals and aggregates sectors. The Directive addresses new or future operations, active and newly-closed operations and abandoned sites for all the extractive industries, including wastes from metal mining, industrial minerals, construction material and aggregates, salt and potash, and coal. The legislation recognises that facilities which pose potentially higher or significant risks (especially transboundary) require particularly stringent regulation. For such facilities a categorisation system is imposed with subsequent specific design, operation and closure permitting requirements. The EWD thus requires all mineral operations to characterise all extractive wastes, both rock and fine particulates, in terms of their geochemical characteristics, and the storage facility in terms of the risk posed in relation to the volume of material stored and its location. The highest-risk facilities are identified as Category A sites, based on two criteria:

(i) if a failure or incorrect operation, such as a collapse or bursting of a dam, could give rise to a major accident, on the basis of a risk assessment taking into account factors such as the present or future size, location and the potential impacts (consequences);
(ii) if it contains wastes, substances or preparations classified as hazardous or dangerous above a certain threshold (Seveso III Directive and Waste Classification).

Three main categories of extractive waste from mineral operations are defined and classified, namely:

- overburden, which refers to the layer of natural-grown soil or massive rock on top of an ore body; in the case of open pit mining operations, it has to be removed prior to extraction of the ore (metallic or mineral);
- waste-rock, which refers to part of the mineralisation without, or with low grades of, ore or poor quality mineralisation which cannot be sold profitably; and
- tailings, which refers to the particulate waste solids which remain after the treatment of minerals by physical and chemical separation processes (e.g. crushing, grinding, size-sorting, flotation and other physicochemical techniques) to remove the economic minerals. They usually comprise a slurry effluent (solids suspended in water containing process chemicals) which is pumped into ponds to undergo sedimentation.

The EWD makes no distinction between the type of extractive operation though, in associated guidance documentation, differentiation is often made between construction minerals (minerals mainly intended for use in the construction industry), industrial minerals (intended for the manufacture of products such as glass, ceramic and paper), metal ores (intended for the production of metals) and energy fuels (intended for energy production). Although the potash and salt industries belong to the industrial minerals sector, they are usually described separately in order to take into account the unique issues relating to them.

The Directive imposes obligations on Member States to ensure compliance with the requirements regarding permitting, location, construction, control, monitoring, closure and preventive and protective measures against any threat to the environment in both the short- and long-term. Best available techniques must be adopted and financial guarantees given where appropriate. Common procedures should be in place to ensure that there is consultation in cases where transboundary effects may be likely. In addition, there is a requirement for inspection to ensure that permit conditions have been complied with and that operators maintain up-to-date records which transfer to successors.

The MWD requirements are set out in 25 Articles and three Annexes, listed in Table 3.3. An overview of the requirements is given in Table 3.4.

The key elements of the Directive with respect to waste and facility characterisation are provided in Table 3.5.

3.7.4 The European MTWR BREF

The current reference document on Best Available Techniques for Management of Tailings and Waste Rock in Mining Activities was published by the European Commission in January 2009. This BREF has undergone review and a revised draft is scheduled to be adopted in 2018 (see http://susproc.jrc.ec.europa.eu/activities/waste/).

The 2009 MTWR BREF covers mineral processing to the extent relevant to waste characteristics and management, tailings (whatever the disposal method) and waste rock management where there is the potential for significant environmental impacts. The BREF addresses the extractive wastes arising from a range of minerals, irrespective of the quantities processed and the processing methods used, for the following extractive operations:

- metalliferous minerals
- industrial minerals
- coal (only if including processing and tailings production)
- oil shales
- topsoil and overburden where they are used in the management of MWFs.

It does not extend to abandoned sites or the mining, processing and tailings management associated with oil and salt from brine. The BREF is not a technical design manual and does not give standards, rules or prescriptions for the disposal of extractive waste. Its purpose is to provide a reference for owners and operators, for their design professionals, for the relevant authorities and for other stakeholders on:

Table 3.3 Organisation of the Extractive Waste Directive

Article no.	Content
Article 1	Intention—to prevent/reduce effects on environment
Article 2	Scope—management of waste
Article 3	Definitions
Article 4	General requirements
Article 5	Waste management plan
Article 6	Major accident prevention and information
Article 7	Application and permit
Article 8	Public participation
Article 9	Classification system for waste facilities
Article 10	Excavation voids
Article 11	Construction and management of waste facilities
Article 12	Closure and after-closure procedures for waste facilities
Article 13	Prevention of water status deterioration, air and soil pollution
Article 14	Financial guarantees
Article 15	Environmental liability
Article 16	Transboundary effects
Article 17	Inspections by the competent authority
Article 18	Obligation to report
Article 19	Penalties
Article 20	Inventory of closed waste facilities
Article 21	Exchange of information
Article 22	Implementing and amending measures
Article 23	Committee
Article 24	Transitional provision
Article 25	Transposition
Annex I	Major accident prevention policy and information to be communicated to the public concerned
Annex II	Waste characterisation
Annex III	Criteria for determining classification of waste facilities

- applying BAT during the design, permitting, operation and closure processes for mining wastes;
- determining what BAT comprises in a range of circumstances in order to achieve consistent environmental performance and reduced risk.

This book provides technical guidance which is generally consistent with the BREF and application of BAT principles and includes technology and practical developments where these have led to both engineering and environmental performance improvements since 2009. A detailed review and commentary on the BREF is beyond the scope of these guidelines and a degree of familiarity with its contents and framework is assumed.

Table 3.4 Overview of the EWD requirements

Key points	Description
Waste and facility classification	A waste facility shall be classified under Category A if: • a failure or incorrect operation, e.g. the collapse of a heap or the bursting of a dam, could give rise to a major accident, on the basis of a risk assessment taking into account factors such as the present or future size, the location and the environmental impact of the waste facility; • it contains waste classified as hazardous under Directive 91/689/EEC above a certain threshold; • it contains substances or preparations classified as dangerous under Directives 67/548/EEC or 1999/45/EC above a certain threshold.
Permitting	A facility operator needs a permit to operate an extractive industry waste facility and Authorities must take measures when a new facility is built, or an existing one is modified, concerning: • its location; • its physical stability and classification; • the waste management plan; • prevention of soil, air and water pollution; • monitoring and inspection; • facility closure, land rehabilitation and the after-closure phase.
Category A waste facilities	For Category A facilities (which pose particular health and environment risks) the following apply: • Operators must prepare a policy for accident prevention, a safety management system and an internal emergency plan specifying the on-site measures to be taken if an accident occurs; • National authorities must draw up external emergency plans specifying off-site measures in the event of an accident; • Operators must provide a financial guarantee to ensure that the Directive's obligations are covered prior to the beginning of operations. They must also ensure that funding is available for site restoration when a facility closes; • Decision 2009/335/EC defines technical guidelines for the establishment of financial guarantees.
Waste management	Operators must draw up a waste management plan which prevents or reduces waste generation and encourages waste recovery and safe waste disposal. It must be reviewed every five years by the authorities and should include: • a description of the waste and its characterisation (i.e. its chemical, physical, geological features). Technical requirements for waste characterisation laid down in Annex II of the Directive are elaborated by Decision 2009/360/EC. In addition, Decision 2009/359/EC completes the definition of inert waste; • a description of the substances which process mineral resources and methods used to transport and process the waste; • the control and monitoring procedures; • measures for facility closure and after-closure monitoring; • preventative measures for water and soil pollution. Authorities must ensure that operators have taken measures to prevent water and soil contamination, in particular, by:

(continued)

Table 3.4 (continued)

Key points	Description
	• evaluating and preventing leachate generation (i.e. any liquid percolating through the deposited waste, including polluted drainage) so that surface water and groundwater can escape waste contamination; • collecting and treating contaminated water and leachate to ensure their discharge. Regarding the use of cyanide in mineral extraction, the Directive introduces measures aimed at limiting its concentration in tailings ponds and waste waters.
Inspections and reports	Inspection and reporting by competent persons are required as follows: • prior to the commencement of deposit operations and at regular intervals thereafter, including the after-closure phase, the competent authority shall inspect any waste facility in order to ensure that it complies with the relevant conditions of the permit; • Member States shall require the operator to keep up-to-date records of all waste management operations and make them available for inspection by the competent authority and to ensure that, in the event of a change of operator during the management of a waste facility, there is an appropriate transfer of relevant up-to-date information and records relating to the waste facility; • Member States should send regular reports to the Commission on the implementation of this Directive, including information on accidents or near-accidents.

Table 3.5 Waste and Facility Characterisation

Article	Title	Content
Article 1	Intention—to prevent/reduce effects on environment	A waste facility shall be classified under Category A in accordance with the first indent of Annex III of Directive 2006/21/EC if the predicted consequences in the short—or the long-term of a failure due to loss of structural integrity, or due to incorrect operation of a waste facility, could lead to: • non-negligible potential for loss of life; • serious danger to human health; • serious danger to the environment.
Annex II	Waste characterisation	The waste to be deposited in a facility shall be characterised in such a way as to guarantee the long-term physical and chemical stability of the structure of the facility and to prevent major accidents. The waste characterisation shall include, where appropriate and in accordance with the category of the waste facility, the following aspects:

(continued)

Table 3.5 (continued)

Article	Title	Content
		(1) description of expected physical and chemical characteristics of the waste to be deposited in the short- and the long-term, with particular reference to its stability under surface atmospheric/meteorological conditions, taking account of the type of mineral or minerals to be extracted and the nature of any overburden and/or gangue minerals which will be displaced in the course of the extractive operations; (2) classification of the waste according to the relevant entry in Decision 2000/532/EC (1), with particular regard to its hazardous characteristics; (3) description of the chemical substances to be used during treatment of the mineral resource, and their stability; (4) description of the method of deposition; (5) waste transport system to be employed.
Annex III	Criteria for determining the classification of waste facilities	A waste facility shall be classified under Category A if: • a failure or incorrect operation, such as the collapse of a heap or the bursting of a dam, could give rise to a major accident, on the basis of a risk assessment taking into account factors such as the present or future size, the location and the environmental impact of the waste facility; • it contains waste classified as hazardous under Directive 91/689/EEC above a certain threshold; • it contains substances or preparations classified as dangerous under Directives 67/548/EEC or 1999/45/EC above a certain threshold.

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Chapter 4
Material Characterisation

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I only know that I know what I don't know
—Socrates

The design, construction, monitoring and closure of all mineral waste depositories require detailed knowledge of the geotechnical and geochemical characteristics of the extractive waste products and the foundation materials underlying the MWF as well as of the construction materials used to build the confinement structures. This Chapter presents in summary the basic principles involved in sampling and laboratory testing in order to fully determine the geotechnical and geochemical characterisation of the extractive waste and associated geotechnical materials.

Good practice indicates that such characterisation involve a competent assessment of both long- and short-term behaviour of all geotechnical materials to be incorporated into the mine waste facility. There is a broad range of standards and guidance documents on the sampling and testing of these materials. However, within the EU this characterisation is also governed by the EWD and by the subsequent Decisions which apply to depositories for the storage of all extractive wastes. The EWD clearly identifies the permitting process for all new and existing mineral sites, and requires all operators and developers to characterise their waste and to apply appropriate design and operating standards to all depositories in order to ensure geotechnical and geochemical stability. The Directive recognises that technical guidance is required in order to ensure that operators are able to submit comprehensive and technically appropriate documentation and that the regulatory authorities are competent to assess any submission prior to issuing the necessary permit to operate a facility. The EWD and the accompanying Decisions therefore included provision for the preparation of a number of technical guidance documents with the aim of providing clarity on geotechnical and geochemical characterisation. To achieve this guidance, a pan-European technical committee was established under the auspices of CENTC292 and a working group (WG8) tasked with the development of characterisation standards for extractive waste.

M. Cambridge (ed.), *The Hydraulic Transport and Storage of Extractive Waste*,
Professional Practice in Earth Sciences,
https://doi.org/10.1007/978-3-319-69248-7_4

The following documents were produced by WG8:

(a) Cyanide testing: CEN/TR 16363:2012 Characterization of Waste—Sampling and analysis of weak acid dissociable cyanide discharged into tailings ponds.
(b) Cyanide testing: CEN/TS16229:2011 Characterisation of waste—Sampling and analysis of weak acid dissociable cyanide discharged into tailings ponds.
(c) Overall guidance: CEN/TR 16376:2012 Characterization of Waste—Overall guidance document for characterisation of waste from extractive industries.
(d) Sampling: CEN/TR 16365:2012 Characterization of Waste—Sampling of waste from extractive industries.
(e) Kinetic testing: CEN/TR 16363:2012 Characterization of Waste—Kinetic testing for assessing acid generation potential of sulfidic waste from extractive industries.
(f) Static testing: EN 15875:2011 Characterisation of Waste—Static test for determination of acid potential and neutralisation potential of sulfidic waste.

Most mine waste management practitioners recognise the importance of undertaking both geochemical and geotechnical assessment in order to fully characterise a waste material. The guidance documents prepared under the mandate of CENTC292 (WG8) were primarily developed to address geochemical sampling and testing methods but recommendations for the parallel geotechnical sampling and testing of mineral waste were provided in limited detail only. In order to complement the recommendations presented in the CENTC292 documents this chapter seeks to provide further detail and description of those recommended site and laboratory protocols for both geotechnical and geochemical characterisation, noting that concentration on one technology alone does not represent good practice and can increase the risks to a mine waste facility. This Chapter summarises the sampling and testing methods for the extractive waste which need to be undertaken in order to provide both short- and long-term physical and chemical characterisation with a view to ensuring stability in the MWF under surface atmospheric and meteorological conditions. A summary of existing standards, codes of practice, reference works and best practice which can be used to characterise hydraulically placed extractive wastes is also included.

4.1 Legislative Requirements

Annex II of the EWD (Table 3.5) indicates that description and characterisation (chemical, physical and geological) of the extractive waste is a technical requirement. The physical and chemical characteristics of these waste materials determine both the design choices in terms of disposal and confinement techniques and their behaviour during operation and post closure. It is very difficult to produce a rational and satisfactory design for a MWF without a proper understanding of the physical and chemical nature of the solids and effluent. It is therefore imperative that all mineral wastes be characterised early in the development of an extractive waste storage facility. Good practice and the development of a robust design and closure strategy require that characterisation be undertaken during all stages of the project. This should cover the initial feasibility and the final design stages as well as the operational phase, since the physical and chemical characteristics of the materials can, and do, change throughout the life of a project. Characterisation is also necessary post closure in order to ensure that the closure objectives are being met and that long-term geotechnical and geochemical stability can be assured. The legislative requirements defined in Annex II and in the accompanying technical guidance are summarised below.

4.2 Sampling

The EWD requires the characterisation of all geotechnical and geochemical properties of extractive wastes necessary to understand their likely behaviour throughout the life-cycle of a project. The success of a characterisation programme relies on being able to test the full range of materials to be encountered, namely:

(a) foundation materials beneath the MWF, including both superficial deposits and the solid geology;
(b) all construction materials for incorporation into the confining embankments and associated structures;
(c) representative samples of all extractive waste materials to be deposited, confined or stored.

The aim is to allow identification of the properties of all geologically derived materials at all stages of the development of a waste facility from initiation to post closure, and to ensure that the materials sampled for testing are truly representative. Further, the samples for testing must accurately reflect the physical and chemical properties encountered on the site. Sampled materials should therefore be preserved, transported and stored so that no alteration or degradation, either physical or chemical, occurs before they are tested in the laboratory and that no significant change in material parameters is experienced.

Sampling campaigns must be properly planned and organised, with the number of samples taken, their type, size, volume and the methods of preservation, storage and transportation to the laboratory being specified. The investigation programme should be supervised by an experienced engineering geologist, geotechnical engineer or geochemist and the work be undertaken by properly accredited contractors using trained staff who have been familiarised with the specification, extraction and sampling requirements and with the prevailing site (topographical, meteorological and geological) conditions.

Sampling will be required when there is a need to characterise the material:

- as part of the development of a new project;
- as part of a regular programme of quality assurance for both construction and deposition;

- during an active operation with the objective of addressing a specific problem;
- as part of life of mine testing;
- as part of the development or updating of a closure plan.

4.2.1 Geotechnical Sampling

Geotechnical characterisation of materials can be achieved either through sampling and laboratory testing or from in situ testing. This section focuses on the former.

Characterisation for geotechnical purposes is intended to assess those physical and mechanical properties of the materials to be incorporated into a MWF, whether for structural or storage purposes, which would have a direct effect on the design requirements of the facility, including determination of both short- and long-term stability. For simplicity, sampling for geotechnical testing is described separately for materials to be used in the confining structures and for those to be deposited and stored. Sampling of the foundation materials is included within the first category. Generic standards for sampling for geological and geotechnical purposes are well-documented and it is not the purpose of these guidelines to review these except where a hydraulic fill project requires non-standard techniques. However, reference is made to existing EN, BS, DIN and other appropriate standards for planning a sampling programme, for contracting the necessary expertise and for obtaining, storing and transporting the samples.

It is important to note that, although sampling and laboratory testing continue to play an important role in geomaterial characterisation, the use of field tests has gained predominance over the past three decades. There are now over 150 different field devices, in situ probes and instruments which can be used for ground investigation work (Mayne 2016), although the most widely-used are the cone penetration test (CPT), flat plate dilatometer test (DMT), vane shear (VST), standard penetration tests (SPT), and pressuremeter (PMT). In addition, the geotechnical engineer also has access to a range of geophysical, non-destructive techniques to characterise geomaterials. Devices such as the seismic cone (SCPT), the seismic piezocone (SCPTu) or the seismic dilatometer (SDMT), which combine geotechnical probing and geophysical mapping, allow for fast and economic profiling of strata and evaluation of material parameters. A number of field tests for geotechnical investigation are fully described in ENISO22476 (13 parts), are fully referenced in EN16907 (2017) and thus not discussed further in these guidelines.

4.2.1.1 The Confining Structure and Foundation Materials

The design of a mine waste facility requires suitable knowledge and understanding of the physical and engineering characteristics of both foundation materials and of the construction fills to be incorporated into the confining embankment. The following sampling campaigns are therefore required:

- pre-development—sampling of a comprehensive range of materials which fully reflect the geological conditions on the site and the local construction materials available in order to determine the baseline parameters for the design of the MWF;
- pre-deposition—sampling of the foundations and confining structure in order to confirm facility design assumptions;
- operation—ongoing sampling of the construction materials incorporated into the confining structure as part of the construction quality assurance programme;
- closure and beyond—sampling of both cover and confining structure as necessary in order to confirm long-term stability.

The sampling programmes should be detailed in advance to suit the overall facility development plan and should identify not only the investigative and sampling methods to be employed at each location but also the appropriate EU or national standards to be adopted on the site. Though on most sites standard investigative and sampling techniques are likely to be appropriate, the sampling programme should be comprehensive and should therefore identify any areas or materials for which non-standard techniques may be required.

The suitability of a site can only be confirmed after a pre-investigation assessment of the sub-surface conditions in order to identify, in particular, the range of material types likely to be encountered. This should be done in accordance with the guidance provided in EN1997. Sampling constitutes an integral part of the evaluation process and any sampling for geotechnical purposes should follow the recommendations included in ENISO22475-1.

The investigation of MWF sites, together with the identification of potential borrow areas for embankment construction materials, should enable a qualified and experienced professional geotechnical engineer to define the following:

- geological profile, including both superficial deposits and the solid geology[1,2]
- spatial variation in lithology of superficial deposits and the solid geology;
- hydrogeological conditions;
- spatial variations in the structure and competence of the superficial deposits and the solid geology.

[1]The long history of mining in Europe indicates that the site characterisation should include an investigation for the presence and extent of old mine workings, particularly in relation to dam foundations and the long-term stability of the storage basin (Cambridge 2004).

[2]Initial desk studies should include, where appropriate, identification of any potential for former/existing services and unexploded ordinance.

4.2.1.2 The Extractive Waste

Characterisation of the extractive waste for geotechnical purposes aims to assess those physical and mechanical properties which have a direct effect on the design requirements of the storage, transport and disposal system. The proper design of a facility for the storage of any hydraulic fill requires adequate knowledge and understanding of the physical and engineering characteristics of the extractive waste from the onset. Further, due to the nature of extractive waste and its potential to change both physically and chemically during the life of the project, there should be adequate testing of representative samples during the design and construction stages in order to be able to determine the following:

- the physical characteristics, including both settling and rheological properties, of the hydraulic fill prior to deposition;
- the engineering characteristics of the deposited solids in terms of storage and stability;
- the potential to interact with the local environment geologically, geochemically and meteorologically.

Pre-deposition

During the initial stages of a project the only source of samples for geotechnical characterisation will come from a comminution and metallurgical pilot plant. As this plant will have operated on a restricted number of samples and therefore volume of the economic material, the properties of this initial extractive waste may differ significantly from those which will be produced during full-scale operation of the process plant. In addition, the degree of weathering of the parent material and the full-scale metallurgical processes employed to extract the economic material developed during the commissioning phase will further influence these physical properties. The pre-deposition pilot plant sampling used for initial characterisation should therefore be considered as a guide only and the results treated with caution. It is advisable to adopt a conservative approach to the selection of design parameters during the early, pre-deposition, stages of the engineering process until such results can be confirmed from tests carried out during the commissioning phase.

Deposition

During operation, geotechnical sampling will normally be performed in order to confirm the parameters used for initial design purposes as well as for those associated with future embankment raises. The waste should be sampled for ongoing characterisation both as a slurry from source, i.e. at the outlet from the process plant (the “tailings box”), and as a settled solid fraction from the deposit.

End-of-Pipe Sampling

The ongoing testing of end-of-pipe samples from the process plant is required in order to confirm design assumptions. A strict protocol for obtaining slurry samples is therefore necessary and should reflect both the ore being processed and the status of the process plant in order to ensure that the waste is suitably representative. The sampling should be arranged in conjunction with the plant management in order to ensure that samples taken are representative, or as near as possible, of the optimum operating conditions in terms of pulp density and particle sizing. It is noted that samples taken during start-up, end of shift or during changes in extraction operation can lead to misleading laboratory results and should be avoided unless a specific process or geological characterisation problem is being addressed. The protocols for sampling should be specified during the design phase and would normally be fully described in the Operating and Maintenance Manual (Sect. 7.2.2.4) to be prepared as part of the initial design studies.

Sampling from the Deposit

Ongoing sampling of the in situ, as-deposited extractive waste is required for confirmatory purposes and, in particular, for storage and stability assessment. Samples for laboratory testing may be obtained from both sub-aerial (beach) and sub-aqueous deposits. Sampling of in situ waste deposits is complex for two fundamental reasons:

(a) the materials to be sampled may contain high levels of water, be very sensitive to disturbance and may not be readily accessible in safety by conventional sampling equipment. Obtaining representative undisturbed samples thus requires specialist equipment and techniques;
(b) the deposition of slurry into a depository generally results in significant spatial variation in material characteristics in relation to the discharge system (sub-aqueous or sub-aerial disposal), distance from the deposition point and the extent and location of the reservoir. Further variations may also occur due to changes in slurry density and to operational issues such as configuration of the distribution system, discharge velocity at the distribution point, sedimentation rates, gradient of the beach and rate of erosion and aggregation.

The sampling programme should recognise that geotechnical properties will be influenced not only by the depositional arrangements but also by the processes applied to the slurry, such as flocculation, thickening, and pumping, the configuration of the transport and disposal system and the settling properties of waste particles. In particular, the discharge arrangements, velocity and sedimentation rate into the depository as well as the deposition environment will affect particle segregation (ANCOLD 2012). Figures 4.1 and 4.2 show the differences in particle sorting between tailings deposited sub-aqueously and sub-aerially under laboratory

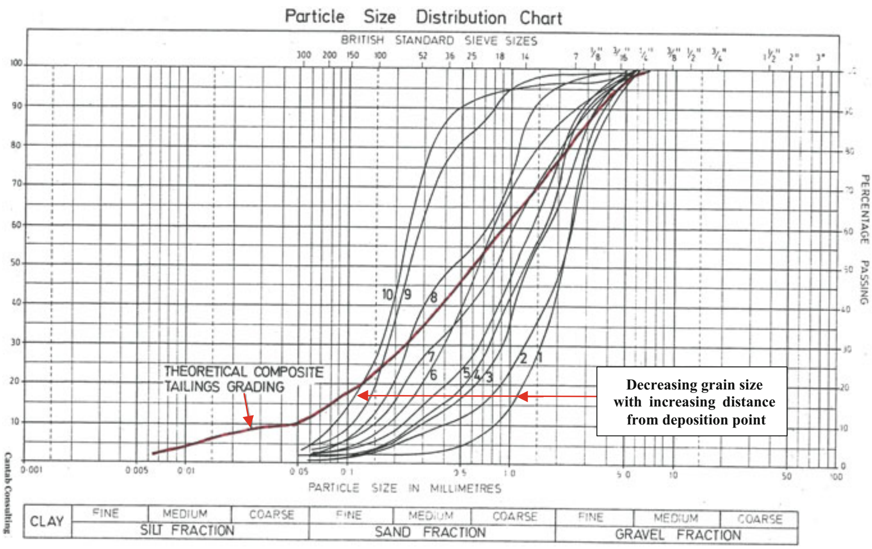


Fig. 4.1 Particle size distribution for sub-aqueous deposition derived from laboratory trials. *Note* Sampling points are equally spaced and numbered sequentially from the discharge point, commencing at 1

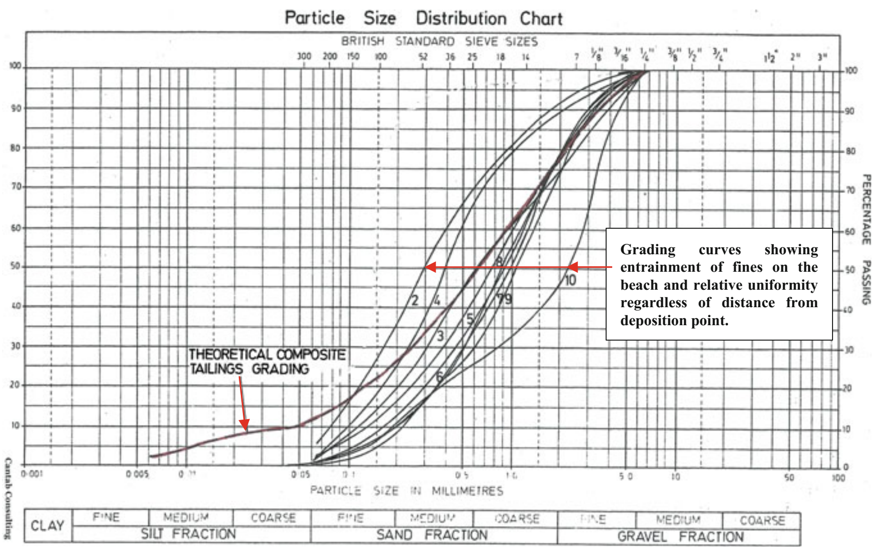


Fig. 4.2 Particle size distribution for sub-aerial deposition derived from laboratory trials. *Note* Sampling points are equally spaced and numbered sequentially from the discharge point, commencing at 1

conditions (Cambridge 1978). The resulting grading curves provide a clear indication of segregation in the sub-aqueous deposit in comparison with a similar sample placed sub-aerially under identical conditions.

To obtain representative characteristics of the waste across the depository requires careful planning of both sampling location and method. A depository involving a multiplicity of disposal locations, a variable pond area or wide fluctuations in plant output will require a greater number of samples in order to address spatial variation. On some complex sites, sampling may need to be targeted at deposited waste representing the upper- and lower-bound density states, and the facility characterisation adjusted accordingly.

The spatial and geotechnical variations will almost certainly require the use of conventional sampling techniques, such as block, open-drive, piston-drive or rotary core. Information on sampling for geotechnical characterisation can be found in the extensive literature on the subject (Hvorslev 1949, amongst others). In addition, guidance on standard sampling techniques for geotechnical practice is provided in ENISO22475-1. However, standard methods are generally only applicable in a competent deposit. Where sensitive materials are to be sampled, specialist equipment such as the Sherbrooke down–hole block sampler (Lefebvre and Poulin 1979), the Bishop sand sampler (Bishop 1948), the Laval sampler (La Rochelle et al. 1981), the nitrogen bubble sampler or special sampling sleeves (such as mylor liners) will be essential. Sampling of soft sediments is a specialised field and reference should be made to the technical literature. The use of sophisticated sampling techniques, however, is expensive and can be time-consuming. Bishop sampling was successfully used during the 1970s on the Clemows Valley Tailings Dam (CVTD) in Cornwall in order to obtain undisturbed beach samples below the phreatic surface (Fig. 4.4) but it was only in 2013 that a Gel-Push sampler was used at the Zelazny Most tailings dam in Poland to obtain samples at depth. Previously, geotechnical characterisation of the tailings on this Polish facility had been done by means of in situ testing (Jamiolkowski 2014).

It is noted that random distribution of sampling locations or perimeter sampling alone will not be sufficient to truly characterise the depository. Reliance on such a sampling programme may lead to over-optimistic assessment of a facility's storage parameters.

In addition to the careful programming of the investigative techniques, the retrieval, packaging, storage and transport of all extractive waste samples requires careful planning if the material received in the laboratory is to be truly representative of the deposit. The handling of such samples is fully described in ENISO22475-1.

Although it is possible to reconstitute samples in the laboratory for testing, it is important to recognise that the actual in situ material will reflect both material grading and the deposition system, as demonstrated in the highly-laminated and spatially-varied deposits shown in Fig. 4.3. The properties of a reconstituted laboratory sample may therefore be an approximation of material parameters only and not representative of the waste, and thus the results of the testing should be treated accordingly. It should also be noted that the physical characteristics of the segregated components of the waste will also differ from those of the original material and not be representative of the deposit. On facilities where the deposit shows

Fig. 4.3 Examples of laminated tailings deposits

significant signs of particle segregation, account of this physical characteristic should be taken into consideration during preparation of samples in the laboratory (ANCOLD 2012). For some elements of the deposit, separate sampling and testing of the segregated components may be helpful in the storage assessment. This is particularly relevant where drainage is governed by specific zones of the deposit, i.e. the coarser fraction is deposited preferentially against the confining embankment and higher permeability values are of significance. Finally, segregation and cross-bedding leads to a laminated deposit and to a high degree of anisotropy and, in particular, to an elevated horizontal-to-vertical permeability ratio, i.e. k_h/k_v. Where this is important to drainage or long-term consolidation rates, the sample returned to the laboratory must reflect this anisotropy and the sample be in a suitable condition such that it can be tested both vertically and horizontally.

Conventional sampling of geomaterials, including sampling techniques and sample disturbance, is extensively covered in the literature on geotechnical site investigation (Clayton et al. 1995; Simons et al. 2002) and in the European standard on geotechnical sampling (ENISO22475). The EU guidance document (CEN/TR16365) specifically addresses sampling of extractive waste but the focus is mainly on obtaining material for geochemical requirements. The sampling plan for geotechnical characterisation must be prepared on the basis of the recognition of the inherent properties of an extractive waste deposited hydraulically and address spatial variations in material properties resulting from the hydraulic filling of the depository. In addition the plan should take cognisance of the accessibility problems, noting that hydraulic fill deposits may not permit access by either operators or sampling equipment. The plan should address all safety issues associated with access to the deposit and make allowance for the provision of low-ground-pressure vehicles, access causeways or other sampling platforms to enable the requisite samples to be taken.

It should be recognised that when samples are taken from a deposit for laboratory testing the process will inevitably result in some degree of disturbance. The sampling plan should allow for obtaining both ‘disturbed’ and ‘undisturbed’ samples and ensure that suitable material from each category is taken to enable the laboratory testing programme to be completed.

EN1997-2 and ENISO22475-1 consider three sampling method categories and five sample quality classes. Whereas sampling method Category A yields samples of quality Classes 1 to 5, Category B provides samples of quality no better than Class 3. Samples of quality Class 5 can only be obtained when sampling method Category C is used. The quality classes define the minimum sample quality required to measure a given material property. Stiffness and strength can only be measured in Class 1 samples, whereas a minimum of a Class 2 sample is needed to obtain an accurate estimate of density and permeability. Class 5 samples can only be used to identify soil type and the sequence of layers. However, it is recognised that both EN1997-2 and ENISO22475-1 were developed for sampling normal geological horizons and are not necessarily applicable to the low density laminated fine-grained materials encountered in a hydraulic fill deposit. Some variation in the use of these sampling categories may thus be required for extractive waste deposits placed hydraulically.

Undisturbed samples are needed in order to replicate in the laboratory the stress changes and drainage conditions expected to take place in the field. Samples must therefore be representative of the in situ material in terms of structure, density, and water content. When undisturbed samples are required for material characterisation, the sampling method must be in agreement with the material tested. The acceptable degree of sample disturbance should be considered when interpreting test results, noting that sample disturbance in soft materials can result in high data scatter and low measured shear strengths (Hight 2000; Simons et al. 2002). The sampling programme should also take account of potential disturbance taking place beyond the sampling stage due to loss or migration of moisture arising from transportation or temperature changes, and the methods of sealing, packaging and transport must be clearly defined to minimise these impacts. Finally, the programme needs to ensure that any samples which might undergo significant physical changes due to chemical processes between sample extraction and the laboratory are preserved effectively in order to prevent any deterioration.

Drilling in soils and soil-type materials permits continuous sampling using the range of samplers previously described. Alternatively, trial pits may be excavated in the deposit in order to obtain larger-volume disturbed samples and undisturbed tube and block samples, as outlined in ENISO22475-1. The choice of sampling method will depend on the quality required, on the condition and sensitivity of the in situ material and, often, on accessibility for machinery or even personnel, as indicated in EN1997-2. However, of primary importance is that the sample should be sufficiently large to allow testing of the in situ structure of the deposit and contain a representative distribution of particle sizes to enable the planned laboratory tests to be carried out. For more sophisticated laboratory testing the material should have a water content which reflects the in situ deposit.

For guidance on sampling for geotechnical purposes, reference should be made to the following European standards:

- EN 1997-1:2004 Eurocode 7—Geotechnical Design—Part 1: General rules.
- EN 1997-2:2007 Eurocode 7—Geotechnical Design—Part 2: Ground investigation and testing.
- EN ISO22475-1:2006 Geotechnical investigations and testing—Sampling methods and groundwater measurements—Part 1: Technical principles for execution.
- CEN/TR16376:2012 Characterisation of waste—Overall guidance document on characterisation of wastes for the extractive industry.

Appropriate methods of handling, transportation and storage of samples, as well as of reporting summary logs, drilling and sampling records, are described in ENISO22475-1 and CEN/TR 16365. Guidance on the transport of soil samples of different quality classes is provided in ENISO22475-1, though special allowance for the particular properties of hydraulic fill will also be necessary.

4.2.2 Geochemical Sampling

The purpose of a geochemical characterisation campaign is to identify any hazardous or dangerous substances, as defined in the EU waste catalogue, as well as to assess the acid generation potential and metal leachability of the mineral waste (EC Decision 2009/360/EC). The EU classification system for waste in terms of hazardous/non-hazardous, inert/non-inert (Council Directive 91/689/EEC on hazardous waste, Decision 2000/532/EC and EWD 2009/359/EC) has been adopted for these Guidelines. However, where there is no relevant standard, reference has been made to international good practice. It should be noted that non-standard geochemical tests may also need to be undertaken should any properties of the material be deleterious to the proposed disposal system.

The EU has developed the standard EN14899:2005 *Characterisation of waste—Sampling of waste materials—Framework for the preparation and application of a sampling plan*, together with more specific guidelines for the extractive industries in CEN/TR 16365:2012 *Characterisation of waste—Sampling of waste from extractive industries*. In addition, the GARD Guide developed by INAP (INAP 2009) also contains international guidance on the development of a geochemical sampling programme and the factors to be considered. These documents provide comprehensive information on geochemical sampling.

4.2.2.1 Characterisation of Waste as Part of a New Project

The source of geochemical samples depends on the metallurgical testing programme and the variability of the ore for which the process plant has been designed.

Good communication with the geological and metallurgical teams throughout all stages of a mine waste project is therefore vital in order to ensure that representative samples are obtained during the development of the process flow sheet.

Extractive Waste

The number of samples of the extractive waste which need to be tested depends on the likely variability of the hydraulic fill material to be generated over the operating life of the facility (Price and Errington 1998). Mineral processing plants are designed for an optimum ore composition, but some deposits can change significantly as extraction progresses. A process plant can be adapted for a range of different ores such that, on mining projects where oxide ores are developed during the initial extraction phase, modification is subsequently required in order to treat sulfide ores. It is this potential variability in ore characteristics over the life of the project which makes it necessary for the characterisation programme to be iterative. Samples must therefore be representative of the material to be deposited but it must also be recognised that the extractive waste generated in a pilot plant might not necessarily simulate that produced during full-scale plant operation. It is therefore important to understand any shortcomings in the representative nature of the samples at the pre-deposition phase. Further, the limited amount of hydraulic fill generated from such a pilot plant may not be sufficient for detailed geochemical characterisation. This issue must be addressed if the material characterisation is to be based on internationally acceptable sampling criteria (BC 1990).

In addition to the basic geochemical testwork it is also necessary to characterise the solution phase of the slurry. This is particularly important with respect to environmental controls on releases and in identifying potentially detrimental constituents in the return water which might affect metal recovery. It is also essential to ensure that the basic geochemical testwork and solution characterisation are appropriate as the basis for longer-term predictive geochemical modelling. Sampling must therefore ensure that any water used in the testwork is representative of that to be produced, as tap or deionised water may give misleading results, with potentially negative impacts on production. The hydraulic transport, deposition and sedimentation processes may lead to particle-sorting, and therefore samples for such testing may need to be divided into fine and coarse fractions to ensure that, particularly where sulfides or other potentially deleterious contaminants are preferentially reduced in size during grinding in the comminution circuit, they are suitably modelled in the laboratory. Figure 4.4 shows the effect of the disposal system on the spatial variations in potentially acid-generating constituents arising from sub-aerial deposition on a beach.

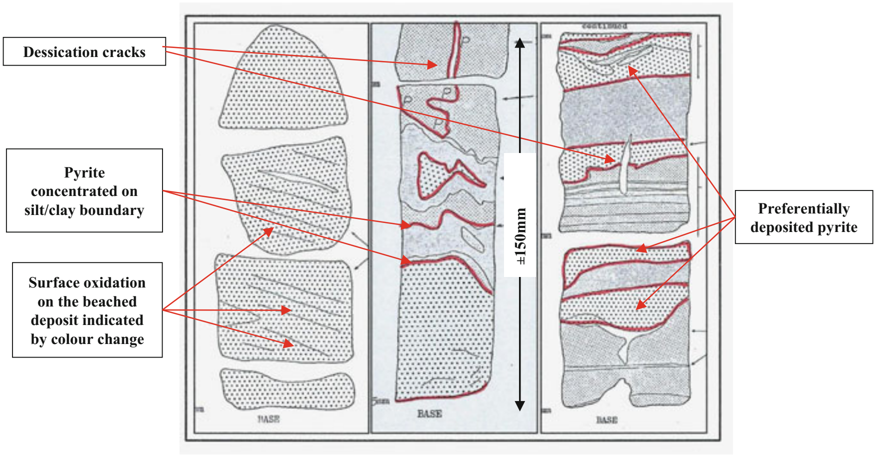


Fig. 4.4 Bishop samples showing geotechnical and geochemical variation in sub-aerial deposit

The Confining Structure and Foundation Materials

In addition to the extractive waste it is important to characterise all materials to be used for construction of the storage facility in order to ensure that only materials with suitable engineering and geochemical properties are adopted in any confining embankment or appurtenant structures. It is evident across mining areas generally that mineralisation and the presence of potentially deleterious mineral constituents are not restricted to underground exposures but are also prevalent on surface. It is noted that this characterisation is a principal constituent of the permitting process and also creates a baseline data set against subsequent quality assurance for construction material selection and placement.

Finally, the location of the disposal site should also be subject to detailed geochemical assessment in order to establish baseline characterisation and also to identify any potentially deleterious foundation materials which might affect the geochemical and environmental performance of the waste facility.

It is normal practice, and often mandatory, for the site of a waste storage facility to be subject to condemnation drilling to ensure that it will not be located above a deposit with economic merit.

4.2.2.2 Characterisation of an Active Operation

Once a project moves into the development phase, further characterisation is essential to ensure that the basis on which the mine waste facility was designed remains valid and to confirm that no fundamental redesign is required. Ongoing characterisation testing is then undertaken for both CQA and permit compliance purposes as part of a life of mine programme in order to confirm adherence to water storage criteria and release assessment. The sampling plan for geochemical characterisation must be also be prepared on the basis of the inherent properties of the hydraulically deposited extractive waste and consider spatial variations in material properties resulting from the deposition mode. Again, the plan should take cognisance of accessibility problems and should address all safety issues associated with sampling from the deposit and the potential issues of low ground pressure, of unstable surfaces and of access to the pond for sub-aqueous sampling. Such ongoing characterisation testing should be subject to expert scrutiny and the scope and extent of testing and sampling regularly reviewed.

It may be necessary to address specific geochemical and geotechnical issues during the mine life, requiring a review of both sampling and testing schedules. Again, expert input is advised, involving a site visit, a review of pre-existing information and of the extraction schedule in order to define and detail the problem-specific sampling programme in suitable detail. CEN/TR 16365 presents a detailed description of the key elements of a sampling plan, and reference should be made to this document when defining a sampling strategy.

4.2.2.3 Characterisation for Closure

It is a regulatory requirement that the closure plan for all extractive waste facilities be regularly updated, for which additional sampling may be necessary to provide information on the future behaviour of the waste in order to select the optimum engineering approach to further development of the project or to the closure of the facility. The sampling strategy will depend on a multiplicity of variables which will affect both frequency and number of samples, and will include such elements as:

- the initial design of the facility;
- the variability of the deposit over the life of the project;
- the climatic regime;
- the operational development of the facility;
- the closure strategy (i.e. dry- or wet-closure).

4.3 Geotechnical Characterisation

The development of a MWF requires the full characterisation (i.e. determination of the key physical and mechanical properties) of the hydraulic fill, of the foundation materials below the facility, and of the materials to be used in construction of the confining embankment and other structures. Such characterisation is an ongoing requirement and under the EWD is mandatory for a Category A facility at all stages from pre-feasibility to post-closure. The extent of the characterisation process will be dependent upon the phase of the project, involving preliminary characterisation during the feasibility study, detailed characterisation of construction materials for final design and confirmatory testing as part of the operational CQA as well as for compliance during both active and passive closure phases. The characterisation to determine physical properties of both the hydraulic fill and the facility construction materials is required for different engineering and environmental needs at each stage of the project, namely:

- during the feasibility and final design stage in order to determine facility design parameters;
- during operational and deposition stages in order to ensure that stability, storage and design assumptions remain valid throughout project life;
- during the implementation of the closure plan in order to confirm the closure assumptions and, in particular, the parameters for any cover materials, for the confining embankment and for the deposit;
- during the post-closure period for compliance purposes.

4.3.1 Site Characterisation: Foundation and Construction Materials

During the development phase of the project, potential sites for a storage facility will need to be evaluated to enable sub-surface conditions to be established and the optimum location for the MWF identified. Once the final location has been agreed, detailed site investigation will be required in order to define the site characteristics and the suitability of potential borrow materials for inclusion in the confining embankment. The evaluation of sub-surface conditions generally requires both intrusive and surficial exploratory techniques in order to identify the geological setting, the nature, extent and sequence of the soils and rocks encountered, and the location of the water table. A primary aim will be to collect samples for laboratory testing and analysis, both geotechnical and geochemical, and to carry out in situ testing. Data collection for characterisation purposes will therefore involve exploratory boring or drilling, test pitting, geophysical surveys, sample collection, in situ testing, geological mapping and detailed logging of all exploratory sites.

The scope of a site investigation should be undertaken to a pre-prepared exploration plan and be integrated with other investigative works on the site, such as geochemical assessment and environmental, landscape and ecological studies. The investigation must be sufficiently detailed to establish the general characteristics of a site and its geological setting, and must provide information on the following:

- lithology, stratification and dominant tectonics of both local and regional geological formations;
- nature, extent and consistency of the surficial soils, particularly liquefaction potential;
- structure, strength, compressibility and permeability of foundation materials;
- nature of the groundwater conditions and the location of any phreatic surface;

- the presence of historic mine workings, their depth and extent;
- suitability of local materials for embankment construction, for natural liners, for drainage media and for cover materials for closure and restoration;
- availability of soil-forming materials for both ongoing and final rehabilitation.

The characterisation of foundation materials in a potential site for an extractive waste storage facility should be undertaken in accordance with a co-ordinated investigation and sampling plan under the supervision of a suitably qualified ground engineering professional who is experienced in this type of work. The site investigation and material characterisation should be undertaken in accordance with the guidance provided in the following European standards:

- EN 1997 Eurocode 7: Geotechnical Design.
- EN ISO 14688 Geotechnical investigation and testing—Identification and classification of soil.
- EN ISO 14689 Geotechnical investigation and testing—Identification and classification of rock.
- EN ISO 17892 Geotechnical investigation and testing—Laboratory testing of soils.
- EN ISO 22282 Geotechnical investigation and testing—Geohydraulic testing.
- EN ISO 22475 Geotechnical investigation and testing—Sampling methods and groundwater measurements.
- EN ISO 22476 Geotechnical investigation and testing—Field testing.
- European Standard Earthworks—EN16907 (2017)

4.3.2 *Characterisation of Hydraulic Fill*

The design and operation of an extractive waste storage facility necessitates a detailed understanding of the properties of the hydraulic fill to be stored. This knowledge can only be gained through testing of representative samples of the waste product in the laboratory, together with later-stage field testing in order to verify the in situ characteristics during operation of the facility. Geotechnical characterisation should include assessing the intrinsic properties of the material, including particle size distribution, particle specific gravity, settling velocity and minimum settled density, together with the engineering properties of shear strength, permeability, compressibility and rheology. Standard laboratory and field tests in general use in geotechnical engineering practice can be adopted to obtain the majority of properties of the hydraulic fill. Such standard tests should be carried out in accordance with the guidance provided in the European standards given above, together with those listed in CEN/TR 16376. However, due to the nature of extractive wastes, non-standard geotechnical testing will be required, the extent of which will depend on the tailings properties, on the configuration of the MWF and on the process flow sheet.

A list of standard and non-standard tests is given in Tables 4.2 and 4.3 respectively and, in addition, the non-standard tests are described in detail in Appendix B2.

4.3.2.1 Standard Geotechnical Testing

The characterisation of any hydraulic fill requires an understanding of the fundamental properties of the extractive waste and an assessment of the variation in the internal arrangement of the constituent particles at each stage of the process from hydraulic transport through deposition, sedimentation and consolidation. Establishing these properties requires an understanding of the phase relationship within the fill and the variation in the constituent masses/volumes in the solid, liquid, and gas phases. The properties of the body of the hydraulic fill are a function of this relationship and enable determination of the engineering parameters which define the performance of the deposit en masse. Although common descriptors of packing and density in particulate materials can be found in any introductory book on soil mechanics or soil physics, the most used parameters are summarised in Appendix B1.

The most important intrinsic and engineering characteristics of hydraulic fill which should be obtained as part of the geotechnical characterisation process are given below. Each is then briefly discussed in turn.

- Particle size distribution
- Water content
- Degree of saturation
- Mineralogy
- Plasticity
- Particle specific gravity
- Void ratio and porosity
- Compaction characteristics of coarse fill
- Permeability
- Compressibility
- Consolidation
- Shear strength

In addition, a summary of methods available to determine each parameter is presented in Table 4.2.

Particle Size Distribution

The distribution of grain sizes constitutes the most important property in soils and soil-type materials such as hydraulic fill. EN ISO 14688-1 divides material into different fractions according to size, from very coarse soils (boulders and cobbles), to coarse soils (gravels and sands), to fine soils (silts and clays). Only material within the sand, silt and clay fractions would normally be expected to be present in a hydraulic fill. The distribution of particle sizes is generally represented graphically by a grading curve. For extractive wastes the comminution process in the plant determines the final grading envelope for the hydraulic fill. It is therefore essential that the testwork programme assess the impact of the comminution circuit on the sizing and ensures that the analysis extends to the finest particle to be produced. In many cases the process reduces a significant proportion to clay size, i.e. smaller than 2 μm, and thus particle sizing requires sedimentation analysis in addition to sieving. It is noted that the experienced practitioner can estimate many of the basic parameters from this grading curve and thus use this information to define the full testwork programme. Typical particle sizings for European extractive wastes are shown in Figs. 4.5 and 4.6.

Water Content and Degree of Saturation

Water content is given by the ratio of weight of water to weight of solid particles, usually expressed as a percentage. In fine materials, particularly clays, the water content is used as an index property with respect to consistency. The water content at which a soil flows like a liquid is defined as the liquid limit and the corresponding value at which a soil starts to display brittle behaviour is defined as the plastic limit (see also Plasticity). These two limits roughly correspond to undrained strengths of approximately 2 and 200 kPa respectively. The range of water content over which a soil displays plastic behaviour is defined by the plasticity index.

A particulate material having all the void space occupied by a fluid is in a fully saturated state. If part of the pore space is occupied by gas, the material is in a partly

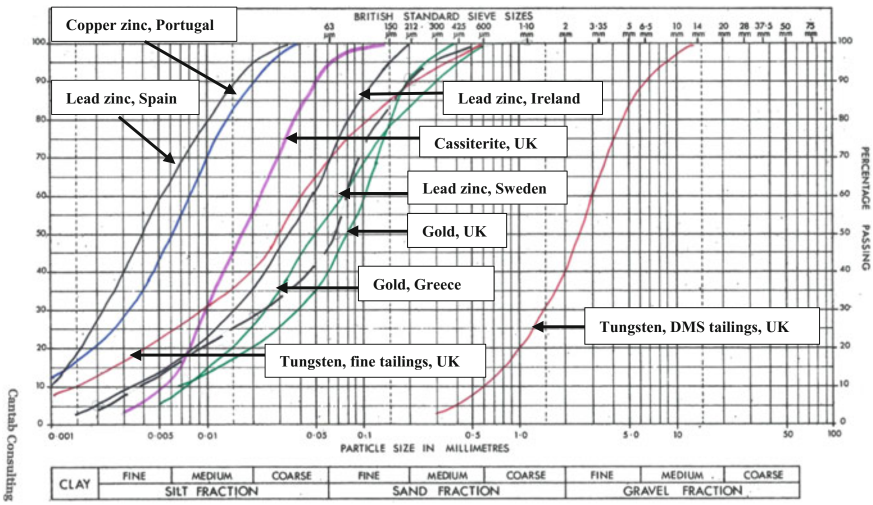


Fig. 4.5 Typical grading curves for European metal mining wastes

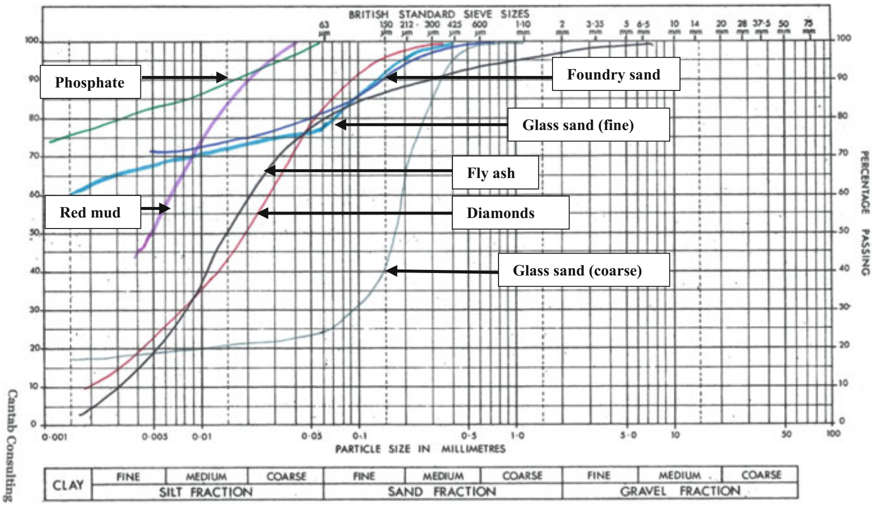


Fig. 4.6 Typical grading curves for industrial mineral wastes

saturated state. The degree of saturation, Sr, is commonly used to express the amount of pore space occupied by a fluid. This term is defined by the ratio of the volume of void space occupied by water to the total volume of void space. Another common parameter used to convey the same information is the air voids content, Av, which corresponds to the ratio of air voids to the total volume of a sample.

Degree of saturation is important, as the strength, stiffness, and permeability of a particulate material are strongly dependant on the volume of fluid occupying the pores. The amount of pore space occupied by fluid is also important in another fundamental respect. At high degrees of saturation, of the order of 85 to 90% depending on the material, the air is occluded. In this case the pore space can be considered to be occupied by a single, compressible fluid phase which is fundamental to the relationship between surface desiccation of a deposited hydraulic fill and the potential for re-saturation during the subsequent deposition phase. At lower degrees of saturation, the air phase becomes continuous and the pore space is effectively occupied by two phases, namely gas and fluid. Conventional soil mechanics is based on the principle of effective stress, which is only valid for fully-saturated materials or materials with a discontinuous air phase. Once the air phase becomes continuous it is not possible to model the response of the material with a single effective stress variable.

Mineralogy

The mineralogy of the hydraulic fill will determine not only the geotechnical but also the geochemical performance of the material. The geochemical properties may indicate that a phase change is likely to occur in the deposited material due to chemical or weathering processes. Determination of the extent to which particle breakdown is likely to occur should therefore be part of the assessment both for performance and stability purposes. The geotechnical assessment may reveal that the final stages of the grinding circuit result in a significant proportion of clay-sized particles and it is important to assess the nature of this size fraction since in hard rock ores the resulting fines may constitute rock flour with no plasticity. Alternatively, the comminution process often gives rise to a significant amount of clay minerals in softer rock ores. The presence of even a small percentage of clay minerals, such as kaolinite, illite or montmorillonite, will have a significant influence on the overall physical and mechanical behaviour of the material.

Plasticity

The determination of plasticity will confirm the influence, if any, of the clay-size fraction (particles smaller than 2 μm). Materials containing clay minerals rather than rock flour will change their mechanical behaviour with variations in water content. The range of water content at which behaviour becomes brittle or liquid is given by the Atterberg limits, the plastic limit (w_P) representing the water content at which the behaviour of a material is no longer plastic and becomes brittle and the liquid limit (w_L) corresponding to the water content at which the material starts to flow. The plasticity index (I_p) is numerically equal to the difference between the liquid and plastic limits.

The type and quantity of clay minerals influence the plasticity of a soil. In order to separate these two effects, it is useful to determine the activity of a material (Skempton 1953), which is defined by the ratio of the plasticity index to the clay size fraction (percentage by weight of particles finer than 2 μm). The activity of a soil is a useful guide to the type of dominant clay minerals present. This information can be used to predict the overall properties, sedimentation and consolidation characteristics of the hydraulic fill.

It is also noted that the relationship between water content and the Atterberg limits can be used to provide an indication of liquefaction or flow potential (liquidity index) and thus plasticity serves as an important indicator of the sensitivity of an extractive waste to disturbance.

Particle Specific Gravity

The particle specific gravity, G_s, is given by the ratio of the density of solid minerals (or particle density) to that of water. This parameter enables an assessment of the relative density of the hydraulic fill and is required for volume/mass calculations and thus prediction of storage parameters. The typical particle specific gravity of extractive waste depends on the mineralogy of the ore and may vary from

Table 4.1 Typical particle specific gravity of extractive waste

Typical metalliferous waste properties		Typical industrial mineral waste properties	
Economic mineral/s	Particle specific gravity	Economic mineral	Particle specific gravity
Cassiterite	2.75–3.2	Borax	2–2.5
Copper/zinc	3.8–4.2	Bauxite	3–3.2
Gold (epithermal)	2.65–3	Kaolin (fines)	2.5–2.65
Lead/zinc	3–3.5	Silica	2.65
Tungsten	2.65	Fluorspar	2.7–3.2

2.5 to 4.5 and higher, as indicated in Table 4.1, which gives typical values for European mine tailings.

Void Ratio and Porosity

Void ratio is given by the ratio of the volume of void space to the volume of solid, whereas porosity is obtained by dividing the volume of voids by the total volume of a sample. These parameters give an indication of density and provide a guide to the performance of the settled solids. They can be used to estimate the mass characteristics of the deposited hydraulic fill, the rate at which densification takes place and, in some instances, together with degree of saturation, can serve as a guide to liquefaction potential. The determination of void ratio and porosity plays a key part in some of the non-standard geotechnical tests such as settling velocity, minimum density determination and air drying and desiccation tests. The void ratio (or porosity) of the hydraulic fill in the settled state, in particular, controls the volume required to impound a given mass of material. Where a robust laboratory model is available, void ratio or porosity may be substituted as the monitoring parameter where access for in situ density testing is impractical.

Compaction Characteristic of Coarse Hydraulic Fill

In many MWFs the coarse fraction of the hydraulic fill is used to form a structural section of the confining embankment, either by separation in the plant and disposal as a separate coarse stream or through separation on the embankment through spigots, spray-bars and cyclones. The use of the fill as a construction material requires the assessment of its density. For some confining embankments this may involve conventional compaction processes to achieve the appropriate engineered state. Compaction is the process of densifying a particulate material by applying energy, which results in expulsion of air and reduction in the volume of voids. The compaction characteristics of a material are generally determined in the laboratory by means of a Proctor compaction test. This gives an indication of the variation in final dry density with compaction water content, which can be compared with field data to confirm compliance with design requirements. For a given material and energy input there will be an optimum moisture content which yields a maximum dry density.

Two Proctor compaction tests are available, namely:

(a) the standard test using a 2.5 kg weight, being representative of light compaction equipment;
(b) the modified test using a 4.5 kg weight, being more appropriate for heavy compaction plant.

Permeability

The coefficient of permeability (k) gives an indication of the rate of drainage in particulate materials. This parameter is a function of grading, particle shape, the amount and type of clay minerals and the density state, and can range over several orders of magnitude in the same deposit dependent on the consolidation state. Hydraulic placement of an extractive waste in a MWF generally results in a laminated deposit with clearly-defined stratification as evident in Fig. 4.3, with segregation resulting in significant spatial variations in permeability across the deposit. In addition, the resulting anisotropy in such deposits commonly results in significant differences in horizontal and vertical permeability and values of k_h/k_v (horizontal and vertical coefficients) exceeding 20. Depending on the gradation of the hydraulic fill, this variation between the point of discharge (Figs. 4.1 and 4.2) and the supernatant pond can range from minimal to significant and the characterisation process should ensure that permeability is measured in the laboratory in both horizontal and vertical directions.

Permeability can be measured in the laboratory by means of constant or falling head tests. For low density fill which cannot be tested in permeameters, laboratory consolidation tests can be used to obtain an estimate of permeability. In addition, the experienced practitioner can obtain an estimate of the permeability of a particulate waste containing mainly sand-size particles from the following relationship, proposed by Hazen (Hazen 1895):

$$\text{Permeability k (m/sec)} = 100 * (D_{10})^2\,(\text{mm})$$

where k is the permeability expressed in m/sec and D_{10} is the diameter at which 10% of the material weight is finer, expressed in mm. When using the above expression it is important to note that the formula was developed by testing clean sand in a loose state and that the presence of silt or clay will greatly diminish the permeability of a sand. Therefore the determination of permeability from Hazen's formula, or any other empirical relationship, should be considered only as approximate.

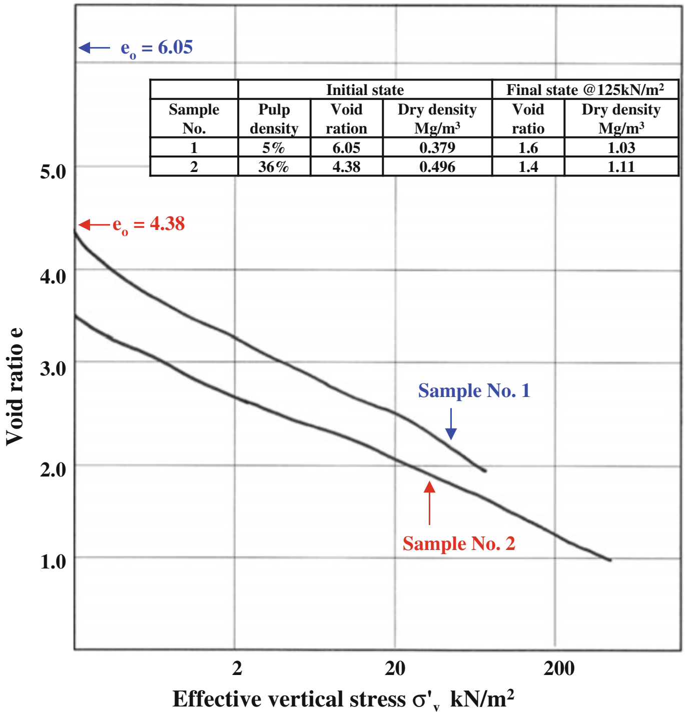
In the field it is possible to measure the in situ permeability by carrying out constant or falling head tests in boreholes. For embankment fills or extractive waste deposits, ponding tests can be carried out on the surface of the material and be used to measure the permeability in the vertical direction. Alternatively, when only a preliminary estimate of permeability is required, simple soak-away tests can be carried out in test pits. Horizontal permeability can be measured on block samples cut from test pits, but this is only possible in competent fill materials.

Compressibility

The state of a hydraulic fill placed into a depository may range from minimum density to fully consolidated. The loading of a deposited hydraulic fill results from self-weight, and significant volume changes are to be anticipated during the life of a facility. The initial deposition of a hydraulic fill in a loose state, combined with a predominance of high particle angularity and narrow grading, results in a higher compressibility than is experienced in most natural soils (Vick 1990). The one-dimensional compression characteristics of deposited fill can be determined using a conventional soil testing approach. However, to assess compressibility over the full range of deposition conditions, modifications of the standard equipment are required to enable testing of a sample from minimum density to maximum anticipated overburden pressure. Further, as MWFs increase in height, consideration needs to be given to ensuring that the stress range may require to be extended beyond that generally experienced in testing of natural soils. As a result of the likely stress range necessary to characterise the material in the depository, a series of overlapping tests may be required in order to determine the full compressibility range of a hydraulic fill (Fig. 4.7).

Consolidation

Saturated particulate materials with low permeability, such as silts and clays, are not able to change volume rapidly following an increase in applied stress. In such cases, the application of an external stress results in an immediate increase in the pressure of the fluid filling the pore space. With time, this excess pressure will dissipate as fluid is able to drain and this is accompanied by a reduction in the overall volume of the fill. This transient process, known as consolidation, is governed by the diffusion equation common to many problems involving gradient-driven flow. The rate of consolidation is controlled by the speed at which fluid can drain. This in turn is determined by the size, shape and packing of the particles which together determine the permeability and the compressibility of the material and define the coefficient of consolidation. This parameter is important in defining the storage characteristics as well as governing the speed at which structural sections of the storage facility, comprising hydraulically placed fill, may safely be constructed as the rate of consolidation controls both drainage and the subsequent increase in strength.



Sample No.	Initial state: Pulp density	Initial state: Void ration	Initial state: Dry density Mg/m³	Final state @125kN/m²: Void ratio	Final state @125kN/m²: Dry density Mg/m³
1	5%	6.05	0.379	1.6	1.03
2	36%	4.38	0.496	1.4	1.11

Fig. 4.7 Compression curves for samples commencing at minimum density

Consolidation in hydraulic fill is a complex process involving large strains and results from a combination of mechanisms, including self-weight consolidation, surface evaporation, the development of negative pore pressures and, ultimately, seepage. Both enhanced lateral drainage resulting from the elevated k_h/k_v ratio and air drying of exposed material lead to significant volume change.

The determination of the compression characteristics governing the consolidation of deposited hydraulic fill can be achieved using conventional oedometers. However, in order to assess consolidation over the full range of the anticipated depositional environment and to model the anisotropy, a three-dimensional approach is necessary, requiring either modifications of standard apparatus or the adoption of more sophisticated testing equipment, such as the Rowe cell. Again, due to the large compressions experienced by samples commencing from minimum density, a series of overlapping tests covering the full stress range will generally be required. These tests provide the key design parameter for a MWF, namely the density of the hydraulic fill both during and after subsequent deposition, and provide a reliable assessment of long-term storage capacity. The consolidation data can also be used to assess mass permeability of the deposit, thus aiding in the determination of basal seepage and long-term drainage predictions. The additional laboratory tests not covered in EN ISO 17892 are briefly described in Appendix B2.

Shear Strength

Shear strength corresponds to the maximum shear stress which the material can resist under normal stress and is a fundamental parameter in defining the structural stability of a MWF and a key determinant from laboratory testing. During the determination of shear strength in the laboratory, loading beyond the maximum stress results either in the complete loss of strength and sudden collapse of the sample or in the accumulation of large plastic strains. The shear strength of any particulate material depends on whether shearing occurs in a drained or undrained environment as well as on the ability of the material to accommodate levels of strain and deformation.

When considering the shear strength of a particulate material such as a hydraulic fill it is important to differentiate between drained and undrained strength. Drained strength is associated with a rate of shearing sufficiently slow to ensure full dissipation of excess pore water pressures. Shearing takes place at constant pore water pressure and effective stress, and is accompanied by an increase or a decrease in volume, depending on initial density and confining stress. Undrained strength, on the other hand, corresponds to a situation where the rate of shearing is high enough to prevent drainage. In this case there can be no volume change and shearing is accompanied by an increase or a decrease in pore water pressure and associated change in effective stress. Whereas drained strength is a material property, the undrained strength depends on the method of testing.

In the laboratory the drained shear strength of a material is normally obtained by means of consolidated drained (CD) or consolidated undrained (CU) triaxial tests, which require pore water pressure measurements in order to plot the results in terms of effective stress. The consolidated undrained tests can also be used to obtain the ratio of undrained shear strength, s_u, to effective vertical stress, σ'_v. However, of paramount importance is the selection of the sample for testing and the assessment of its representative characteristics in relation to its location in the proposed MWF.

In the field, estimates of in situ shear strength of the hydraulic fill can be obtained from vane shear (VST), pressuremeter (MPT) and cone penetrometer tests (CPT). Although it is possible to use results from standard penetration tests (SPT) to derive estimates of shear strength, this method of testing is not sufficiently sensitive for application to low strength materials such as hydraulic fill and results should therefore be interpreted with caution.

When evaluating the stability of a MWF it is important to ensure that the correct strength parameters are obtained and that these are employed in a drained or undrained strength analysis. A discussion on the strength appropriate for the assessment of stability of MWFs can be found, for example, in (Ladd 1991), (Carrier 1991), (Vick 1992) and (Szymanski 1999).

Table 4.2 Geotechnical parameters and determination methods—standard test methods

Parameter	EN standard	Other references	Remarks
Particle Size Distribution (PSD) or Particle Size Analysis: sieving procedures	EN ISO 17892-4 Geotechnical investigation and testing—Laboratory testing of soil—Part 4: Determination of particle size distribution		EN ISO give two methods of sieving: dry and wet. Dry sieving is used only in clean granular materials containing negligible amounts of particles of silt or clay size; whereas wet sieving is applicable to soils containing silt or clay, even in small quantities (Head 2006)
Particle Size Distribution (PSD) or Particle Size Analysis: sedimentation procedures	EN ISO 17892-4 Geotechnical investigation and testing—Laboratory testing of soil—Part 4: Determination of particle size distribution		EN ISO give two methods of determining the PSD for fine particles smaller than 63 μm down to clay size by sedimentation: pipette and hydrometer. The pipette analysis is the standard method for fine particle analysis, although the apparatus is expensive and delicate. The simpler hydrometer analysis is not done in samples with less than 10% of material passing the 63 μm sieve (Head 2006) Combined sieving and sedimentation procedure allows plotting a continuous PSD curve from coarse down to clay size particles
Mineralogy	BSI EN 932-3 Tests for general properties of aggregates—Part 3: Procedure and terminology for simplified petrographic description BSI EN 13925 (all parts) Non-destructive testing—X-ray diffraction for polycrystalline and amorphous materials		Identification of fine-grained minerals can be done by X-ray diffraction, whereas microscopy can be used to determine the composition of the non-clay fraction Mineralogy may determine whether non-standard tests are required to confirm long-term stability
Water content	EN ISO 17892-1 Geotechnical investigation and testing- Laboratory testing of soil—Part 1: Determination of water content		The standard method of measuring water content is by drying a sample in an oven at 105 °C for 24 h. Care must be taken with some clays to ensure that the drying temperature does not lead to

(continued)

Table 4.2 (continued)

Parameter	EN standard	Other references	Remarks
			the water of adsorption being removed during the test
Atterberg limits or plasticity limits	EN ISO 17892-12 Geotechnical investigation and testing—Identification and classification of soil—Part 12: Determination of liquid and plastic limit		The Atterberg limits are related to the amount of water attracted to the surfaces of particles and are based on the concept of a fine soil existing in various states (semisolid, plastic, liquid) depending on the water content (Lambe and Whitman 1979) The Atterberg limits of a soil include the liquid limit, the plastic limit, and the shrinkage limit
Activity index	Standard calculation from PSD and Atterberg limits		Determines the effect of clay mineralogy and amount of clay on the plasticity index of a material. Activity is given by the expression proposed by (Skempton 1953): Activity = Plasticity Index/(% sample by mass of size <2 μm)
Liquidity index	Standard calculation from water content and Atterberg limits		Provides an indication of the susceptibility of the material in its in situ state to flow/liquefy
Particle Specific Gravity or Particle Density	EN ISO 17892-3 Geotechnical investigation and testing—Laboratory testing of soil—Part 3: Determination of particle density—pycnometer method		The pycnometer method uses the fluid displacement method to determine the volume of a known mass of soil
In situ Density or Bulk Density	EN ISO 17892-2 Geotechnical investigation and testing—Laboratory testing of soil—Part 2: Determination of density of fine-grained soils		The three methods for the determination of the bulk and dry density of a soil include linear measurements method, immersion method, and fluid displacement method

(continued)

Table 4.2 (continued)

Parameter	EN standard	Other references	Remarks
Proctor laboratory compaction (optimum water content and maximum dry density)	EN 13286-2 Unbound and hydraulically bound mixtures—Part 2: Test methods for laboratory reference density and water content—Proctor compaction		The laboratory compaction test gives the relationship between dry density and water content for a given compaction effort, the optimum water content to achieve a given maximum dry density for a given compaction effort, and the value of this maximum dry density The two most common methods for determining the dry density versus water content relationship are light compaction using a 2.5 kg hammer, and heavy compaction using a 4.5 kg hammer
Permeability (in situ)	EN ISO 22282 (all parts) Geotechnical investigation and testing—Geohydraulic testing	Clayton et al. (1995)	In soils, in situ permeability can be determined using two methods: (i) rising and falling head tests in relatively permeable soils, and (ii) constant head tests when stress changes can result in significant consolidation and swelling In rocks, in situ permeability can be determined by means of the packer or 'lugeon' test. These are similar to a constant head test
Permeability (laboratory)	EN ISO 17892-11 Geotechnical investigation and testing—Laboratory testing of soil—Part 11: Determination of permeability by constant and falling head	Head and Epps (2011)	Two tests are available: constant head for highly permeable soils, and failing head for intermediate and low permeability soils. A constant head test is performed in a permeameter cell, whereas a falling head test can be carried out in a permeameter or in an oedometer consolidation cell. The measurement of horizontal and vertical permeability can be achieved by orientating undisturbed samples accordingly

(continued)

Table 4.2 (continued)

Parameter	EN standard	Other references	Remarks
Compressibility and consolidation (oedometer cell): One-dimensional compression and consolidation	EN ISO 17892-5 Geotechnical investigation and testing—Laboratory testing of soil—Part 5: Incremental load oedometer test		The test can be used to obtain the coefficient of volume change, m_v, and the coefficient of consolidation, c_v, for a given stress range, as well as the void ratio versus vertical effective stress relationship
Compressibility and consolidation (Rowe cell): One-dimensional compression and consolidation		Head and Epps (2011)	The Rowe cell apparatus overcomes the disadvantages of the conventional oedometer when testing materials of low permeability. It can be used to test large-diameter samples (up to 254 mm in diameter) and to measure large deformations. During a test it is possible to control drainage, measure pore water pressure, apply a back pressure, and define horizontal and vertical drainage conditions
Shear strength (static)	*Shear box* EN ISO 17892-10 Geotechnical investigation and testing—Laboratory testing of soil—Part 10: Direct shear tests *Ring shear* – *Vane shear (laboratory)* – *Vane shear (field)* EN ISO 22476-9 Geotechnical investigation and testing—Field testing—Part 9: Field vane test *Undrained compression (QU)* EN ISO 17892-7 Geotechnical investigation and testing—Laboratory testing of soil—Part 7:	*Shear box* – – – *Ring shear* Head and Epps (2011) *Vane shear (laboratory)* Head and Epps (2011) *Vane shear (field)* –	A number of test methods can be employed to measure the drained and undrained strength of a material: *Direct shear tests*, which include the shear box and ring shear test. The shear box test can be used to determine the drained strength of coarse-grained materials, as well as fine-grained materials of sufficiently high permeability. The ring shear test gives an indication of residual strength The *laboratory vane shear test* can be used to obtain the undrained strength of very soft soils, whereas the *field vane shear test* will give an

(continued)

Table 4.2 (continued)

Parameter	EN standard	Other references	Remarks
	Unconfined compression test on fine-grained soils. *Triaxial (UU, CU, CD)* EN ISO 17892-8 Geotechnical investigation and testing—Laboratory testing of soil—Part 8: Unconsolidated undrained triaxial test. EN ISO 17892-9 Geotechnical investigation and testing—Laboratory testing of soil—Part 9: Consolidated triaxial compression tests on water-saturated soils. *Pressuremeter* EN ISO 22476-4 Geotechnical investigation and testing—Field testing—Part 4: Menard pressuremeter test. EN ISO 22476-6 Geotechnical investigation and testing—Field testing—Part 6: Self-boring pressuremeter test EN ISO 22476-8 Geotechnical investigation and testing—Field testing—Part 8: Full displacement pressuremeter test. *Cone penetrometer* EN ISO 22476-1 Geotechnical investigation and testing—Field testing—Part 1: Electrical cone and piezocone penetration test EN ISO 22476-12 Geotechnical investigation and testing—Field testing—Part 12: Mechanical cone penetration test (CPTM)	– *Undrained compression (QU)* – – *Triaxial (UU, CU, CD)* Head and Epps (2013) – – – – *Pressuremeter* Clayton et al. (1995) Mair and Wood (1987) – – – – – *Cone penetrometer* Clayton et al. (1995)	indication of undrained strength in very soft to firm soils *Quick undrained (QU) tests* include the *unconfined compression* and the *triaxial compression test*. In both cases there is no drainage during the application of the confining pressure or during axial loading, and the strength obtained corresponds to that associated with no change in water content The *undrained (UU) triaxial test* is similar to the *QU* test but includes measurements of pore water pressure In the *consolidated undrained (CU) triaxial test*, a sample is allowed to consolidate to a given effective stress before loading in the undrained condition. Measurement of pore water pressures allows drained strength parameters to be determined In a *consolidated drained (CD) triaxial test*, a sample is allowed to drain freely during the consolidation and loading stages. The test is also used to measure drained strength The *pressuremeter test (PMT)* can be used to determine in situ undrained strengths The *cone penetrometer test (CPT)* can also be used to obtain an estimate of in situ strengths

(continued)

Table 4.2 (continued)

Parameter	EN standard	Other references	Remarks
		Lune et al. (1997) – – –	
Shear strength (dynamic)	*Cyclic testing* - *Cone penetrometer* EN ISO 22476-1 Geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone penetration test EN ISO 22476-12 Geotechnical investigation and testing – Field testing – Part 12: Mechanical cone penetration test (CPTM)	*Cyclic testing* Kramer (1996) *Cone penetrometer* Clayton et al. (1995) Lune et al. (1997) – – –	A number of test methods can be employed to measure the dynamic shear strength of a material The *cyclic triaxial* and the *cyclic direct simple shear tests* will provide information on the dynamic properties of a material at high strain levels Results from the *cone penetrometer test (CPT)* can be used to determine the in situ liquefaction potential of a material using, for example, the methods suggested by Fear and Robertson (1995) and by Olson and Stark (2003)

Liquefaction Potential

The grading characteristics and the particulate nature of fine extractive waste products indicate whether they will be susceptible to static or dynamic liquefaction. The assessment of liquefaction potential in these materials is complex, requiring both expert knowledge and specialist test procedures which are beyond the scope of these guidelines. Static liquefaction is an issue for all MWFs as the trigger for failure is not necessarily related to seismic activity (Cambridge 2013) and the designer needs to ensure that characterisation adequately defines any susceptible materials so that any failure risk is fully mitigated through design.

The potential for seismic disturbance exists at all prospective MWF sites and thus characterisation depends not only on the geotechnical properties of the mineral waste but also on the seismic risk and the predicted ground accelerations at the site. Any susceptible hydraulic fill, particularly if it is to be incorporated into the confining embankment cross-section, needs to be tested and the design and construction CQA addressed accordingly. The potential for liquefaction will need to be determined from an initial review of particle size distribution, degree of saturation and in situ density. This can be supplemented by ensuring that any triaxial testing continues to around 25% strain to assess dilating or contracting states in the sample at failure. In the case of those higher-risk facilities where the probability of significant seismic activity is elevated, specialist testing to assess the performance of materials under pre-defined accelerograms may be required, necessitating both specialist expertise and laboratory equipment. In the case of an operating or closed facility, field testing involving cone penetration testing and shear wave velocity measurements will assist the assessment. There is a large bibliography on the subject and reference in particular should be made to case histories (Makdisi et al. 1978) and (Sarma 1981). In addition, a review of the "simplified procedure" for assessing the liquefaction resistance of soils can be found in (Youd and Idriss 2001) and the subject of soil liquefaction is extensively covered in (Jefferies and Been 2006).

4.3.2.2 Non-standard Geotechnical Testing

The singular characteristics of hydraulic fill and the methods employed for both production and placement have required the development of non-standard testing procedures which, though not included in any European standard for soil testing, have received industry-wide recognition as valid means of characterising the physical properties of hydraulically placed extractive waste. Key tests are listed in Table 4.3 and a brief description of each is presented in Appendix B2. The list is not exhaustive and is only included as a guide and to highlight the complexity associated with the proper characterisation of the physical and mechanical properties of a hydraulic fill. When specifying or performing any non-standard test, proper advice should always be sought.

Of key importance in the design of a MWF is the understanding of the sedimentation and drying characteristics of the waste, as discussed below.

Table 4.3 Geotechnical parameters and determination methods—non-standard test methods

Test method[a]	Comments
Percentage solids test	Test undertaken over a range of solid contents (pulp densities) to allow for process discharge changes
Particle settling velocity test	Test to determine the settling velocity of the fine fraction of hydraulic fill
Undrained settling test	Test to determine the minimum settled dry density of sub-aqueously deposited hydraulic fill and the quality of the supernatant water
Drained settling test	Test to determine the improvement in minimum settled density due to the incorporation of under-drainage
Air-drying test	Test to simulate the deposition of hydraulic fill using sub-aerial techniques and the effect of air-drying on dry density and shear strength
Slurry consolidation test	Test to determine the consolidation characteristics of the tailings commencing at very low stresses (0–5 kPa)

[a]A brief description of each test is presented in Appendix B2

Sedimentation

The rate at which extractive waste settles following hydraulic deposition in a facility, and the resulting properties of both the water column and the settled solids, are important design parameters for the MWF both in terms of process and storage capacity. A particulate extractive waste will settle with time, resulting in a generally relatively clear water column (supernatant) and a settled mass at or near to minimum density. It is noted that both clarity and quality of the supernatant will be influenced by process chemical interactions and clay proportion. For finer wastes, clarity of the supernatant may never be achieved due to colloidal properties. The sedimentation process can be simulated in the laboratory through "jar settling tests", which have become industry-standard (Fig. 4.8 and Appendix B2). Such tests enable the settling rate of the finest waste fraction, the settled density, and the quality of the supernatant to be defined. These parameters are fundamental to the characterisation process as they influence storage volume and minimum reservoir area for decanting purposes. They also determine the extent to which return water can be used in the process without further treatment. The settling tests are typically run for a number of days, depending on the percentage clay present, with clear water developing within hours or, in some cases, never.

Settling tests are also influenced by the pulp density of the hydraulic fill with, in general, higher minimum settled densities resulting from higher pulp density. Lower pulp densities and an elevated clay fraction give rise to a lower final settled density. When undertaking the tests there should be a clear objective in terms of target parameters, i.e. minimum density, supernatant quality or minimum settling velocity. When undertaking the tests it is important that the initiating pulp density and solids fraction be chosen to reflect, as closely as practicable, the product from the process plant. It is also important that the geochemistry of the slurry replicate as far as possible the water quality to be generated by the plant. However, given the

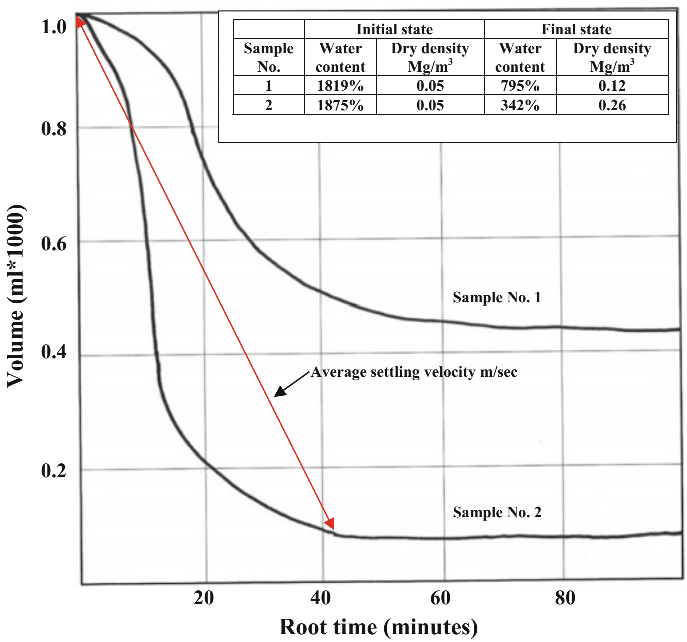


Fig. 4.8 Mudline curves from jar settling tests

changes in the process flow sheet during operation, the test can be used to assess the range of values, particularly of settled density, likely to occur and thus enable the storage assessment to be robust. The addition of basal and side drains can be incorporated into the testwork in order determine the influence of underdrainage on initial density state, as well as defining starting density conditions for subsequent oedometer consolidation tests.

The sedimentation test can be used to develop an understanding of the water balance of the MWF in more detail. For example, the initial settled density of the solids provides the minimum volume of water which will report to the decant pond during the sedimentation process and thus be available for recycle. In addition, the minimum density results provide an important indication of losses due to interstitial water volume. Though additional water will be released through consolidation this will report as seepage to the embankment or underdrainage system and need to be recycled separately.

It is possible to modify the basic “jar settling test” arrangement to record additional parameters during the sedimentation process. In particular, sensors can be mounted on the sides and base of the container to measure the spatial and temporal variation in the mechanical and electromagnetic properties of the slurry. Examples of such measurements, together with interpretation of results, can be found in (Santamarina et al. 2001), (Blewett et al. 2001) and (Monroy and McCarter 2017) amongst others. Finally, the settling velocity determined from the jar tests can be used to define the minimum reservoir area required to settle the hydraulic fill for a given throughput. The minimum reservoir area is defined as the ratio of the slurry inflow in m^3/sec to the velocity in m/sec necessary to achieve settlement of 95% of the solids (Twort et al. 1994):

$$\text{minimum reservoir area A} = \text{q}\left(\text{slurry inflow in m}^3/\text{sec}\right)/\text{v}_\text{s}(\text{settling velocity in m/sec})$$

Air-Drying Tests

Air-drying tests can be used to assess the effect of desiccation on the surface of a deposited hydraulic fill and are particularly useful in determining the optimum disposal mode for finer tailings. There are no standards for this testwork, the method being determined to suit laboratory conditions and material properties. The deposition of the hydraulic fill into a series of wide containers or deep trays enables controlled settlement and decantation to simulate sub-aerial disposal on to a beach. Density, water content, degree of saturation and void ratio are logged at frequent intervals and the key stages of air-drying monitored in order to define the material properties at the critical points, as follows:

(i) minimum density at commencement of test for comparison with the jar settling results;
(ii) bleed point, corresponding to the condition at which moisture ceases to appear on the surface of the deposit;
(iii) crack point, corresponding to the condition at which the sample first exhibits desiccation cracking.

These critical points are shown in Fig. 4.9 and indicate the relevant sample water content and density at each stage. These data have proved useful, not only for deposition mode but also for establishing operational criteria such as disposal cycle times.

The gain in shear strength as the deposit desiccates can also be measured throughout the test procedure using a hand vane, as shown in Fig. 4.10. However, in order to avoid sample disturbance, and thus jeopardise the accuracy of the water content data, vane testing for this element of the test procedure is ideally carried out in a number of separate discrete trays, each containing a similar depth of settled desiccating tailings.

Air-drying tests have been used not only as geotechnical performance indicators but also as a means of assessing environmental performance. At a number of projects air-dried samples have been subject to wind tunnel tests to establish critical environmental data such as the release rate and quality of surface emissions. In the case of the Jamestown project the tests were used to measure the volume of radon gas emitted from the surface of uranium tailings facility (Skolasinki et al. 1990).

It is advisable in all cases to ensure that the scope of the air-drying tests be clearly defined and agreed in advance and that the laboratory arrangements are confirmed as being suitable as they require both a stable platform which prevents

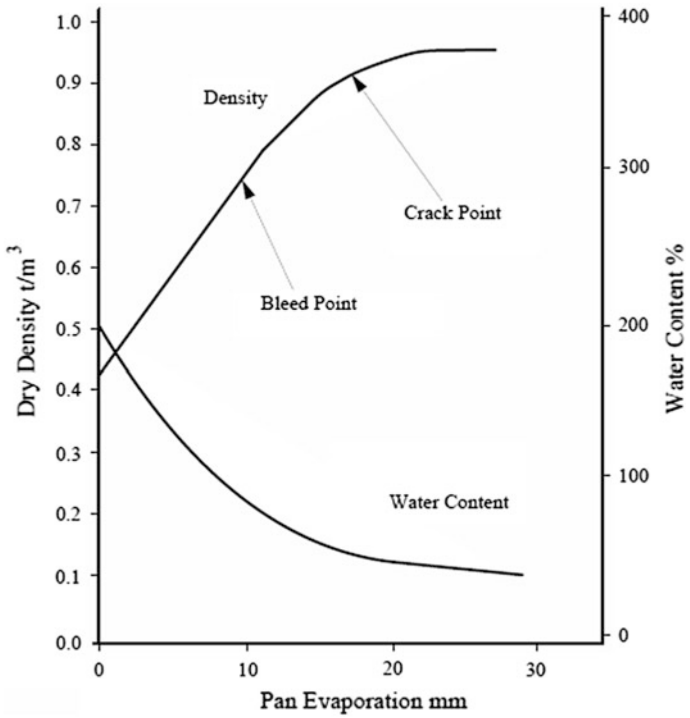


Fig. 4.9 Typical density/water content relationship for desiccation tests

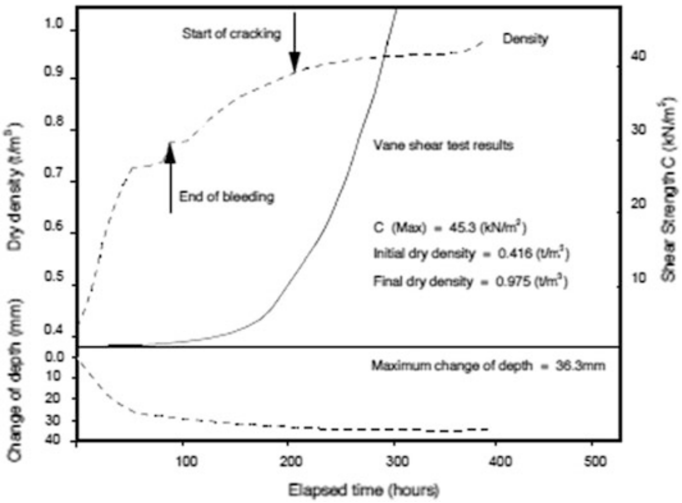


Fig. 4.10 Typical density/vane shear relationship for desiccation tests

untoward disturbance and constant environmental conditions (temperature and humidity). It is imperative that a detailed laboratory protocol be developed which addresses sample preparation, disposal and decanting and the necessary monitoring procedures before embarking on any air-drying tests.

4.4 Geochemical Characterisation

Geochemical characterisation of all extractive waste and the assessment of its long-term chemical stability is a principal requirement of the EWD as part of the overall characterisation of a waste facility. This characterisation is therefore a fundamental part of the permitting and long-term operational management of a MWF. This requires classification of the waste with respect to its long-term geochemical stability, as well as assessment of whether it contains substances or preparations classified as dangerous or hazardous, as defined in the Hazardous Waste and Dangerous Substances Directives (EC 2009). This characterisation process needs to be undertaken in addition to the assessment of the chemical substances to be used during processing and treatment of the mineral resource/ hydraulic fill.

There is extensive literature on how to determine dangerous and hazardous substances (CENTC292) and it is not the intention of these guidelines to repeat this. There is in addition a broad framework of technical literature addressing the long-term geochemical stability of an extractive waste, the associated implications for stability and environmental performance of a MWF and, in particular, on Acid Mine Drainage (AMD) (or Acid Rock Drainage [ARD] in the more recently-accepted terminology). However, much of the documentation is narrowly focused and does not address geochemical stability in the overall context of the development, construction, operation and closure of a MWF and, in particular, too frequently ignores the geotechnical setting and its influence on chemical changes. In the context of these guidelines, therefore, not only the geochemical characterisation process but also the interactions with other key performance parameters in a MWF are considered.

4.4.1 Background to ARD

ARD takes place when reactive sulfides present in many mineral resources come into contact with oxygen and water in the presence of oxidising bacteria and there is insufficient or ineffective alkaline material to stop the oxidation reaction or to neutralise its products. ARD is a dynamic and spatial problem which occurs when the acidity generated is higher than the neutralisation capacity of the system during the cycle of sulfide oxidation. The term ARD is applied to the resulting leachate, seepage or drainage, and its presence in a MWF may lead to major structural

Table 4.4 Geochemistry of acid generation

Acidic drainage is generated according to the following three overall equations:	
Equation 1	$2FeS_2 + 7O_2 + 2H_2O \xrightarrow{bacteria} 2FeSO_4 + 2H_2SO_4$
Equation 2	$4FeSO_4 + 2H_2SO_4 + O_2 \xrightarrow{bacteria} 2Fe_2(SO_4)_3 + 2H_2O$
Equation 3	$FeS_2 + Fe_2(SO_4)_3 \rightarrow 3FeSO_4 + 2S$
The neutralisation aspect of the problem is usually represented by the following equation:	
Equation 4	$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$

changes in the confining embankment and in the long-term to release of potential pollutants unless it is addressed at source and its impact fully mitigated in the design and operation.

The two main sulfide minerals associated with ARD are the gangue minerals pyrite and pyrrhotite. Pyrite is relatively abundant and is not usually recovered in the processing of ore, such that it reports to one or to all of the waste streams. When pyrite and pyrrhotite are not recovered or fully oxidised in the process they may subsequently oxidise and thus become a source of acidity. Carbonate-bearing rock (e.g. limestone) and reactive silicates usually provide the naturally-occurring neutralisation capacity of the system and may, if available in sufficient quantities, negate this process and lead to chemically benign conditions. The geochemistry of the generation of acidic drainage and its subsequent neutralisation is summarised in Table 4.4.

Equations 1–3 in Table 4.4 represent, in very general terms, the basic chemistry of ARD. However, its manifestation can vary depending on the physical and mineralogical characteristics of the extractive waste, the method of disposal and the local climatic conditions and it is thus considered to be a site-specific problem. The background to ARD has been well documented as per the web sites summarised in

Table 4.5 Organisations and Programmes

Description	Reference
Canadian Mine Environmental Neutral Drainage (MEND) programme started in 1989 has an extensive library of studies on ARD	http://www.mend-nedem.org/default-e.aspx
International Network for Acid prevention (INAP). An international organisation led by the major mining companies. It is supporting research on the subject and sponsored the GARD Guide	http://www.inap.com.au/index.htm
Global Acid Rock Drainage (GARD) Guide sponsored by INAP (INAP 2009)	This document is easily accessible via the Office of Surface Mining Reclamation and Enforcement of the USA
European Commission Hazardous Waste	ec.europa.eu/environment/waste/hazardous_index.htm

Table 4.5 and the numerous scientific journals devoted to research on ARD or related subjects. Best practice documents and proceedings are associated with, but not limited to, the following conferences:

- International Conferences on Acid Rock Drainage (ICARD). This series of conferences has documented the advance in understanding of the ARD phenomenon.
- Sudbury Mining and the Environment International Conferences. This series started in 1995 and has also documented the advance in understanding of the ARD phenomenon.

The objectives of any geochemical characterisation for ARD can be summarised as follows:

(i) prevention or reduction of harm associated with waste production by considering, amongst other factors, the changes that the waste may undergo during the increase in surface area and exposure to conditions above ground;
(ii) description of expected short- and long-term physical and chemical characteristics of the waste to be deposited. This description should make particular reference to stability under surface atmospheric and meteorological conditions by taking account of the type of mineral or minerals to be extracted and the nature of any overburden and/or gangue minerals which will be displaced in the course of the extractive operations;
(iii) prevention of water status deterioration by evaluating the leachate generation potential, including contaminant content of the leachate and of the deposited waste during the operational and post–closure phase of the MWF.

The International Finance Corporation (IFC) Performance Standards (PS) (IFC 2012), the de facto regulations in non-OECD countries, and PS 3: Resource Efficiency and Pollution Prevention (January 1, 2012) state that "where waste cannot be recovered or re-used, the client (mining operation) will treat, destroy or dispose of it in an environmentally sound manner that includes appropriate controls of emissions and residues resulting from the handling and processing of the waste material." (IFC 2012). This statement mirrors that of the EU policy on recycling, re-use and storage of mineral residues which requires that, in order to comply with the above, the following extractive waste characterisation parameters must be determined:

- whether the material is inert, according to the EU criteria defining "inert" waste (Commission Decision 2009/359/EC);
- whether the material contains any hazardous/dangerous substances as defined in the EU Waste Catalogue (2009/360/EC);
- whether the material has potential for acid generation and, if so, how it will be realised;
- whether there are any significant metal leachability issues.

In addressing these issues a characterisation programme needs to consider not only the properties of the deposited hydraulic fill but also any future physical or chemical changes which might take place and which might affect the characteristics of the material and its behaviour during both operational and post-closure phases. The adopted methodology has to be iterative and needs to carefully consider all the information available, as recognised by EU documentation and international best practice, and must take into account the variability of ore deposits and the different leaching rates which the same mineral can exhibit depending on the origin and marginal changes in composition.

4.4.2 Characterisation Methodology

Figure 4.11 shows the methodology which needs to be followed in order to properly characterise extractive wastes. An initial review of background data and literature (a process which needs to be iterative throughout the project) is required in order to define the general characteristics of the waste and to assess the sample numbers required to achieve a robust data set. Completion of this review permits the detailed geochemical characterisation to commence with an initial determination of whether the material is "inert" and, if not, the necessary programme required to lead to detailed characterisation, proceeding through screening and static testing before continuing, when appropriate, with the full testing programme.

4.4.2.1 Definition of Inert Material

The extractive waste would be exempt from geochemical testing, from a detailed characterisation programme and from the associated criteria (Commission Decision 2009/359/EC) if the waste were classified as inert. The criteria for this classification are as follows:

- the mineral waste will not undergo any significant disintegration or dissolution;
- the maximum sulfide-sulfur content is 0.1% or the maximum sulfide-sulfur content is 1% as long as the neutralisation potential ratio is higher than 3 based on the results of EN 15875 static testing;
- the mineral waste presents no risk of self-combustion and will not burn;
- the content of substances potentially harmful to the environment or to human health (specifically As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, V and Zn) is sufficiently low to be of insignificant human and ecological risk;
- the mineral waste is substantially free of products used in extraction or processing which could harm the environment or human health.

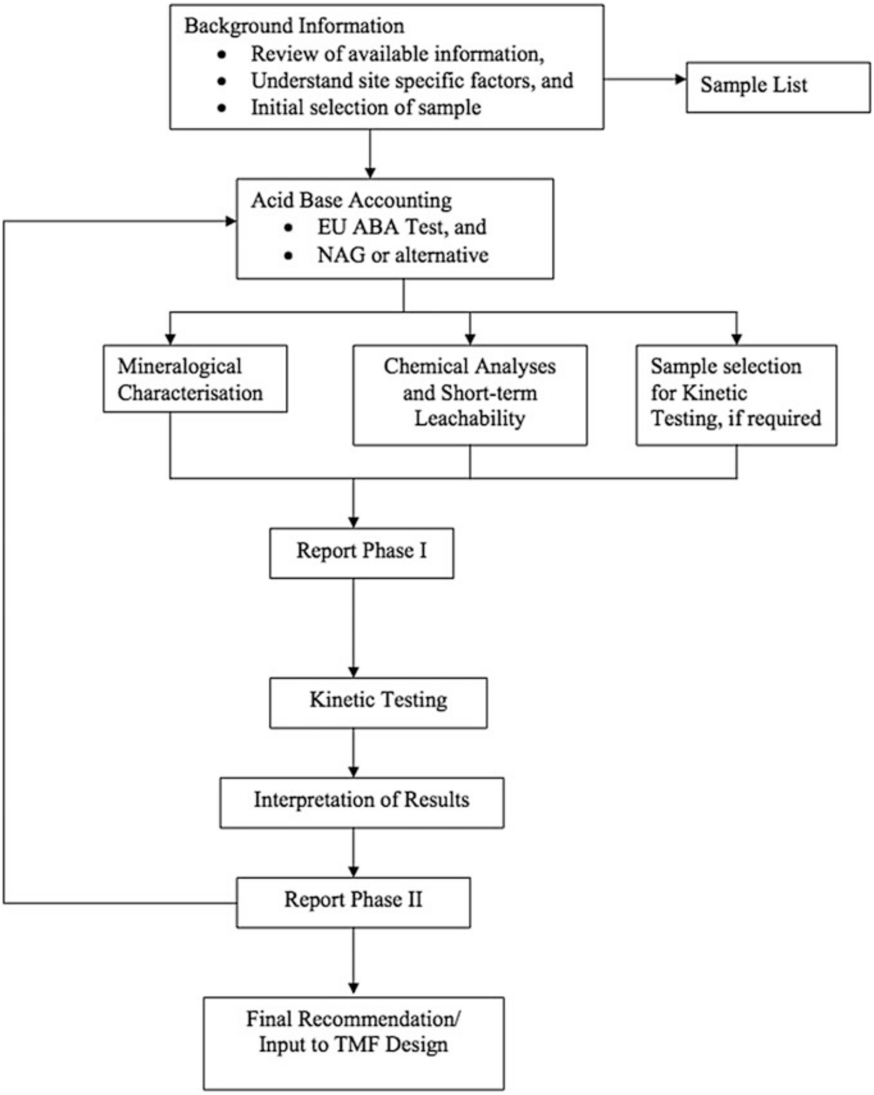


Fig. 4.11 Methodology for the characterisation of mineral waste materials

A review of geological information and historical data should enable a preliminary assessment of whether the extractive waste is inert, as exemplified by many extractive wastes derived during the production of quarried aggregates for the construction industry. Regardless of the conclusion, this assessment should be fully documented and, where the waste cannot conclusively be determined to be inert, a test programme should be initiated and confirmation from the laboratory sought in order to assess whether the material has any potential for the generation of ARD.

4.4.2.2 Potentially ARD-Generating Hydraulic Fill

The testing programme to determine acid generation potential should be properly planned and documented. Preparation of the testing schedule should involve both a review of the geological information and process circuit, together with an assessment of available samples to ensure that suitably representative material is available for testing.

Static Testing

Static testing, e.g. Acid Base Accounting (ABA) or Net Acid Generation (NAG), is usually the first step in the prediction and evaluation of ARD. In general, static testing aims to determine the acid generation potential, directly related to the sulfide content of the sample and to the neutralisation potential. By comparing these two values samples may be classified as potentially acid-generating, as lying within a zone of uncertainty or as unlikely to generate ARD (Fig. 4.12). This diagram exemplifies the use of the plot of Net Acid Producing Potential (NAPP) against the Net Acid Generation (NAG) pH in order to classify samples into Non Acid Forming (NAF), Potentially Acid Generating (PAG)/Potentially Acid Forming (PAF) and uncertain (UC). Static testing can be considered to be equivalent to characterising the chemical thermodynamics of a system, i.e. static testing indicates what can happen but does not predict either that it will or at what speed it might occur. Static tests can be undertaken relatively rapidly, are generally inexpensive, and provide an indication of the potential for, or lack of, acid generation as per EN15875:2011

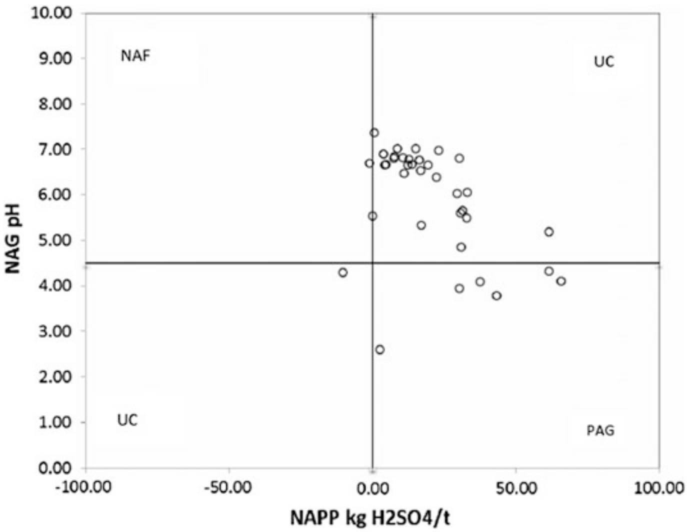


Fig. 4.12 Diagram showing example of NAPP versus NAG used to classify samples

Characterisation of Waste—Static test for determination of acid potential and neutralisation of sulfidic waste. The ABA tests should be accompanied by parallel short-term leaching tests and chemical analyses in order to complement and contextualise the mineralogical data. This parallel testing strategy is fundamental to being able to provide any conclusions on ARD potential.

Mineralogical assessment is important to the characterisation programme as it enables identification of the types of minerals present, specifically sulfides, and their degree of liberation (potential exposure to leaching agents). Different minerals are able to provide neutralisation at different rates, and mineralogical characterisation can assist in determining the minerals which are capable of maintaining a neutral pH.

The purpose of short-term leachability tests is to provide an indication of the mobility of the constituent metals when the hydraulic fill is exposed to a leaching agent capable of simulating either acidic or alkaline environments. Some of these tests can be used to classify the samples into hazardous or non-hazardous categories, using criteria developed by regulators, e.g. the BC Waste Management Act, Canada or the US Environmental Protection Agency. By collecting and analysing the information as part of the initial phase of the testing programme it is possible to produce a reliable prediction regarding the potential for acid generation from the hydraulic fill. If a sample is potentially acid-generating or classified as uncertain, kinetic testing is then necessary in order to confirm whether the fill will generate ARD and with what intensity.

Kinetic Testing

Kinetic testing may be carried out either in the field or in the laboratory. Field-testing has the following disadvantages with respect to overall geochemical characterisation of the hydraulic fill:

- it is less easily controlled;
- it may take longer to generate the required data;
- it is generally preferred for addressing the generation of long-term ARD as part of closure trials;
- it is often only undertaken during the final years of a MWF.

Therefore for geochemical characterisation, particularly during permitting and the early life of the project, laboratory testing is generally preferred. Two main types of apparatus are used for kinetic testing in the laboratory, namely humidity cells and columns. Kinetic tests provide a measure of the “reactivity” of exposed minerals, and humidity cells may be used to predict primary reaction rates under aerobic weathering conditions. The resulting data provide a measure of the rates of metal release, acid generation and acid neutralisation under laboratory conditions. Such conditions may enhance or depress rates of sulfide oxidation, leaching rates and carbonate dissolution relative to field conditions. The results enable an estimation of the depletion times for the minerals present.

The key question which kinetic testing addresses is whether the sample will generate net acidity at any point in time. The primary rates of acid generation, neutralisation and metal release are the main parameters obtained from kinetic testing. By determining the rates at which sulphides are oxidised and alkalinity is released from the samples it is possible to determine whether acid-generating sulphides or alkalinity-generating minerals are likely to be exhausted first. Furthermore, the mineralogy can indicate whether the alkalinity-generating minerals are capable of sustaining a neutral pH. Kinetic testing is, however, expensive and may need to be undertaken over an extended project period, generally for at least one year. These tests need to be carefully designed due both to the cost and to the time-lag between starting the tests and obtaining the results. The use of experienced professionals in the interpretation of the results is also required.

The EU has published recommendations in the following guidance documents on the interpretation of geochemical testing:

- CEN/TR 16363:2012 Characterization of Waste—Kinetic testing for assessing acid generation potential of sulfidic waste from extractive industries.
- CEN/TR 16376:2012 Characterization of Waste—Overall guidance document for characterisation of waste from extractive industries.

Metal Leachability

In the case of hydraulic fill materials which are not ARD-generating, the final analytical stage requires assessment to ascertain whether the release of certain elements of environmental concern in concentrations above which they are considered safe for the environment and for human health might occur.

Commission Decision 2009/360/EC on waste characterisation recommends the evaluation of metals, oxyanions and salt leachability over time by one or more of the following:

- pH dependence leaching tests;
- percolation tests;
- time-dependent release tests;
- other suitable testing.

The combination of short-term leaching testing over the pH range, together with kinetic testing, provides a solid basis on which to determine the likelihood of any metal leaching concerns.

4.4.2.3 Geochemical Testing Procedures

The following testing procedures are presented as guidelines only as within the EU there are no agreed standards and Eurocode 7, in particular, does not describe the requirements for geochemical investigations. The sequence of testing, from initial screening to the final reporting on ARD potential with the resulting recommended mitigation measures, is illustrated in Fig. 4.11, which shows the testing programme needed to define the geochemical characteristics of the hydraulic fill. However, it is important to note that the mineral waste characterisation programme is iterative and therefore sample assessment and testing may need to be cyclical if there is to be confidence in the final conclusions and recommendations.

Static Testing

Though a number of static testing procedures have been developed, the most common (best practice) methods are:

- EN15875:2011 Characterisation of Waste—Static test for determination of acid potential and neutralisation of sulfidic waste;
- Sobek Acid Base Accounting (ABA) (Sobek et al. 1978);
- Modified Acid Base Accounting (ABA) (Lawrence and Wang 1997);
- Net Acid Generation (NAG) (Miller et al. 1997).

In the case of ABA, the interpretation of the neutralisation potential (NP) depends on the procedure used and the mineralogy of the samples. Consequently, when reporting results, the laboratory testing procedures should always be specified in order to ensure correct interpretation and classification of the samples.

Mineralogical Characterisation

Mineralogical characterisation is essential in interpreting screening samples and kinetic test results. Two main methods are used, namely Rietveld quantitative X-ray diffraction or QUEMSCAN. Both methods are capable of quantifying the mineral phases, but it is important to understand the limits of the test and of the methods used.

Chemical Composition and Short-Term Leaching

It is necessary to determine the chemical composition of a sufficient number of material samples to provide a worst-case scenario and in order to provide context to the results obtained from the short-term leaching programme and from other characterisation methods. The two best practice methods are the whole rock analysis using X-ray Fluorescence (XRF) or the instrumental method using a type of digestion and Inductively Coupled Plasma (ICP) and Mass Spectrometry (MS). ICPMS can determine concentrations up to one part per trillion but, depending on the digestion method used (e.g. aqua regia), it is possible that some elements will not be released into solution from the matrix of the minerals. By comparing the concentrations obtained using short-term leaching versus chemical composition it is possible to classify the solubility of the different elements.

The recommended EU test is:

- CEN/TR 16376:2012 Characterization of Waste—Overall guidance document for characterisation of waste from extractive industries.

However, there are many other methods for determining short-term leaching as selectively indicated below:

- CEN/TS 14429:2005 Characterization of waste—leaching behaviour tests—Influence of pH on leaching with initial acid/base addition.
- CEN/TS 14997:2006 Characterization of waste—leaching behaviour tests—Influence of pH on leaching with continuous pH-control.
- EN 12457—1/2/3/4 Characterisation of waste—leaching compliance tests of granular waste materials and sludges.

The CEN/TS tests aim to establish the mechanism of leaching, while EN 12457—1/2/3/4 is a compliance test.

It is noted that short-term leaching tests will never provide all the detailed information which can be gained from a long-term kinetic test, but they can provide a good indication of the likely elements of environmental concern.

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EN ISO 14689:2003 Geotechnical investigation and testing—Identification and classification of rock
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Chapter 5
Engineering Design

Mike Cambridge, Gavin Ferguson, Nick Coppin, Ciaran Molloy and Kris Czajewski

All projects are intended to have an impact on an environment.
—Jean Paul Sartre

Mineral extraction and processing operations result in a significant volume of coarse and fine mine waste materials and, though a proportion might be recyclable, the majority require storage in purpose-built mine waste facilities. The coarse waste (labelled as mine waste rock in Fig. 2.2) is generally stored in mine waste dumps on surface or used for backfilling mining voids, though that with suitable characteristics may be used for infrastructure development, including a MWF. The fine waste (labelled as hydraulic fill in Fig. 2.2), the principal subject of these guidelines, derived from the mineral processing is likely to be transported hydraulically and deposited into a purpose-built reservoir, invariably stage-constructed throughout the operating life of the project. Such a facility needs to be designed to accommodate both the fine extractive waste, the process water and, on many sites all local runoff, and to be designed and constructed in accordance with good practice in order to achieve safe storage and to comply with all statutory requirements throughout its operating life and beyond. This Chapter reviews the principle design characteristics of a MWF, with particular emphasis on a risk-based approach.

5.1 Background to Design

MWFs are among the most visible legacies of an extractive operation and, after closure and rehabilitation, are expected to be stable and to have no detrimental effects on the environment, effectively in perpetuity. Poorly designed or badly managed waste facilities lead to higher closure costs, to ongoing impacts to the environment and to an increased risk to public health and safety. Mining companies therefore face the challenge of

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effectively and efficiently managing MWFs throughout their life-cycle, from initial site selection and design through construction and operation to eventual decommissioning and closure. Responsible corporate entities therefore need to prescribe internal health and safety strategies which include a specific policy for the hydraulic transport and storage of extractive wastes against which operational standards can be developed and subsequently managed. This policy will normally contain business, operational and environmental objectives which can be developed within the framework of the prevailing regulatory and legislative environment. The role of the Regulator is to confirm that these objectives are consistent with EU and national waste management and environmental policy, to permit the facility, to set compliance targets and to ensure that the MWF remains fully compliant both with Regulations and permit conditions throughout its life and beyond.

The engineering design of a waste management facility is complex and must be undertaken by competent consulting engineers with relevant experience in order to meet the requirements of cost-efficiency, safety and stability, as well as compliance with planning, environmental regulations and closure strategy. The design of a mine waste facility should therefore include the following provisions:

- safety—design and construction to meet both short- and long-term geotechnical and geochemical stability requirements;
- economy—use of mining waste, where appropriate, for confining embankment construction;
- water management—maximisation of water recycle and re-use whilst managing flood events in safety;
- facility management—operation, inspection and monitoring in accordance with good practice and with statutory requirements;
- environmental management—control and monitoring of all potential emissions against compliance targets;
- closure—design of facility at mine closure to achieve a sustainable landform which minimises long-term liabilities and impacts.

The principles of tailings and waste management best practice should be founded on a risk-based approach to planning, design, construction, operation and closure, as described in these guidelines. Such an approach, predicated on an understanding of all potential failure mechanisms, enables consideration of alternative solutions and the establishment of a design basis which meets internationally recognised good practice. This Chapter provides an overview of the engineering design and risk assessment process (civil, geotechnical and environmental) together with the derivation of the key project parameters enabling the design criteria for all stages of project development to be defined (Table 5.1).

Table 5.1 Waste facility development phases

Regulatory	Project phasing	Investigation and review phases
Pre-development	Project initiation	
	Conceptual design Prefeasibility study	Desk study Regulatory scoping study Environmental scoping study
Permitting	Feasibility study	Phase I site investigation Environmental baseline study Preliminary facility characterisation Preliminary material characterisation
	Design Project approval	Phase II site investigation Environmental impact assessment Facility characterisation Waste characterisation Emergency planning Independent design review
	Pre-deposition construction Operating permit	Construction CQA Preparation of as-built drawings Preparation of operating and maintenance manual Independent inspection and reporting
Compliance	Operation Annual compliance reporting	Inspection and monitoring Waste characterisation Stage construction design/CQA/Approval Preparation of as-built drawings Revision of operating and maintenance manual Update of emergency/closure plans Annual independent inspection and reporting
Closure	Active closure Compliance reporting	Implementation of closure plan Initiation of facility rehabilitation Inspection and monitoring Annual independent inspection and reporting
	Passive closure Final compliance reporting	Completion of closure plan Initiation of long-term rehabilitation and maintenance plan Initiation of long-term inspection and monitoring plan Independent inspection and sign-off

5.2 The Design Process

5.2.1 Mine Waste Disposal Principles

The fine residues resulting from the refining of a geological resource in the process plant generally comprise a sandy silty particulate waste which is discharged in slurry form. Such materials, regardless of their consistency, need to be placed in a secure containment facility and, in most cases, would not be stable without being suitably confined. The cost-efficiency of the refining process and the site water balance generally necessitates that the greater part of the water contained within the slurry be recycled and re-used. Thus any containment facility should include capacity for both the hydraulic fill and a process water storage and recycle element. The residue is usually pumped from the plant to the storage facility as a hydraulic fill (slurry), the consistency of which will vary depending on the economic material, the refining process adopted and the configuration of the storage basin. The slurry may take the form of a very thin pulp with low solids concentrations (<5%), as for many silt lagoons, or be thickened to between 70 and 80% solids and be deposited as highly-thickened tailings. The consistency of the hydraulic fill will determine the construction of the confining structure, the sedimentation and return water (decanting) system incorporated into the MWF and the proportion of clarified industrial water to be returned to the plant for re-use. The purpose of a mine waste management facility is therefore twofold, namely:

- to provide a cost-effective and environmentally appropriate means of storing the waste and of recycling the process water;
- to provide safe and stable storage of the waste such that at closure the facility achieves geotechnical and geochemical stability.

The engineering design process for any MWF therefore requires the development of the following:

- a strategy for the placement and storage of the extractive waste materials;
- detailed characterisation of the various extractive waste materials to be stored;
- investigation of potential placement environments, both physical and Regulatory;
- detailed description of the physical, environmental and Regulatory factors associated with each potential storage location;
- development of alternative design elements to meet strategic objectives and to mitigate all potential impacts;
- development of an understanding of all MWF failure mechanisms and of their risk ranking;
- selection of the optimum design configuration for the MWF, fully supported by appropriate qualitative and quantitative risk analyses;
- the establishment of an implementation schedule for the selected MWF;
- the design and implementation of a quality assurance programme to monitor the design, construction, operation and performance, including the ongoing assessment of potential failure mechanisms;
- the development and implementation of inspection routines for the waste facility at all levels of operation and management;
- the initiation of independent expert and Regulatory auditing, together with the ongoing review, analysis and reporting of the data and information gathered in order to:

– confirm ongoing safety, stability and Regulatory compliance;
– apply the lessons learned for future facility design, construction and operating practices;
– improve knowledge of potential failure mechanisms and methods of mitigating downstream impacts.

5.2.2 Basis of Good Design

Engineering design is based not only on technical knowledge but also on an appreciation of the process of developing solutions within a systematic and unified framework. The nature of the design process can therefore be characterised as follows:

- Hierarchical—the development of an understanding of the complexity of each design element and its inter-relationship with the project;
- Functional—the creation of a product which will perform in a satisfactory manner;
- Evaluation—the selection of the most appropriate engineering solution from the options considered;
- Iterative—the ongoing co-ordination, modification and improvement of the design objectives and function;
- Optimisation—the creation of an optimal coherent design system.

Solving practical engineering problems involves more issues than those of simply developing complex technical parameters. The design, operation and closure of a mine waste facility encompasses a broad spectrum of technical skills, from civil and structural engineering to environmental management and impact assessment. The range of expertise required must be recognised from the onset if the facility is to meet its design objectives and achieve successful implementation. In addition, the application of the various technologies to be adopted must be managed to ensure that they are fully integrated and that the necessary assessments have been undertaken at each stage of the process to ensure that all risks are fully mitigated. The key elements in the assessment of risk are defined below, noting that the role of the engineer is to identify the hazard, risk and consequence and minimise any impact throughout the life of the project:

- hazard—a source of danger or risk;
- risk—a chance of danger, injury or other adverse consequence;
- probability (Pr)—the likelihood of death, injury or damage occurring;
- consequence—ranging from none to death, injury or damage;
- risk assessment—the identification of all potential hazards and their risk of occurrence—simplistically, a sophisticated term for a “what if?” analysis;

- risk mitigation; the reduction of probability of occurrence to the highest acceptable rate of death, injury or damage, a value generally determined by societal norms;
- risk management—engineering design, operation and closure to achieve the agreed level of mitigation;
- ALARP—as low as reasonably practical, often expressed in societal norms, i.e. acceptable occurrence rate of death or injury.

The facility design elements should be developed in accordance with accepted national and international standards and be based upon a fundamental understanding of the characteristics of the facility, of potential failure mechanisms and on the impacts of construction and operational issues. The selection of an appropriate design solution should be based upon a quantitative risk analysis to establish the most cost-effective risk management approach (avoidance, mitigation, contingency or risk acceptance). The severity of the risks identified will normally influence the selection of an appropriate risk-management strategy. For example, design alternatives with a very high severity risk rating should be avoided and a different strategy adopted, whereas very low severity risks might be acceptable providing that suitable mitigation measures have been designed and implemented. The philosophy of design safety is summarised in Fig. 5.1.

The level of cost uncertainty with respect to deriving the final design parameters for a MWF also needs to be balanced against the cost of refining the required design

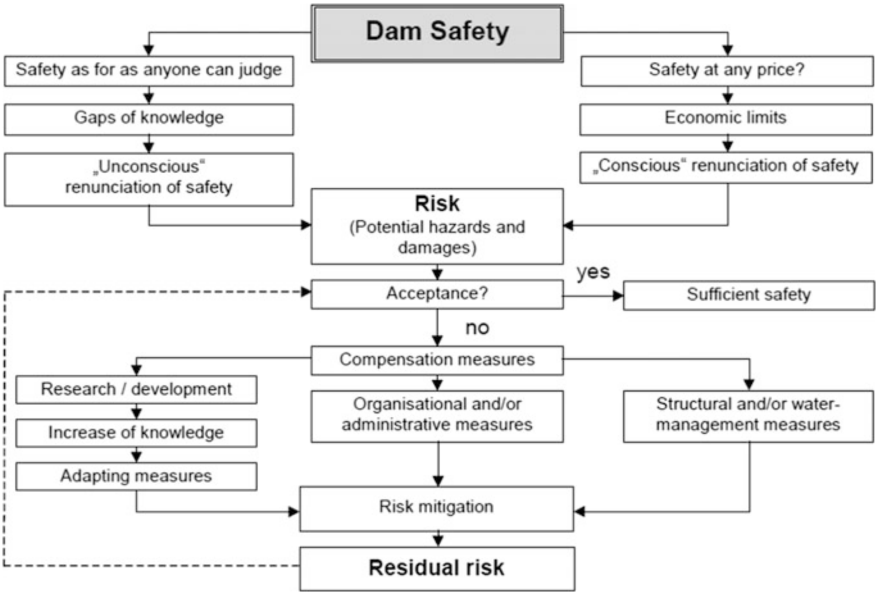


Fig. 5.1 Philosophy of dam safety (Sieber 2000)

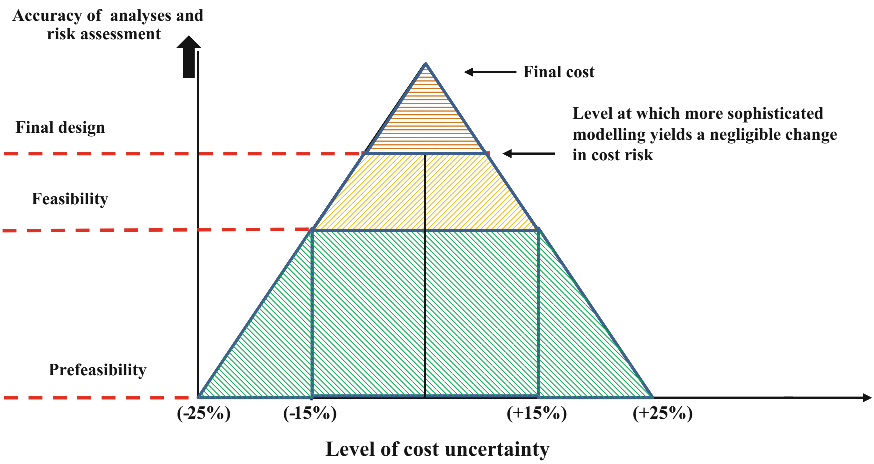


Fig. 5.2 Definition of design parameters against cost of data refinement (Cambridge 2013)

data. Designers should work towards a level of cost uncertainty at which the impact becomes negligible in relation to other design factors as shown in Fig. 5.2.

The facility design process should be fully documented and, where appropriate, be supported by a detailed engineering design register (Table 5.2). This has the benefit of ensuring that the engineering process is transparent and compliant and can be readily audited by a third party. In a typical register, strategic objectives are generally linked directly to design function, load case and material properties, and are specified for each design element. A detailed design support register is useful, not only as a guide to the structural engineering process, but as a record of decision-making and should include:

- strategic objectives—functions and properties (per objective);
- design elements (per function and property);
- design criteria, engineering practice applied and key assumptions;
- identification of risks, hazards and risk severity (multiple consequences and probabilities);
- economic impact of risks and the risk response plan;
- conclusions;
- recommendations.

Though the following sections refer specifically to extractive waste, similar provisions and technical requirements will be necessary during the design of other classified waste depositories.

Table 5.2 Preliminary risk register for a MWF

Sector	Primary risk	Risk parameter	Design strategy
Mine development	Ore geology Resource	Mineralogy and alteration Tonnage and mine life	
Mine dewatering	Minewater volume	Quality Seasonality	
Mine waste rock	Mineralogy Production schedule	Geochemistry and geotechnics Quantity and rate of availability	
Ore extraction	Extraction rates Mining method	Ore dilution and contamination Geotechnics	
Ore comminution	Grind size	Geotechnics and geochemistry	
Mineral processing	Chemical alteration	Geochemistry and geotechnics	
Hydraulic fill	Slurry quality Production rates	Geotechnics and rheology Chemistry	
Mine waste management	Quantity and quality	Consistency and sources	
Effluent recycle	Quantity and quality	Metal recovery Overall minewater balance	
Closure	Long-term liability	Geotechnics and geochemistry	

5.2.3 *Regulatory Requirements*

Within the EU, the disposal of all extractive waste must be undertaken in strict compliance with regulations throughout operating life and beyond. The classification of both the extractive waste and of the storage facility is an overarching requirement and the process of categorising both the MWF and the extractive waste is illustrated by the flow chart given in Fig. 5.3. This regulatory flow diagram is a typical example developed by a Regulator (SEPA 2010) for the permitting and approval of a new Category A mine waste facility in Scotland. The flow chart presents the technical steps required to identify Category A or Non Category A status as well as all those necessary for ensuring compliance with the EWD, and mirrors those adopted in other EU member states. This approach, which underwrites both design and operation of the MWF, has been used as the basis for these guidelines.

The EWD applies to all extractive waste facilities as defined in Articles 2 and 3, i.e. waste rock dumps, tailings management facilities, silt lagoons and, in some jurisdictions, is referenced with respect to good practice for ash and sewage sludge lagoons. Figure 5.3 and similar national guidance documents (HMSO 2011 and

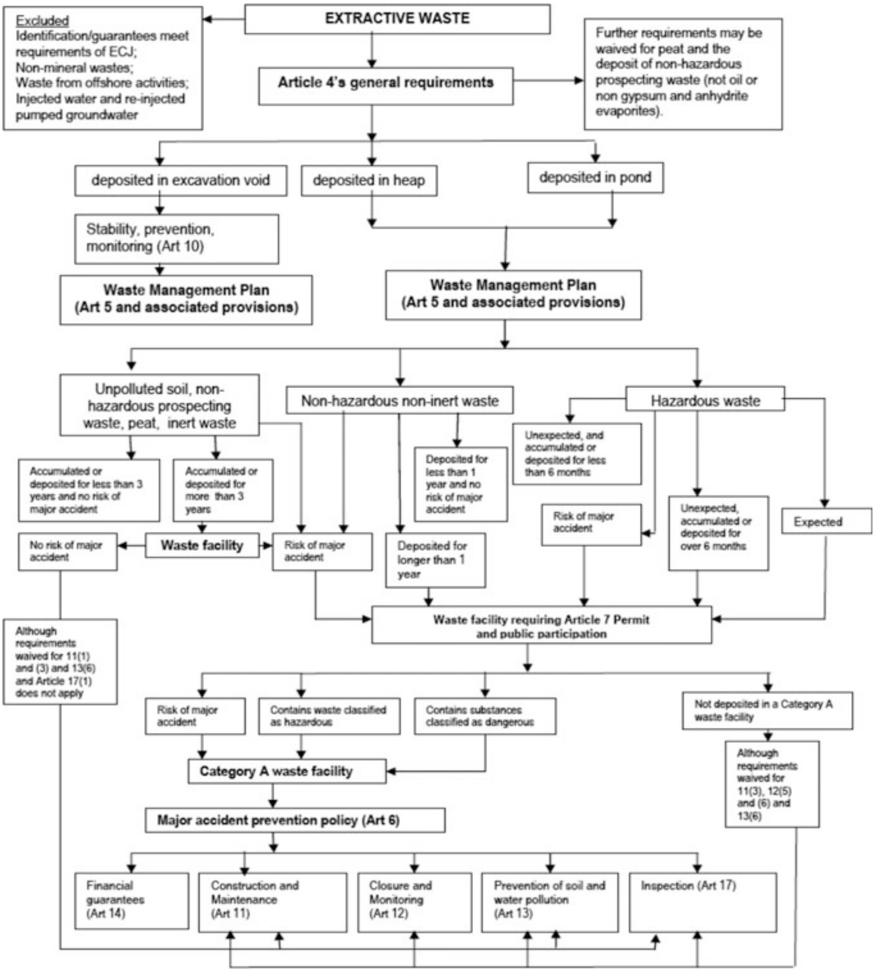


Fig. 5.3 Classification of a residue waste management facility (SEPA 2010)

SEPA 2010) recognise the importance of the categorisation process, the assessment of the hazardous nature of the extractive waste and of the risk posed by the facility in defining the MWF as either Category A or Non Category A. Of importance in the context of these guidelines are the additional design considerations necessary for a Category A facility as required by the EWD, as indicated below:

Waste categorisation
Facility categorisation
Emergency planning
Permitting (Environmental Permitting in the UK)
Competence in design and operation

Inspection
Financial guarantees
Closure

In addition, and of particular relevance to these guidelines, is that the EWD specifies that the design shall be undertaken by competent personnel, be reviewed and inspected from time-to-time and be certified by the Regulator and, as appropriate, by an independent expert in order to verify both construction standards and the ongoing stability of the facility.

5.2.4 Waste Storage Strategy

The design of a facility for the storage of hydraulically placed extractive wastes requires a corporate waste management policy against which all designs and operational standards can be developed and subsequently managed and which is in strict compliance with the prevailing regulations. Three essential requirements need to be met in order to ensure that the strategic objectives are achieved:

- waste materials must be correctly characterised, as outlined in Chap. 4, given their overriding importance in driving the facility design process;
- storage objectives must ensure optimal use of the placement environment under all operating conditions;
- the functional requirements and properties of each strategic objective must be resolved by specific design elements.

5.2.5 Waste Material Characterisation

The geotechnical properties of the waste materials to be deposited fundamentally affect the design and the performance of the disposal facility during both operation and post closure. Material characterisation as described in Chap. 4 forms a fundamental part of the pre-deposition investigation and design phase, as well as being essential during operation to ensure that the assumed parameters for the deposit are being achieved. Though for the most part the materials used for hydraulic fill have similar properties to normal geological soils, the processing, the hydraulic transportation and the geochemical characteristics may impart non-standard properties to the material both at particulate and mass deposition level.

Characterisation of the waste involves geotechnical classification to determine both short- and long-term physical properties, as well as separate geochemical assessment in order to identify any hazardous or dangerous substances or acid generation potential.

5.2.6 *Establishment of Design Criteria*

The principal purpose of a confining system is the storage of the mine waste in a controlled manner for an infinite amount of time (Bjelkevik 2005) and the design of the facility must therefore consider the following:

- the existence of adequate capacity to store not only the particulate waste but also process waters and any run-off from precipitation on the mine site and, potentially, on the upstream catchment. The importance of waste storage capacity lies in the fact that it controls the quantity of mineral reserves which can be extracted;
- the local topography, geology, hydrology and climate, as well as the characteristics of the waste material to be stored, which will determine the site, type and available volume of the depository;
- the nature of any confining structure or dam required to contain the waste and the available sources of construction material, local borrow materials, the mine waste product or combination of both natural and waste materials;
- the method for constructing the confining embankments and placing the hydraulic fill into the facility in the context of its configuration, recognising that in comparison with water retention dams, which are often built to the final height in one operation, there is the need for staged raising as the extractive or process activities proceed and the volume stored in the impoundment increases.

The methodology adopted for raising the embankments and for hydraulic placement, as well as the waste characteristics, may change during the operation of the depository, often with radical impacts on both the design and the operation process.

5.2.6.1 Design Elements

A MWF for the retention and long-term storage of hydraulically-placed extractive waste would normally comprise one or more confining embankments, dependent on the configuration of the depository, together with all necessary infrastructure to enable safe and efficient management of disposal operations, including emergency spillways, decant and river diversion structures, hydraulic fill and return water pipelines and seepage control systems. Additional impoundments comprising further embankment dams may be required on an extractive site to provide emergency process water supply or for control of seepage flows and site runoff. Figure 5.4 shows the general arrangement of the confining embankments and associated infrastructure at the Instalação de Resíduos do Cerro do Lobo MWF (IRCL) at the Minas de Neves Corvo in southern Portugal. This facility includes the following principal features:

- main confining embankment and seven saddle dams at topographic lows;
- emergency spillway;
- flood diversion impoundments and stream diversion system;
- industrial water storage and return and recycle water system;
- seepage management, control sumps and recycle pumps;
- pollution control dams.

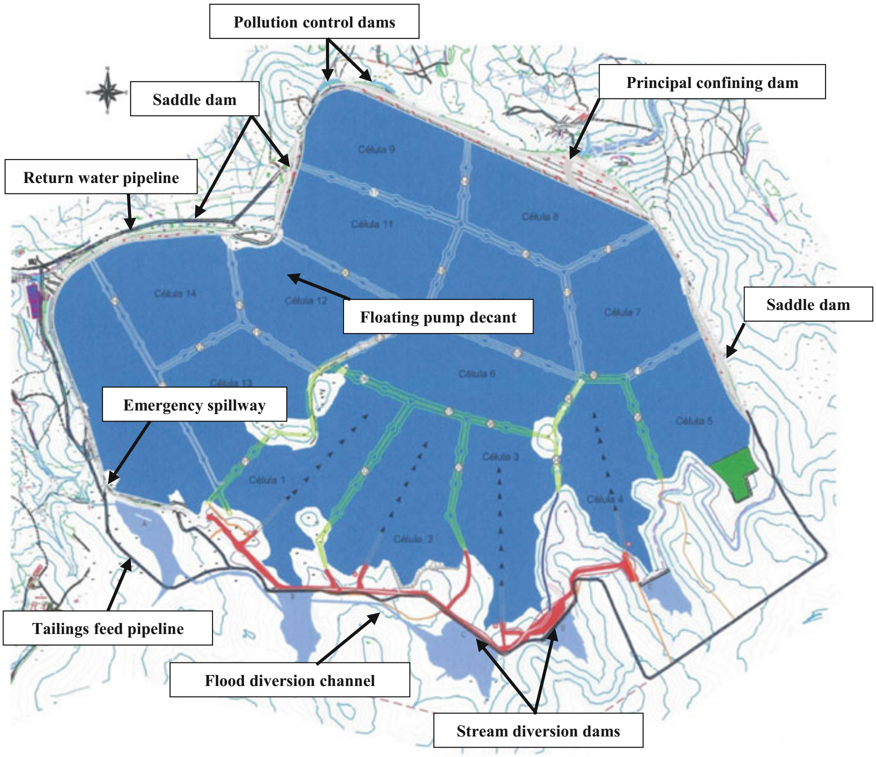


Fig. 5.4 Generalised layout of the IRCL MWF, Portugal

5.2.6.2 Design Parameters

The MWF requires adequate capacity to store not only the extractive waste but also process waters and direct rainfall falling within the impoundment area. The confining embankment should therefore be sited to ensure sufficient storage volume, and be robustly designed to prevent any failure or long-term deterioration which might lead to an untoward release of the waste product or of the contained process water. The MWF should include all necessary infrastructure to enable the facility to be operated and closed in accordance with the design parameters and with both planning and environmental constraints. The MWF and all such infrastructure should be designed and constructed in accordance with statutory requirements, i.e. with both national and international standards and with good practice in order to store the extractive wastes and process waters in safety. The design principles should be developed by the designer and reviewed at each development phase (Table 5.3) in close consultation with the owner's independent engineer (EC 2012) (Fig. 5.5), who will provide certification of the final design to the regulator and confirm that construction and operation is proceeding in accordance with the design. In particular, all material parameters, factors of safety and stability and flood assessments need to be compliant with good practice and to meet standard national and international criteria for such facilities. The design and construction of the embankments should be subject to regular (at minimum annual independent review), due to the dynamic nature of a MWF, in order to confirm the stability of the embankments and the ongoing validity of the risk assessments together with standards of construction and maintenance.

Compared with water-retention dams (McLeod 2003), which are often built to the final height in one stage, mine waste confining embankments are not only raised in a number of lifts as mining activities proceed but the methodology for raising them, for hydraulic placement, and even the waste characteristics, may change during the operational period. The facility therefore needs to meet all necessary design requirements at each staged raise and the risk analysis should include the possibility that materials, as well as the surrounding conditions (including extreme hydrological or seismic events), may change during the operating life, as shown in Table 5.4. The basis of the design and risk assessment should also be reviewed regularly throughout the life of the project and be updated by the designer as appropriate.

A MWF is required to store the wastes generated over the mine life and needs to accommodate appropriate statutory and legislative obligations, as well as those of local planning, with respect to the safe, efficient and environmentally acceptable disposal of the waste products emanating from the extractive waste project. The materials for permanent storage may comprise tailings, silts, mine waste rock and other process residues which could potentially be produced during the project life. The storage facility, therefore, must meet the following requirements:

- design, construction, operation and closure in accordance with the prevailing Directives and standards of good practice;
- disposal to ensure the settlement and consolidation of the finest particles and the maintenance of satisfactory supernatant quality;
- the control and recycling into the facility of all seepages and potentially-contaminated waters;
- the arrangement of the facility to suit the requirements of the process plant, of land availability, of the economics of the project, of environmental constraints and of operational flexibility throughout its design life;
- the retention or over-spilling in safety of all surface water flood flows after project closure.

In addition, the facility must be designed to operate safely and efficiently throughout the mine life, and to resist effectively all potentially destabilising factors. The hazardous elements of such events, together with the associated consequences, should be addressed in the design of the facility, and appropriate factors of safety adopted.

Table 5.3 Waste facility development risk assessment phases

Regulatory	Project phasing	Design/risk assessment phases
Project initiation		Preliminary financial assessment
Pre-development	Pre-feasibility study	Preliminary project risk assessment
	Conceptual engineering	Qualitative assessment of preferred option Preliminary environmental risk ranking Permitting risk assessment
Permitting	Feasibility study	Phase I quantitative risk assessment Definition of environmental risk and mitigation Geotechnical and geochemical risk assessment
	Final design Project approval	Phase II quantitative risk assessment Environmental design risk assessment and mitigation strategy Engineering design risk assessment and mitigation strategy Failure risk assessment for emergency planning Independent review of risk evaluation and mitigation strategy
	Pre-deposition Operating permit	Risk management through construction CQA Independent overview of risk management and CQA
Compliance	Operation Annual compliance reporting	Risk management through strict compliance with design Ongoing review of risks through facility inspection and monitoring Regular updating of operating and maintenance manual Ongoing waste and facility characterisation Regular review of emergency and closure planning Annual independent design overview, inspection and reporting
Closure	Active closure Compliance reporting	Confirmatory engineering stability risk assessment Finalisation of closure plan, design risk assessment and mitigation Confirmatory assessment of rehabilitation strategy Independent closure plan overview, inspection and reporting
	Passive closure Final compliance reporting	Risk management through closure completion CQA Ongoing review of risks through facility inspection and monitoring Long-term performance review through independent inspection Independent inspection and sign-off

Table 5.4 Risk summary for all design stages (Adam et al. 2004)

Event	Typical risk assessment for a MWF		Typical applicable UK standards
Natural event	*Hazard*	*Consequence*	Ref. CIRIA report, risk management for UK reservoirs
Seismic event	Catastrophic failure Untoward discharge	Extreme loss of life Environmental damage	BRE report "An engineering guide to seismic risk to dams in the UK"
Extreme flood	Catastrophic failure Untoward discharge	Extreme loss of life Environmental damage	ICE report "floods and reservoir safety" Recent Defra guidance EU directives
Unknown geology	Progressive failure Uncontrolled release	Possible environmental damage and loss of life	BRE "An engineering guide to the safety of embankment dams in the UK" BS5930/Eurocode 7 ICOLD Bulletins
Upstream instability	Overtopping Untoward release	Extreme loss of life Environmental damage	ICE report "floods and reservoir safety" Recent Defra guidance ICOLD bulletins Eurocode 7
External event	*Hazard*	*Consequence*	
War or sabotage	Progressive failure Uncontrolled release	Possible environmental damage and loss of life	ICOLD bulletins
Internal event	*Hazard*	*Consequence*	
Internal instability	Progressive failure Uncontrolled release	Possible environmental damage	BRE "An engineering guide to the safety of embankment dams in the UK" ICOLD bulletins Eurocode 7
Operational fault	Catastrophic failure Untoward discharge	Extreme loss of life Environmental damage	HSE guidance ACOP ICOLD bulletins

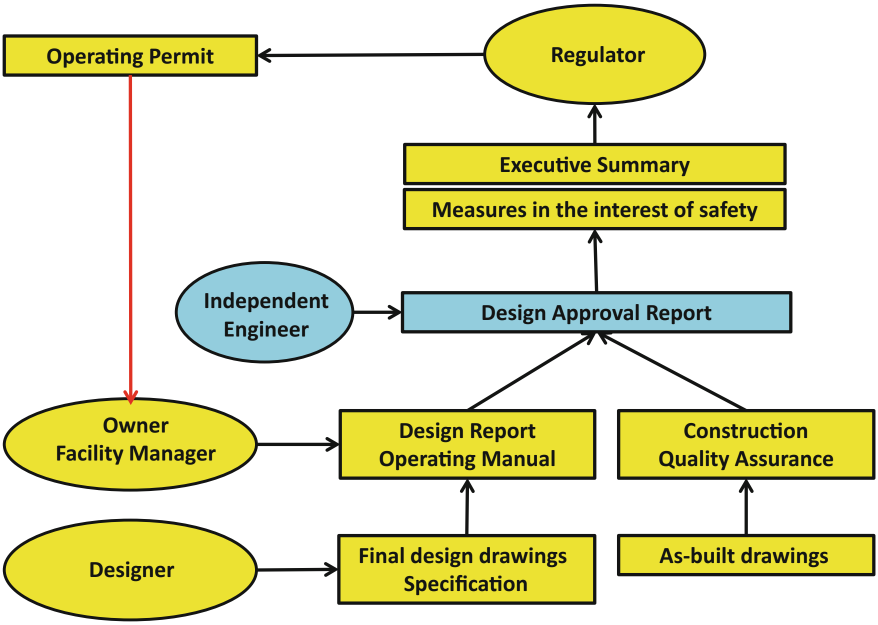


Fig. 5.5 Review and approval process for a MWF (Cambridge 2015)

5.2.7 Design Risk Assessment

The design process should involve the identification of all potential hazards, not only during operation but post closure as well. This enables the designer to mitigate the risks at each stage of the facility during the design and construction process. The key risks which must be addressed in addition to those normally associated with dam design are the geotechnical and geochemical characteristics of the extractive waste, the site water balance, the local hydrology, the robustness of the design under seismic loading and the potential for untoward releases, as well as those posed as a result of poor management or operation. The risk to life and to the downstream environment must be identified in order to assess the risk category of the facility and thus allow appropriate factors of safety to be used in the design (Sect. 5.6). Again, these risk assessments must include an evaluation of the potential for long-term geotechnical and geochemical deterioration of the materials stored in the depository or used to confine the waste product. The stability, hydrological and seismological design assessments, in particular, must be robust for each phase of dam raise construction.

The assessment of the design and construction risks benefits from a review of case histories of similar structures and, in particular, of failures. Such an assessment of the frequency of the dominant failure modes for MWFs was undertaken by the tailings dam sub-committee of ICOLD and is summarised in Fig. 5.6. These data provide a useful starting point for an overall risk assessment of a MWF.

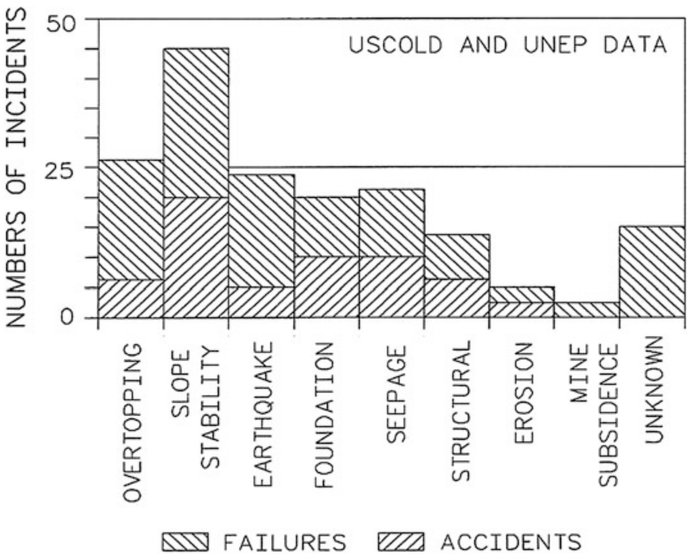


Fig. 5.6 Summary of historic tailings dam incidents (ICOLD 2001)

ICOLD Bulletin 121 concluded that "attention at the design stage to the critical issues that can affect the long term safety of a tailings facility will pay dividends throughout the life of the facility". The Bulletin provided a list of the primary features affecting the design of a tailings disposal facility and, in particular, those concerning the stability of the confining embankment, namely:

- detailed foundation conditions;
- ultimate height and angle of the outer slope;
- the rate of deposition and the detailed properties of the tailings;
- provision of adequate drainage;
- seismic influences;
- control of hydrology to avoid overtopping;
- control of the phreatic surface within the main embankment body to prevent high pressures.

The identification and assessment of the risks associated with the implementation of a MWF is a fundamental phase in the design process, and should provide the basis for the mitigating measures required in order to ensure that the construction, operation and the reclamation of the project site after the cessation of activities are effected in a safe and environmentally acceptable manner. A simplistic assessment of potential failure mechanisms is shown in Table 5.5, the elements included being

Table 5.5 MWF risk assessment

Failure mode	Consequence	Mitigation measures
Foundation instability	Failure of embankment leading to loss of production and discharges downstream, with potentially severe consequences for danger to life, environmental impact and corporate reputation	Detailed site investigation and laboratory study of underlying geology and foundation zone, leading to stability assessment with factors of safety exceeding minimum international and national criteria
Embankment overtopping	Failure of embankment leading to loss of production and discharges downstream, with potentially severe consequences for danger to life, environmental impact and corporate reputation	Spillway designed to pass or store routed PMF in safety at all stages of construction
Embankment stability	Failure of embankment leading to loss of production and discharges downstream, with potentially severe consequences for danger to life, environmental impact and corporate reputation	Detailed site investigation and laboratory study of construction materials, together with ongoing CQA, leading to stability assessment with factors of safety exceeding minimum international and national criteria
Seismic instability	Failure of embankment leading to loss of production and discharges downstream, with potentially severe consequences for danger to life, environmental impact and corporate reputation	Adoption of national seismic and stability guidelines which exceed minimum international criteria
Uncontrolled seepage	Development of sinkholes and promotion of internal instability leading to localised failure of embankment, with potential loss of production and discharges downstream and severe consequences for environmental impact and corporate reputation	Design of internal drainage control system to cater for seepage volumes at all stages of deposition, with suitable factors of safety and quality control of embankment construction materials to ensure internal filter relationships
Appurtenant structures	Potential for piping failure and promotion of internal instability leading to localised failure of embankment, potentially to loss of production and discharges downstream and to severe consequences for environmental impact and corporate reputation	Decant and other internal structures designed to accommodate total embankment stresses, with built-in redundancy and full instrumentation
Erosion	Potential for erosion of embankment and spillway walls as well as untoward discharge of tailings and process waters, potentially leading to loss of production and discharges downstream with severe	All embankment surfaces to be placed at slopes which encourage controlled runoff and all vulnerable pipelines to be instrumented to enable untoward leakage and discharges to be identified. No

(continued)

Table 5.5 (continued)

Failure mode	Consequence	Mitigation measures
	consequences for environmental impact and corporate reputation	pressurised pipelines to be laid on embankment surfaces
Mine subsidence	Potential for settlement beneath embankment walls and instability leading to localised failure and untoward discharge of tailings and process waters, potentially to loss of production and discharges downstream with severe consequences for environmental impact and corporate reputation	Detailed site investigation and historical research of old workings, leading to design of suitable stabilising measures in accordance with national guidance for treatment of underground voids, adits and shafts

a direct reflection of the principal historic failure modes for mine waste facilities. This table provides outline guidance as to the modes to be considered in assessing the overall risks associated with a facility to confirm that the proposed mitigation measures are in line with good practice.

5.2.8 Risk Mitigation Strategy

Having reviewed any relevant historical precedents and assessed the potential risks and impacts associated with the facility it is necessary to demonstrate how these are being (or should be) mitigated. The design-mitigating features should be developed on the basis that loss of life or risk of serious injury to either operators or those in the downstream catchment is not acceptable and that there should be no net loss of environmental or social assets, i.e. community, land or habitat quantity or quality. The design and construction must therefore clearly demonstrate that the facility include mitigation elements for all potential risks in accordance with the following hierarchy:

- avoidance—potential risks or impacts being removed or avoided altogether by the design and by the selection of technology and/or location;
- reduction—the risks or impacts being reduced or minimised where avoidance is not possible;
- restoration—mitigation by restoration, translocation, rehabilitation or clean-up where residual impacts are inevitable but reversible;
- offset—some form of offset or compensation for the residual impacts being applied, usually provided as a long-term replacement for any assets lost where other mitigation strategies are either not practicable or acceptable.

Risk assessment is an ongoing process during the development and implementation of a mine project, commencing at the conceptual design stage with the selection of site location and process circuit. It is further developed during the basic and detailed engineering stages, during the operation and upgrading of the installed facilities, and is concluded during the implementation and monitoring of the closure plan in the post-operation period. Risks can change as the project develops and therefore the corresponding measures for their prevention and mitigation may need to be modified in order to reduce risk exposure and achieve the specified structural or environmental objectives. The basis of the design risk assessment should be reviewed regularly and verified or updated by an independent engineer (see Chap. 7) during the life of the project.

The risk assessment process requires the systematic application of management policies and procedures in order to identify, assess, control, mitigate and monitor risk during the whole life-cycle of a project (Adam et al. 2004). Risk analysis is unique to each project but the basic logic is similar, i.e. identification of the potential risk, classification of the level of the risk which may occur in order to understand if it is high or low priority, and planning for remediation and/or mitigation in order to lower the potential for the event to occur. Reducing hazard potential should be achieved through design, monitoring and remediation and the accompanying risk analysis should include the possibility that the surrounding conditions, such as land use, demography or climate, may change. This risk analysis needs to be reviewed and updated regularly to take account of any such changes, particularly those related to extreme hydrological or seismic parameters (Cambridge and Drielsma 2007) and should make allowance for the impact of climate change. A generic flow path for a typical risk assessment is illustrated in Table 5.5 with an example design assessment for a MWF in a location with well-developed engineering standards being shown in Table 5.6.

The risk assessment methodology for MWFs adopted under the EWD is based on consequence, a procedure well-accepted throughout the EU for water supply reservoirs. Dam failures (total or partial), as well as incidents related to the stability of a MWF, may be caused by a range of faults. Particular issues associated with a MWF relate to the use of the extractive waste for dam construction and require both the analysis of risk and the characterisation objectives to be aligned to ensure that all factors which could potentially lead to dam failure are addressed. The characterisation of a waste facility as Category A imposes a number of strict requirements on both owner and the regulator, including specific provisions for the waste management and emergency planning as well as for closure. It is noted that these constraints do not extend significantly beyond those already required for compliance with good practice and, particularly, with ICOLD and other national guidelines. The assessment of the proposed design, construction and operation parameters should be undertaken against such guidelines, noting in particular the criteria summarised in Table 5.7 in order in order to confirm the appropriateness of the design proposals and of the associated mitigation measures. Further, the mitigation measures to be incorporated into the design should reduce the overall risk of a significant failure event during construction or operation to an extremely low level.

Table 5.6 Example of the principal embankment design assessments from the UK

Design assessment	Description
Embankment stability	Embankment at all stages designed in accordance with national, international and ICOLD guidance Minimum long-term factor of safety f > 1.5 Minimum short-term or dynamic factor of safety f > 1.1
Hydrological considerations during design and construction	Designed in accordance with current national guidance for flood standards for dams and for the identified risk category (ICE 2015a, b)
	The "safety check flood", often made equal to the probable maximum flood or in some jurisdictions to the 10,000-year event. It is considered acceptable practice for the crest structure, all waterways and the energy dissipater to be on the verge of failure, but to exhibit marginally safe performance characteristics for this flood condition
	The "design flood", strictly representing the inflow which must be discharged under normal conditions with a safety margin provided by the freeboard. It is usually taken as a percentage of PMF or a flood with a given probability of exceedance (such as 1:100, 1:1000)
Seismic design considerations	The stability assessment includes seismic design considerations in accordance with national and international standards and guidelines (ICOLD 1995 and BRE 1991, 1999), as follows: Maximum credible earthquake—when subjected to the MCE, damage is limited and no catastrophic failure will occur
Embankment stability at closure	At closure, the final embankment profile complies with EU and ICOLD sustainability guidelines (ICOLD 2011)

Table 5.7 Design risk criteria to prevent untoward failure (ICOLD 1995, 2001)

Component	Design questions
Dam and foundations	Has the dam been designed by competent engineers, with due regard for foundation condition, internal drainage, slope stability, seismic loading and contaminant containment? Are tailings or cyclone sand to be used for construction and has the structure been assessed with the same rigour as an earth/rockfill dam? Is the dam instrumented and/or monitored so as to reveal any abnormal behaviour?
Waterways	Are the decant systems secure and have all pipes through the dam or foundation been adequately sealed? Is there sufficient flood storage capacity and are spillways and/or diversions adequate for the design floods? Are there any hazards associated with the tailings delivery lines and water reclaim lines?
Closure	Has the structure been designed to accommodate potential changes in operating conditions over the closure period, e.g. erosion, floods, sediment, inflows or natural landslides?

5.2.9 Adoption of 'Good Practice' Standards

As previously described, the fundamental principles of good practice for a MWF are underpinned by a risk-based approach to planning, design, construction, operation and closure. Using a risk-based design approach to generate an understanding of all potential failure mechanisms which might occur within the MWF facilitates the adoption of appropriate design solutions in order to achieve the most cost-effective risk management approach (avoidance, mitigation, contingency or risk acceptance) and to define the optimum operating parameters.

Adoption of good practice project management standards enable:

- determination of the optimum system for construction, operation and closure of the facility;
- adoption of appropriate standards (CQA) throughout each stage of development of the MWF;
- all risks to be considered and suitable mitigating measures incorporated into the design, operation and management.

5.3 MWF Design Considerations

The materials for permanent storage may comprise, in addition to hydraulic fill, mine waste rock and other treatment residues which could potentially be produced during the project life. The associated MWF must therefore meet the following requirements:

- design, construction, operation and closure in accordance with prevailing Directives, national standards and good practice;
- disposal to ensure the settlement and consolidation of the finest particles and the maintenance of satisfactory supernatant quality;
- the retention or over-spilling in safety of all surface water flood flows both during and after project closure;
- the control and recycling into the facility of all local seepages and potentially-contaminated waters;
- the arrangement of the facility to suit the requirements of the process plant, land availability, economics of the project, environmental constraints and of operational flexibility throughout its design life.

In addition, the facility must be designed to operate safely and efficiently throughout the mine life, and to resist effectively all potentially destabilising factors. The hazardous elements of such events, together with the associated consequences, should be addressed in the design of the facility, for which appropriate factors of safety should be assigned.

Since the extractive waste generated during mine life needs to be confined behind an embankment dam to suit engineering and environmental requirements, the location of the embankment has to be chosen to provide robust waste storage capacity, an acceptable dam fill and reservoir storage ratio and suit local topography, geology and geotechnical conditions. The main confining embankment should be developed using locally-available materials where possible, either from borrow or, subject to suitability, mine waste and the most cost-effective cross-section and construction method chosen to suit the site. The facility should be constructed on competent foundations proved by geological mapping and intrusive geotechnical exploration using embankment fill materials, both structural and lining, which meet the needs of stability and environmental performance. All materials need to be proven geochemically and geotechnically to provide a robust design satisfying environmental and stability criteria under both static and dynamic loading.

5.3.1 Design Basis

The design process therefore involves the identification of all potential hazards, not only during operation but post closure as well. This enables the designer to mitigate the risk during the design and construction process. The key risks which should be addressed in addition to those normally associated with dam design are the geotechnical and geochemical characteristics of the mine waste, the site water balance, the local hydrology and the robustness of the design under seismic loading. The potential consequences to life and the environment downstream should be identified in order to assess the risk category of the facility, thus enabling appropriate factors of safety to be used in the design. Again, these risk assessments should include an evaluation of the potential for long-term geotechnical and geochemical deterioration of the materials stored in the depository or used to confine the waste product. The assessments must be robust for each phase of dam raise and construction.

In some EU Member States national regulations require that storage facilities be designed, constructed and operated in accordance with good international practice and that the same risk categories be applied to such items as flood design, seismic criteria and to emergency planning as used for large raised reservoirs (Cambridge 2008a, b). This generally indicates that the MWF requires special consideration for these design elements and that the confining embankment and appurtenant works should be designed by an experienced competent engineer in accordance with both national and international standards and to a design brief agreed with the owner's independent engineer.

The key design factors to be studied in detail during the final design stage are summarised below.

5.3.2 Site Selection Considerations

Site selection for a MWF is dependent on its location in relation to the process plant and to the economics of transportation and deposition, as well to local conditions such as topography, geology and climate, environment and social implications in the specific context of the geotechnical and geochemical characteristics of the hydraulic fill product. A simple risk assessment and site screening process based on preliminary site reconnaissance and a desk study for evaluating the initial MWF site and for focusing the initial detailed investigations is shown in Table 5.8. Such an assessment using a simplistic but effective ranking from 1 (unacceptable) to 5 (acceptable) enables preliminary screening of all available sites, the elimination of unacceptable locations and a more cost-effective investigation of the optimum site and configuration.

The preliminary screening enables the development of the optimal option/s for the MWF for further investigative works. This phase should entail a detailed investigation programme, enabling consideration of the chosen site/sites in more detail, and provide not only the pre-feasibility assessment but an evaluation of the costs of developing a particular site in terms of construction, operation, closure and

Table 5.8 Typical initial site risk assessment for a mine waste facility

Project risks	Weighting	Ranking (1–5)				
		Site A	Site B	Site C	Site D	Site E
Topographic suitability, i.e. dam wall volume and waste storage ratio						
Geological and geotechnical site suitability						
Seismic considerations						
Hydrology under both extreme drought and flood conditions						
Mine site water balance						
Environmental considerations (general)						
Environmental considerations (vulnerability of downstream catchment)						
Site access and mine site location						
Climate						
Total score						
Possible additional screening elements						
Waste characterisation						
Facility characterisation						
Historic mine workings						

environmental and social mitigation. Given the current legislative environment, the cost of permitting the particular site should also be assessed.

The site chosen for the feasibility study (DFS or BFS as appropriate) should be justified during the final design phase against an appropriate balance between engineering, operational, economic and environmental criteria, taking into account the local regulatory framework. The options will have considered the following, set against the known material and site parameters:

- site location in relation to the risks and potential impacts, the transportation distance, engineering requirements and construction costs;
- extractive metallurgical process and technology options in relation to the physical and chemical behaviour of the fill itself, as well as to the constituents of the process water storage and return system;
- construction of the MWF in relation to the properties of the engineered fill, the configuration and zoning of the confining embankment and the ongoing containment of seepage through the embankment and base of the facility;
- deposition of the hydraulic fill in relation to the properties of the tailings slurry, variations in feed characteristics, sedimentation and consolidation rates;
- control of all potential releases to the downstream environment with respect to seepage, flood events and airborne emissions.

The adoption of the optimum site will enable a BFS and permitting design to be prepared for a MWF based on the chosen location. The design detail to be provided for permitting will be dependent on the specific regulatory environment but the documentation to be submitted should present the intended outline design of the MWF and the supporting data be suitably robust such that the regulator can have confidence in the overall design, in the construction system and in the environmental mitigation measures proposed.

Receipt of a permit enables the final design of the pre-deposition works, which should address not only the detailed engineering for this phase but its interaction with the final construction details for each element of the facility and their phasing. During the pre-deposition works the designer should prepare the detailed methods of construction and associated quality assurance procedures together with the Operating and Maintenance Manual. This Manual should specify not only the ongoing quality assurance procedures and control systems for the staged construction works but also detail the operation of the facility, the control and management of the hydraulic disposal system and industrial water circuit, and the instrumentation and inspection requirements.

These processes and procedures should apply to the development of a MWF proposed for a new site as well as to the extension of an existing facility to which the same engineering criteria and regulations will apply.

5.3.3 Material Properties

The site investigation and other laboratory testwork should be undertaken in order to indicate that all potential construction materials have suitable properties for inclusion in the confining embankment. It should be recognised that the characteristics of any extractive waste materials used to construct the MWF, and also of the hydraulic fill deposited, may change during the operational period, particularly if extraction operations progress from an oxide to an unaltered ore body. The design of the confining embankment and the associated construction practices should be suitable to enable such changes to be accommodated without compromising safety. Similarly, the storage characteristics and the staged design should be robust enough to meet any changes in extractive waste production rates.

The construction of the confining embankment, though following normal geotechnical design procedures, may be undertaken using a wider range of techniques and engineered materials than is common for water supply dams. The confining embankment may be constructed from locally won borrow materials, from waste rock derived from the mineral extraction operation or from the finer waste materials (tailings) themselves. In each case the intrinsic geotechnical and geochemical properties of the materials to be used must be characterised (see Chap. 4) and the design prepared accordingly, using recognised good practice. The storage facility, and particularly the confining embankment, must be configured in the knowledge that materials available for construction and the properties of the waste product may change during the life of the facility, and thus a degree of flexibility must be incorporated into the design.

5.3.4 Confining Embankment

The confining embankment should include a main structural section comprised of engineered mine waste or imported fill, together with the necessary filter zones, underdrains and seepage collection systems. The earthworks used for the construction of the confining embankment should be comprised of engineered fill placed to an appropriate specification to suit the properties of the fill materials. The material gradings should be checked for compatibility and be based on international standards for filter design (Sherard et al. 1984), such as the following ratio:

$$D_{15f}/D_{85s} <= 5$$

where D_{15f} is the grain size of the filter material at 15% passing.

where D_{85s} is the grain size of the base soil at 85% passing.

The compatibility criteria should be applied throughout the full embankment section including, for a MWF, the tailings deposition zone. The site investigation and laboratory testing should therefore assess the available embankment fill materials and determine and define the following:

- the full range of grading characteristics of all engineered and hydraulic fills, including both pre- and post-compaction;
- the extremes for each material grading;
- the grading and filter material selection criteria, ensuring full compliance with the specified compatibility;
- the CQA testing protocols, frequencies and allowable failure rates (non-compliances);
- the failure criteria and remedial actions.

All the above must be clearly specified in the earthworks specification and construction procedures.

The seepage control zones should be designed to ensure the effective capture of embankment and extractive waste seepages. The system should collect and control seepages, and recycle these either via settlement ponds or through separate pump and return arrangements. The main embankment seepage system should control the lateral movement of interstitial water through the structure into a basal collection drain via engineered filter zones, thus enabling all releases to be controlled and recycled back to the main reservoir or discharged downstream as appropriate.

At closure, the rate of seepage from the deposit and the confining embankment reporting to the downstream collection system should reduce, particularly once the reservoir (surface water) has been removed. Ultimately, the water reporting to the seepage control system in a well-engineered facility will comprise runoff only. Experience from historical tailings disposal facilities has shown that seepage control during disposal can lead to effective drainage of the mine wastes and to a decline in the volume reporting to the downstream outlet within a few years of cessation of mining operations (Cambridge 2004). The rate of this decline is generally enhanced by the early landscaping of the upper surface of the depository in order to limit infiltration and water migration through the deposit.

5.3.4.1 Static Stability

The stability of the main embankment and any saddle dams should be assessed for a range of conditions, and the design of each stage of construction reviewed to ensure the safety of the confining structures at all times during the development. Material parameters, partial factors of safety and the stability assessment should be compliant with good practice and meet standard international and national criteria for such facilities. The overall stability should be calculated using industry-standard software, and include consideration of both normal and extreme conditions as well as the range of "what-ifs?" defined from the risk assessment. In summary, competent stability analyses for embankment design depend on the following:

- selection of conservative baseline soil parameters (characteristic values);
- identification of all potential failure conditions under all operating scenarios;
- identification of all potential failure mechanisms both upstream and downstream;

- review of soil parameters for each condition, i.e. drained or undrained and post-liquefaction;
- review of stability algorithm, with subsequent validation for the proposed analyses;
- establishment of a critical stability verification system such as hand calculations or rule of thumb;
- review of stability results for consistency;
- future-proofing of records of analyses.

It is noted that if the project is to be independently reviewed and approved, the brief for the stability analyses should be agreed with the review engineer in advance.

Typical static load cases for the stability assessment should consider the following:

- unexpected geological conditions in the foundations, such as the presence of:
  - underlying weak strata
  - historical surface and deep mine workings
  - adverse faults and fractures in the underlying geology
  - adverse hydrogeological conditions
- induced instability in the upstream catchment from:
  - natural faults and fractures in valley slopes
  - rising storage levels and inundation of natural slopes
  - rising storage levels and inundation of upstream rock dumps with the storage area
- sensitivity of embankment stability at all construction stages to:
  - changes in material properties
  - the range of operating and flood storage reservoir levels
  - adverse tailings or water storage conditions
  - the implications arising from:
    - failure of the drainage/filter system (embankment drains-blocked analysis)
    - blocked underdrains (foundation drains-blocked analysis)
  - poor construction practices leading to:
    - non-compliant fill materials
    - loss of material compatibility
    - missing filter zones
    - untoward stratification of compliant and non-compliant fill
  - poor disposal management practices leading to:
    - loss of reservoir control
    - inadequate mine waste for embankment construction purposes.

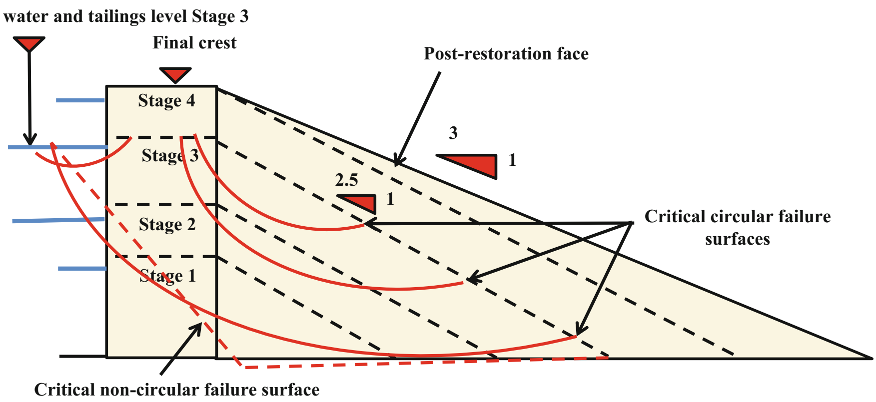


Fig. 5.7 Typical staged stability analysis

Further, the stability analyses should consider not only the highest and steepest cross-section with failure surfaces emerging at the embankment toe but also those emerging at higher elevations in order to ensure that the critical section can be identified (Fig. 5.7). The stability analyses should be completed for each critical section for the main embankment and saddle dams and both upstream and downstream failure surfaces should be considered. It is evident that the load cases specified above are not comprehensive due to the site-specific nature of embankment design and therefore some conditions may not need to be analysed in detail but may be addressed by inspection. However, all load cases considered must appear in the design register and the mitigation, or indeed design analysis, be referenced accordingly as per the example in Table 5.9.

5.3.4.2 Dynamic Stability (Seismicity)

As all mine waste facility sites should be considered to be located in seismically active regions, appropriate seismic codes need to be adopted during the design of a MWF embankment. These codes should be compliant with accepted national or international best practice and involve the identification of the Maximum Credible Earthquake (MCE) for the site, enabling the adoption of appropriate dynamic design parameters. Though determination of the Operating Base Event (OBE) is usually considered for water supply dams it is not generally deemed to be appropriate for a MWF due to the staged nature of construction and the consequences of failure associated with such structures. The materials to be included in the MWF

Table 5.9 Example of simplistic static stability design support register

Project stage	Failure mode	Stability analysis	Exit point	Reservoir level mOD	Storage level mOD	Phreatic surface	Soil parameters		Factor of safety
							Upper bound	*Lower bound*	
Permit	Upstream	Circular	Upstream toe			High			
						Low			
		Non-circular	Upstream toe			High			
						Low			
	Downstream	Circular	Downstream toe			High			
						Low			
		Non-circular	Downstream toe			High			
						Low			
Stage 1	Upstream	Circular	Deposition level			High			
						Low			
		Non-circular	Deposition level			High			
						Low			
	Downstream	Circular	Downstream toe			High			
						Low			
		Non-circular	Downstream toe			High			
						Low			
	Downstream	Circular	Berm level			High			
						Low			
		Non-circular	Berm level			High			
						Low			
Stage 2	The analyses should be repeated for all subsequent construction stages								

should, where appropriate, be resistant to loss of shear strength under seismic loading and appropriate factors of safety should be obtained for all embankment slopes from the dynamic analysis. The impact of seismic disturbance in the natural terrain within the MWF catchment also needs to be considered with regard to the risk of landslides, wave surge development and embankment overtopping. Both static and dynamic analyses of the valley side slopes should be included in the design approach, and appropriate factors of safety obtained. In addition, a review of both regional and local seismo-tectonics needs to be undertaken in order to identify the susceptibility of local geological formations to reactivation during an extreme seismic event. This is necessary in order to ensure, in accordance with recognised international practice for embankment dams, that possible active fault zones do not cut across, or daylight beneath, the MWF foundations. The results of the regional study should, as a matter of good practice, be incorporated into the final seismic design considerations for the embankment, thus ensuring that the facility is robust under the extreme event.

The basic seismic stability assessment should be based on current national guidance and may generate basic screening such as that shown in Table 5.10 and adopted in the UK (BRE 1991). It is noted that, though this screening was prepared for water dams, it is equally applicable to a MWF.

Using such a preliminary assessment, the MWF Hazard Category can be established and provide general guidance based on regional zoning of seismic risk

Table 5.10 Example of UK seismic classification (BRE 1991)

Parameter	Value	Classification factor	Classification criteria
Capacity (includes both water and solids)	20,000,000 m^3	4	>120,000,000 m^3 (6) <120,000,000 m^3 >1,000,000 m^3 (4) <1,000,000 m^3 >1000 m^3 (2)
Height	>45 m	6	>45 m (6) <45 m >30 m (4) <30 m >15 m (2)
Evacuation requirements (Number of persons)	1–100	4	>1000 (6) <1000> 100 (4) <100> 1 (2)
Potential downstream damage	High	8	High (12) Moderate (8) Low (4)
Total		22	
Seismic classification results	*Seismic zone*	*Seismic safety evaluation*	*Seismic design parameters*
	Zone A	Dam category III	Peak ground acceleration of 0.25 g Return period of 10,000-years

and on a generic maximum credible earthquake and peak ground acceleration against which the facility needs to be assessed. This preliminary assessment may indicate that, due to construction and location, static analyses or pseudo-static assessment are adequate. However, a more detailed seismic safety evaluation will be required if the overall height of the embankment is significant and if the cross-section incorporates materials with an elevated risk of liquefaction. Such an evaluation will necessitate inclusion of detailed geological mapping and identification of susceptible faulting, together with reference to regional or national detailed seismic databases such as those managed in the UK by the BGS. Such studies will generally need to be undertaken by specialists and will enable the peak accelerations and, in most instances, applicable accelerograms, to be derived for the Maximum Credible Earthquake (MCE) event.

The subsequent analyses may require an assessment of embankment settlement under seismic loading (Makdisi and Seed 1978; Sarma 1981; Newmark 1965) or a detailed simulation of post-event liquefaction and failure using advanced laboratory techniques and complex computational modelling of the embankment section. A more detailed review of seismic analytical methods is beyond the scope of these guidelines. However, a word of caution is appropriate regarding the use of pseudo-static analyses for stability assessments for a MWF for which the risk of seismic disturbance is elevated. The designer should ensure that the algorithm adopted in standard pseudo-static software is appropriate for assessing the stability of the MWF and that the results can be relied on to accurately reflect the performance and characteristics of the facility under seismic loading. Recommended minimum factors of safety are shown in Table 6.10.

5.3.4.3 Seepage Management and Control

The control and management of seepage through the confining structure and its foundations is fundamental to the ongoing stability of the facility. The designer must ensure that the embankment zoning is proof against uncontrolled seepages and their destabilising effects and that the risk of piping is fully mitigated. The design must reflect the importance of material compatibility in the adoption of suitable construction materials and with respect to the grading of the extractive waste. Further, it should also ensure that the necessary protective zones are robust against the risk of uncontrolled seepage, particularly where this may increase with time due to rising hydraulic gradient or deterioration of materials, either physically or geochemically induced.

The development of uncontrolled seepages through an embankment is shown in Figs. 5.8 and 5.9 which provide examples of physical and geochemical defects which may lead to structural problems in the embankment.

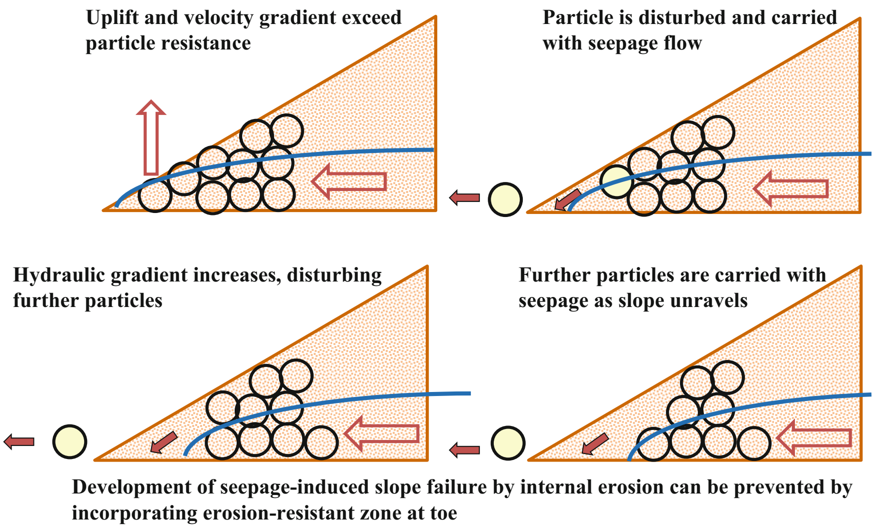


Fig. 5.8 Development of seepage-induced slope failure (Cambridge 2015)

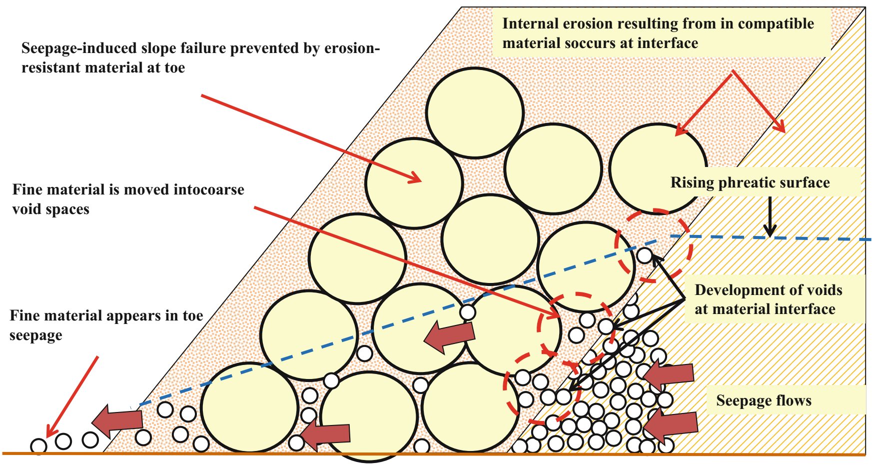


Fig. 5.9 Physically-induced seepage issues (Cambridge 2015)

Physical Seepage Control

At minimum, the effect of uncontrolled seepage will lead to localised sloughing on the face of an unprotected embankment, but in more extreme conditions may result in internal erosion (piping) and sinkhole development (Fig. 5.10) which may ultimately lead to embankment failure. The results of internal erosion in embankment dams are well-documented and the resulting catastrophic failures should be a

Fig. 5.10 Sinkhole in embankment surface caused by poor CQA on filter zone

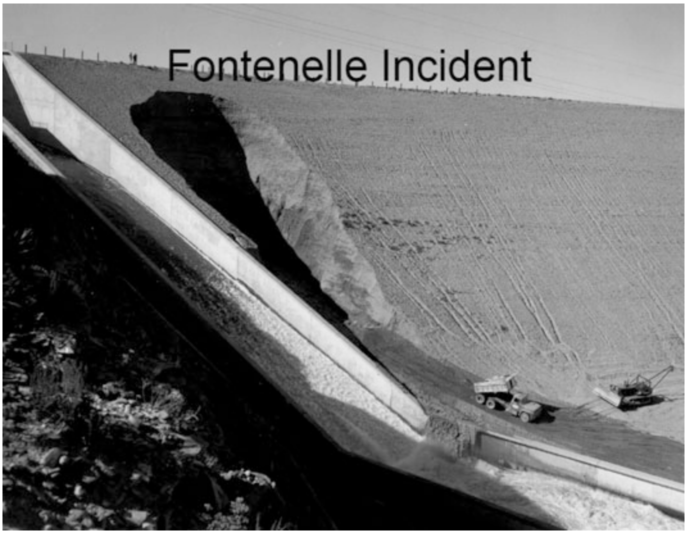


Fig. 5.11 Piping in dam face (Snorteland 2013)

warning to designers (Fig. 5.11) (Snorteland 2013). MWFs are similarly prone to piping/internal erosion, particularly where the confining embankment cross-section incorporates hydraulic fill. There are numerous instances of MWFs in Europe of poor material specification and placement control leading to internal erosion, causing sinkholes in the embankment and to their appearance at the surface of either the depository or in the embankment face. Catastrophic failures such as Bafokeng (Jennings 1979) were also in part a result of piping due to untoward reservoir elevation and lack of material protection. Failure to address such issues and to design against piping under all design circumstances and situations will lead to progressive evacuation of the structural zone and ultimately to a loss of stability, with potentially catastrophic effects. The mechanism of internal erosion and piping in dams and foundations has been studied in great detail in recent years and the findings and recommendations are included in ICOLD Bulletin 164 (ICOLD 2014).

Geochemical Seepage Control

> The reservoir's completely gone, the dam we'll see no more;
>
> For what they thought was H_2O was H_2SO_4
>
> (Cambridge 2008a, b) with apologies to chemistry teachers everywhere

The long-term performance and, especially the geotechnical and geochemical degradation of fill materials, should be factored into the design of the filter system. It is noted that many fill materials will weather in an embankment with time and the subsequent particle breakdown may render the filter design ineffective unless an adequate factor of safety has been employed.

The design risk assessment should be applied to geochemical effects as oxidation can result in hydroxides being generated and carried in the seepage through the protective zones (Cambridge 2008a, b) (Fig. 5.12). Such precipitates often comprise low-density flocs which are known to clog the pore spaces of drainage zones, again rendering them ineffective. This will result in a rising phreatic surface, with

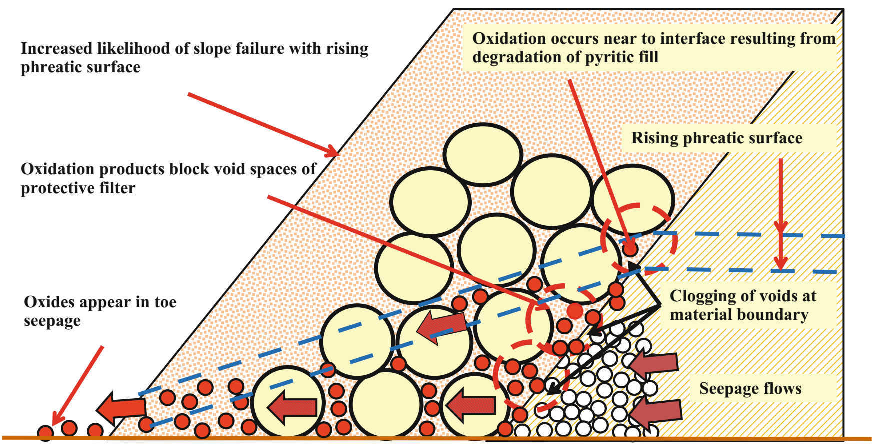


Fig. 5.12 Geochemically-induced seepage issues (Cambridge 2015)

potential destabilising consequences and severe implications for closure designs (Oliveira Toscano and Cambridge 2006).

The designer must be aware of the risks associated with the materials adopted, and ensure the following:

(i) that material gradings meet international guidance for compatibility and filter protection (Sherrard et al. 1984, ICOLD 2014);
(ii) that suitable construction quality control and management is in place to prevent out-of-specification materials being incorporated into critical embankment zones;
(iii) that compatibility checks include the extractive waste as an ongoing process to ensure that piping cannot occur;
(iv) that the adopted fill materials will not degrade physically or geochemically and render the design inadequate;
(v) that the design is proof against internal erosion under all phreatic surface, seepage and reservoir conditions;
(vi) that all filter compatibility criteria have an adequate factor of safety against failure.

5.4 Disposal Management

Hydraulic placement of the fine extractive waste and the configuration of the deposition system should be arranged to minimise transportation costs, achieve maximum storage density and efficient disposal, and ensure that closure targets are achievable. The hydraulic fill should therefore be discharged into the MWF to ensure, where appropriate:

- optimum transportation from process plant to MWF;
- integrated slurry transport and hydraulic distribution system;
- effective sedimentation in the reservoir to maximise settlement of solids;
- satisfactory physical and chemical clarification of supernatant water for return to, and re-use in, the process plant;
- management of disposal to maximise deposited densities and achieve short- and long-term effective consolidation;
- cost-effective management of the disposal system to ensure safe and efficient tailings deposition;
- controlled management of stored water to reduce the risk of untoward releases and elevated seepage levels.

The design of the deposition system requires the exploitation of the properties of the hydraulic fill, of the configuration of the depository, of the production process and of the climate to ensure cost-effective and environmentally appropriate disposal. Disposal management comprises two elements, namely hydraulic transport from the plant to the MWF and the distribution and placement system on to the surface of the depository.

5.4.1 Hydraulic Transport

The design of the deposition system generally includes the reticulation pipework from the process plant to the point of disposal. In the process of hydraulic design the key parameters of pulp density, pressure head and throughput need to be considered. The design must resolve the balance between pulp density and pumping (energy) costs, which may dictate not only the configuration of the main feedline but also of the deposition system. The design of the pipeline from plant to MWF should take account not only of the hydraulic capacity requirements but also of the abrasive nature of the tailings with respect to assessing pipe wear and longevity. These factors will be key to determining pipeline configuration, frequency and type of jointing and location of both operational and safety control valves. Further, the risk of leakage and untoward pipe-bursts should be assessed and suitable mitigating measures be taken, such as pipeline bunding and small impoundments at topographic lows being installed to prevent an uncontrolled release in the case of a joint failure or leak.

The design of the pipeline should also consider the following:

- potential extreme climatic conditions, with elevated temperatures resulting in buckling and instability in the pipeline, or freezing conditions leading to pipe fracture and leakage;
- water hammer and hydraulic surges leading to pipe fractures;
- pipe blockages cause by sedimentation in the pipeline following shutdown;
- chemical precipitation in the pipeline, particularly of gypsum, leading to reduced hydraulic capacity;
- traffic damage;
- security of the pipeline against theft of control units or untoward valve operation and other vandalism.

Finally, the design of the main feed line must consider accessibility for inspection and maintenance of the pipeline system, noting that a fracture or leak in a buried pipeline may not manifest itself for some time, potentially enabling uncontrolled releases off site.

5.4.2 Hydraulic Disposal

The choice of a hydraulic disposal system will be determined by the configuration of the MWF, the hydraulic transport infrastructure, the grading and characteristics of the tailings and ultimately by the permit conditions. In some jurisdictions in

Europe, regulatory controls have effectively specified the disposal method, resulting in owners being forced to adopt sub-aqueous deposition or filtered tailings. Storage of filtered tailings on surface does not involve hydraulic filling and is thus beyond the scope of these guidelines.

Regardless of whether sub-aqueous or sub-aerial disposal is planned, the deposition system needs to be flexible such that the natural tendency of the hydraulic fill to develop a cross-bedded laminated deposit is exploited. This will enable the elevated horizontal-to-vertical permeability ratio in the deposit to promote horizontal drainage, maximising lateral seepage, reducing saturation levels and thus increasing storage density. The extent to which this can be achieved, and the rates of consolidation, are principally dependent on the waste properties and on the confining system. The basic geotechnical characterisation of the waste forms a fundamental part of the design process and its importance in defining ongoing stability and closure should not be underestimated. Enabling effective drainage and consolidation provides a progressive improvement in overall stability as a result of the decrease in pore pressures and the corresponding rise in effective stress. The desaturation of the tailings also leads to the reduction of risk of both liquefaction and the potential for mobilisation on disturbance. Both factors further emphasise the importance of assessing the geotechnical characteristics of the hydraulic fill, not only at design phase but also during the early stages of deposition. The hydraulic deposition arrangements, together with the design and installation of internal drainage systems, need to be fully integrated to ensure that consolidation and storage density are maximised. The primary objective must be to increase surface stability with the aim of enabling early restoration, rehabilitation and landscaping at closure.

5.4.2.1 Sub-aqueous Disposal

Sub-aqueous disposal requires specific confining and disposal systems and, in particular, the requirement to confine both a lower density waste deposit and a significant reservoir, which is generally impounded against all or part of the retaining embankment. The MWF for sub-aqueous disposal necessitates a confining embankment able to retain the surface water without developing either elevated pore pressures or excessive seepage volumes. The accompanying reticulation system needs to enable the relatively even distribution of the fine waste across the reservoir basin with the aim of forming a uniform underwater surface. However, as sub-aqueous tailings achieve steeper underwater slopes, the disposal pipework must be arranged such that it can effectively distribute the tailings across the entire reservoir basin and thus be designed to be flexible. The disposal arrangements will require a perimeter manifold system which permits discharge via floating pipelines from around the perimeter of the depository. The system will need to be designed to ensure that critical velocities are maintained in the pipeline in order to prevent sedimentation and precipitation at topographic lows or where there are low gradients or pinch points. The floating pipeline will require an anchorage system which enables the outlets to be manipulated across the reservoir surface in order to minimise the extreme underwater topography of ridge and furrow, achieve a level surface to the extent practicable and maintain a minimum depth of water above the upper surface of the tailings. The design must accommodate the reduced storage density and thus increased storage volume requirements.

5.4.2.2 Sub-aerial Disposal

Maximising sub-aerial deposition by beaching across the depository is the key to effective storage, with increased pulp density implicitly leading to greater densification and the resulting physical benefits. The reticulation system, whether using open-ending, spigots, spray-bars or cyclones, must be arranged to achieve the maximum beach length compatible with water storage and return. Regular rotation of deposition points ensures the development of perimeter beaches, enabling thinner layers and thus encouraging air-drying and desiccation. Rotation also ensures control of the reservoir perimeter, improves embankment stability and prevents excessive erosion and re-deposition. In addition, as the tailings themselves may vary considerably in grain size, mineralogy and pulp density, a key function of the design is to deposit in such a way which maximises sedimentation and minimises solids return to the plant. Except for highly thickened tailings, which only generate bleed water, the minimum settling velocity of the tailings, often taken as the velocity at which 95% of the solids settle, will determine the minimum operating area of the surface water pond (Twort 1994) as follows:

$$A_R = q_i / v_{95}$$

where:

A_R is the minimum reservoir area required to settle 95% solids
q_i is the tailings inflow in m^3/s
v_{95} is the settling velocity in m/s of the 95 percentile.

However, where there is an ultrafine clay fraction, or where flocculants are used to achieve satisfactory water quality, the criteria may need to be based on quality of the return water and not on a minimum pond size. The deposition system therefore needs to be managed to ensure effective sedimentation of the finest portion and that minimum reservoir area is available at all times.

The surface slope of the hydraulically deposited beach relates to the characteristics of the waste and to the discharge velocity from each deposition point, and there are a number of methodologies for beach slope prediction (McPhail 2008). However, a rule of thumb for encouraging non-erosional sheet flow is to limit the velocity at each discharge point to between 0.5 and 1 m/s. This has been shown to limit erosion and channelling as the upper limit is less than the critical velocity required to move a particle of the equivalent diameter of approximately 200 μm (Leeder 1982). Ultimately, variations in plant performance and in climate may have a greater influence on the beach deposition and thus site-specific experience is the ultimate governing element. The Operating and Maintenance Manual prepared at the design stage for the pre-deposition works should include the disposal strategy to be adopted during the early stages of operation with the following key parameters as the driver:

- hydraulic placement to maximise available storage capacity by sub-aerial deposition;
- hydraulic placement to ensure ongoing stability of the confining embankment;
- placement strategy to encourage consolidation via the embankment and under-drainage;
- controlled deposition to manage the size and location of the supernatant pond;
- disposal management to minimise the potential for airborne pollutants;
- management of seepage control to maximise collection and recycling;
- management of disposal practices to minimise operating costs;
- instrument installation in order to confirm storage parameters;
- disposal management to facilitate early implementation of the closure strategy.

The deposited wastes should be regularly tested and fully instrumented to ensure that the disposal system performs in accordance with the design parameters at all stages of operation and closure. The Manual should set out the monitoring and instrumentation recording practices and the general inspection criteria and should be regularly updated to reflect site disposal and operating experience.

5.4.2.3 Basal Liners

The designer should recognise that consolidation of an extractive waste is adversely affected by the installation of a geomembrane liner throughout the MWF. This has the effect of reducing drainage, inhibiting consolidation and densification and reducing overall storage efficiency (Cambridge and Dale 1993). There are numerous sites where drainage has been inhibited in this manner, with the result that long-term increases in stored density were negligible and rehabilitation required the installation of band drains or their equivalent in order to achieve access to the surface of the depository at closure. The consolidation rate in a MWF is significantly reduced as the proportion of fines in the waste increases. The rate of consolidation is inversely proportional to the square of the length of the minimum drainage path and thus, in a laminated system with a potentially elevated k_h/k_v ratio, reducing lateral drainage can significantly impair consolidation rates and increase the required storage volumes. Consolidation rates in the deposited waste products are often enhanced by the installation of a drainage layer over the basal geomembrane, often supplemented by additional drains installed on the face of the embankment liner. However, the efficiency of such measures will depend on the establishment of effective flow paths to these drains, the portion of fines in the tailings and the long-term ability to effect seepage control under gravity through buried pipelines or by pumping from deep collection sumps. The long-term effectiveness of such an underdrain system must be assessed during the design phase as blinding of basal drains with increasing tailings depths may reduce their life to a few years, if not months. Further, buried pipelines through the confining wall or the installation of pump return lines over the embankment crest increase risks to the integrity of the structure. Where a geomembrane underliner is proposed, the design of the deposition system should ensure that the storage calculations are robust and take into account the reduced rate of consolidation and thus of densification of the tailings which will result. Any cost-savings in embankment zoning or permitting are likely to be negated by the additional storage requirements and increased closure costs.

5.5 Water Management

The design of a MWF needs to consider the geotechnical and hydrological parameters conventional for any dam, but also to incorporate the flexibility to provide continuous water supply to the plant and to meet the stringent environmental conditions often associated with mining projects (Cambridge 2010).

A MWF, unlike a conventional water reservoir, involves the retention of both settled solids and process water which may, if released, give rise to degradation of water courses and of the downstream catchment. Flood control measures for MWFs therefore require environmental controls during operation as well as safe design against extreme events. Such measures are complicated by the construction method commonly adopted for such confining structures and by the staged crest raising with successive, often annual, lifts over a period of many years to meet the demands of process and mine life. The facility will therefore need:

- to be capable of flood management at every stage of construction, and thus may require to incorporate a series of hydraulic control structures (emergency spillways) throughout its operational life;
- to provide a robust water supply, since the majority of the water used during mineral processing is likely to be derived from recycling of that discharged with the hydraulic fill into the depository;
- to comply with strict regulation of any discharge into local water courses, or indeed to accommodate zero release where there are overriding environmental concerns.

5.5.1 Water Balance

Under normal operating conditions the annual water balance for a MWF is used to address long-term storage requirements and to assess seasonal excess or deficit, and comprises the following elements (Fig. 5.13):

- process supply;
- other potential industrial demands;
- precipitation from both residual and upstream catchments;
- losses due to seepage;
- encapsulation in the settled solids;
- evaporative losses;
- inflow from mine or open pit dewatering.

The water balance will determine annual and monthly storage volumes whilst also defining flood capacity and any discharge requirements. The ability of an operator to manage the water balance effectively over the life of the project will be heavily influenced by the permitting conditions, i.e. the agreement as to the permitted quality and volume of any waters discharged into the downstream environment. On many mine sites the water quality of the reservoir and the sensitivity of the downstream receptors may preclude the release of waters at any time, and a "zero controlled-release" facility may be a condition of project development. Under such conditions the designer will need to ensure that the MWF, as the only significant water storage body on the mine site, has sufficient capacity to enable it to be operated in a compliant manner. For such facilities some mitigation can be achieved by the expedient of reducing runoff entering the MWF by diverting as much of the upstream catchment as is practicable, i.e. the effective separation of catchment and process waters (Fig. 5.13). A careful balance must be struck, however, between

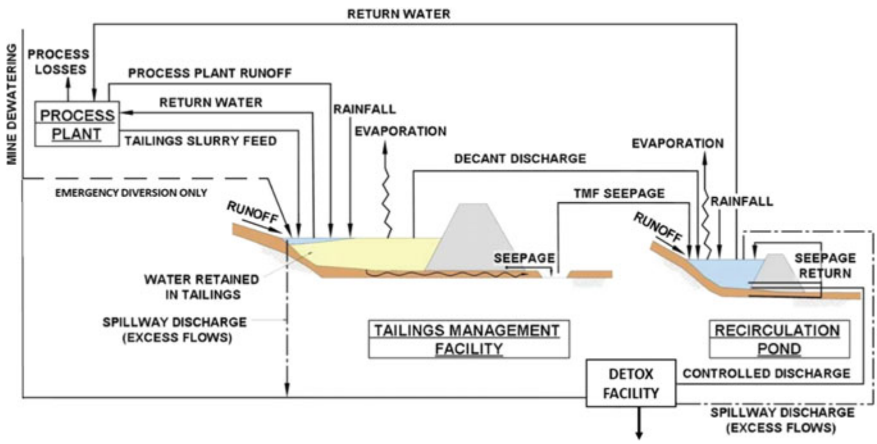


Fig. 5.13 MWF water balance

upstream diversion and continuance of water supply during dry periods, requiring detailed calculation of the monthly water balance for all climatic conditions. Where regular discharge from the MWF is permitted, both volume and quality will be fully regulated via discharge consent. Regardless of this consent, the operator must have the ability to control and manage water levels in the reservoir in accordance with the permit and with safe operation under all circumstances, whilst ensuring water supply for continued plant operation.

The development of a MWF water balance is influenced by the various project elements, including the tailings continuum, water availability, the environment and operational constraints as well as the recycle and re-use criteria of the process plant. Water used to transport the hydraulic fill to the MWF and released to the supernatant pond will be recovered for re-use in the process. In water-negative environments, additional make-up supplies will be required from external sources such as groundwater, mine or open pit dewatering and/or natural watercourses. Separate surface water impoundments are often developed to provide both a source of clean or raw water for use in key process elements such as gland seals and potable consumption and, additionally, as a robust industrial supply during periods of low rainfall and drought. As the primary water storage facility on a mine site the MWF may be required, either seasonally or throughout the year, to receive mine water from the open pit or from underground. However, it should be recognised that all additional water derived from external sources, particularly from the extraction operations, must not detract from the quality of the process feed abstracted from the MWF supernatant pond, and the water balance should allow for seasonal fluctuations in the inflow from such sources. The generic water balance presented in Fig. 5.13 illustrates the importance of this issue for an extractive site.

The water balance must not be considered in isolation but must be fully integrated with the parameters for the MWF which, generally being the largest water retaining body on the site, will play a major role in site water management. The control of water levels, and in particular the maintenance of an appropriate freeboard (Fig. 5.14) between the surface of the supernatant pond, minimum beach and embankment crest levels at all times, is an important design and management factor.

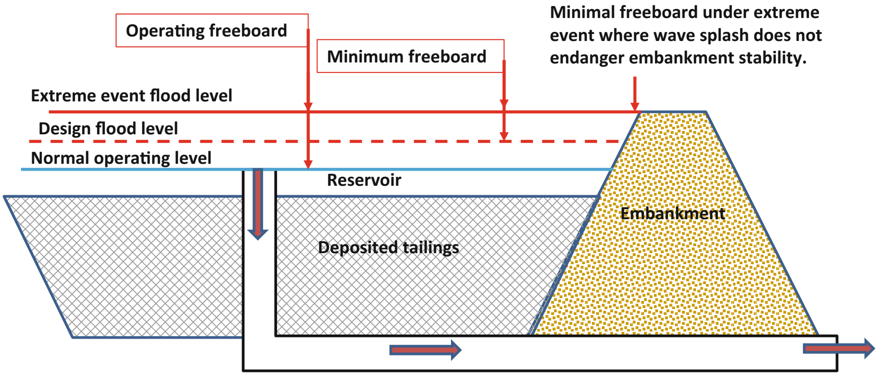


Fig. 5.14 Critical freeboard considerations for a MWF (Cambridge 2015)

5.5.2 Flood Studies

The hydrology of the catchment to the MWF must be assessed using the most appropriate national rainfall and runoff models and the approach to this assessment should be similar in character to that adopted for water supply reservoirs. The flood model should consider both summer and winter storm events and adopt appropriate catchment characteristics in order to derive a range of flood hydrographs for adoption in accordance with national and international practice. The design criteria adopted should include the ability to retain or, where permitted, to pass in safety the extreme hydrological event during operation. In addition, where an embankment is stage-constructed, the facility should be designed to retain similar flood volumes at all times by virtue of the storage capacity of the reservoir and the operating freeboard. The robustness of this freeboard should be tested as part of the risk assessment with respect to the potential for extreme events, such as landslide of the upstream valley slopes into the MWF and failure of the diversion dam towards the main depository.

During the final construction stage a long-term spillway structure may be required in order to cater for the post-operative condition and to meet the requirements of long-term flood management.

The facility should be designed to accommodate both extreme drought and flood conditions. The mine site water balance will be used to derive storage requirements and to assess the volumes of any necessary releases. Of particular importance is the flood standard to be applied to the storage facility, which must accord with current national guidance for dams for the identified risk category, as well as with accepted international practice. These flood standards are as follows:

- The “extreme design flood” for a MWF is generally defined as the Probable Maximum Flood (PMF) and corresponds to the “safety check flood” for a water supply reservoir. It is considered acceptable practice for the crest, waterways and energy dissipater to be on the verge of failure but to exhibit marginally safe performance characteristics under this extreme flood condition.
- The “normal design flood” for a MWF is the equivalent of the “design flood” for a water supply reservoir and represents the inflow which must be discharged under normal conditions with a safety margin provided by the freeboard. It is usually taken as a percentage of PMF, or a flood with a given probability of exceedance, such as 1:100-years or 1:1000-years. However, for a MWF this standard is only applicable if an emergency spillway is maintained at all times and where discharge of an extreme event (such as >1000-years) is permitted (Sect. 5.5.3).

It is not considered appropriate to adopt return periods with an enhanced probability of occurrence for the normal design flood unless the predicted outcomes arising from overtopping of the MWF during a more extreme event can be shown to have negligible consequences for life and the environment. The likelihood of such a scenario being acceptable in Europe is considered to be extremely unlikely and thus the internationally accepted return periods for the extreme event of 10,000-years or the PMF should be adopted for all stages of a MWF from the initial deposition period through to closure.

Therefore, in summary, the flood study and risk analyses depend on the following:

(i) selection of appropriate rainfall and runoff parameters;
(ii) identification of potential downstream impacts;
(iii) identification of preliminary flood risk category for a MWF based on potential impacts;
(iv) identification of all potential reservoir conditions (under all operating scenarios);
(v) identification of all potential overtopping mechanisms;
(vi) review of flood risk data with subsequent validation of the proposed routing analyses;
(vii) establishment of a critical flood verification system;
(viii) review of flood routing results for consistency;
(ix) future-proofing of records of analyses.

5.5.3 Flood Risk

The MWF must be robust under the appropriate flood standard and thus for a "zero controlled-release" facility sufficient freeboard will need to be available at all times to store this event (generally the PMF or equivalent).

As discussed above (Sect. 5.5.2), for most MWFs the flood design criterion will always be the PMF. However, it is evident that this imposes a significant restraint on the design of the facility and, moreover, may impose overly conservative operating criteria and negatively impact on disposal efficiency. Maintaining such retention capacity at all times often results in inefficient construction and operation, and may threaten the viability of the facility and thus of the project. In the past ten-to-twenty years, as the magnitude of design floods has tended to increase and discharge controls have become tighter, a more flexible approach to the design and operation of emergency spillways has been developed with regulators in Europe. It has been recognised that a limited discharge from a MWF during an extreme flood event will be likely to have a negligible contributory effect on any flooding impacts downstream. Further, the environmental risks are also likely to be minimal due to the significant dilution which will occur during such events.

In recent years, therefore, flood control structures for MWFs in Europe have been designed to minimise reservoir rise resulting from a combination of process water discharges and extreme flood events. For safety reasons these structures are required to be robust under the extreme design flood. However, the design no longer considers only retention of the PMF but addresses the discharge of a portion of this volume via an emergency spillway. This pragmatic approach assumes a two-tier flood control system, with the safety design being based on robustness under the PMF and the operating design on environmental constraints and permitting requirements (Cambridge 2010). In the UK the operating criteria at three facilities have been modified during the last twenty years and, though emergency spillways are provided to pass the PMF in safety, the approach to the normal operating conditions has been revised and a more realistic, less onerous but environmentally acceptable set of flood release standards derived. Accordingly, the hydrology of the catchment contributing to flood design for the MWF has been assessed to define not only the PMF but also the 1000-year event, from which peak flood discharges and volumes have been calculated. Flood routing of the extreme event through the emergency spillway has been undertaken to confirm the capacity of the waterways and, in addition, the flood volume for the lower-bound (1000-year) event has been assessed. These reservoirs are now operated on the basis that all floods up to the 1000-year event will be retained and that sufficient freeboard is maintained to accommodate this flood volume at all times (Fig. 5.14) (Cambridge 2015).

The overall design approach for a MWF should be to provide sufficient storage and to adequately manage water during operations such that no process water is released directly from the hydraulic fill containment into the environment other than through internal seepage during the life of the facility. It is conventional for storage facilities to be designed, constructed and operated in accordance with good international practice and that the same risk categories as are used for large raised reservoirs be applied to flood criteria (Cambridge 2008a, b). Therefore a mine waste facility which includes the potential to store a significant volume of water [often cited as being more than 10,000 m^3 (HMSO 1999) would be placed in the highest risk category for flood storage (ICE 2015a, b) due to the implications of an untoward release for both life and the environment in the downstream catchment. A suitably qualified civil engineer should therefore be engaged to advise on the necessary flood standards to be applied in order to ensure that the required hydrological assessment is compliant with this standard. A "suitably qualified civil engineer" in this instance is one with sound hydrological experience who is competent both to define flood standards and to approve the hydrological model to be used.

In summary, therefore:

(i) the flood standard to be applied to the MWF should be in accordance with current national guidance for dams for the identified risk category but should generally be the PMF;
(ii) a MWF should include robust storage capacity or an emergency spillway designed to pass in safety the PMF at all construction stages, as overtopping of the confining embankment is rarely, if ever, permissible;
(iii) the engineering and cost implications involved in retaining the PMF may require an alternative flood management approach;
(iv) in some jurisdictions it is accepted practice for a MWF to be designed to retain all floods arising from storm events up to and including the

1:1000-year event without spilling but to pass in safety those arising from greater storms up to and including the PMF;

(v) the acceptance of the design criteria must be based on a suitable risk assessment to confirm that flood discharges do not compromise environmental risk downstream;

(vi) if the project is to be independently reviewed and approved, the brief for the flood study should be agreed with the review engineer in advance.

5.5.4 Emergency Spillway

A major design criterion for a MWF is that it can either store or pass in safety the flood arising from the PMF on the site. As previously indicated, it is often uneconomic to store the PMF, and thus the extreme event must be discharged into the downstream catchment in a controlled manner via an emergency spillway. This operating criterion is obviously dependent on any additional downstream flood risk or environmental detriment being assessed as not significant and posing no additional threat to life or the environment. Under these circumstances the MWF needs to include a suitable hydraulic control structure and outlet channel for the extreme event. The design criterion should be the full containment and control of the routed peak flow to a point beyond the toe of the confining wall at which out-of-channel flow poses minimal risk to the embankment. The control structure is normally achieved with a series of weirs, either in concrete or in natural rock, which are constructed sequentially up the abutment to suit the embankment phase. Often, for reasons of economy, each successive spillway discharges into a single outlet channel which is also extended at each stage but which is located outside the final footprint of the MWF.

The precise design of such structures is site-specific and is dependent on catchment size, topography, rate of rise and land ownership. However, it is now accepted that all MWFs must be robust under the extreme event and that the risk to the embankment of either overtopping or toe erosion should be fully mitigated in the design.

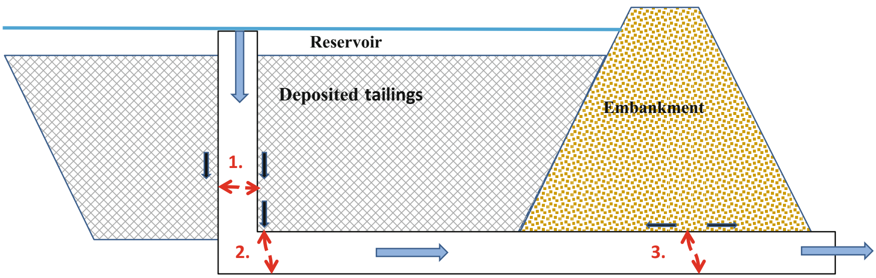
5.5.5 Decant Design

The decant structure functions primarily as the return system for recycling stored water to the plant throughout operations. The decant facility needs to be designed in tandem with the flood management system and, in some MWFs, may also function as the emergency spillway where the catchment is limited and outflow can be guaranteed. The decant may comprise either a gravity system with weirboard control or a pumped return from a floating barge or fixed tower. The engineering design may therefore comprise a barge and floating walkway or causeway or, alternatively, a buried concrete structure fitted with a rising offtake crest. The decant may also need to function as the emergency drawdown facility.

For each system the key design requirement is functionality under all operating scenarios, including the full range of climatic conditions. Therefore even a simple floating barge and pipeline or walkway must be able to operate in all circumstances and provision must be included for access for operational and emergency reasons during extreme weather, i.e. under heavy rain, snow, ice or strong winds, and the control valves located such that flow can be initiated or shut down in safety under all conditions, often defined as during a severe storm in the middle of the night.

Surface or fixed decants vary in design from central towers to side chutes, are generally constructed in concrete and include a system for raising the offtake level as the height of deposition increases. Circular towers located in the centre of the depository have the advantage of enabling peripheral deposition of hydraulic fill and of reducing the risk from flood events, and can be the most efficient and cost-effective means of returning water since the associated infrastructure is fixed and installed during pre-deposition. However, central towers carry an increased risk due to the structural issues associated with their configuration, particularly from the vertical loading imposed by the consolidating tailings, from the vulnerability of the tower foundations and from the presence of a buried pipeline through the embankment (Figs. 5.15, 5.16, 5.17 and 5.18). The risks were evidenced by a number of tower decant incidents which occurred in the 1960s and 1970s. These structures failed structurally at or about 20 m in height due to the stresses imposed by the consolidating tailings (Forbes et al. 1991).

The realisation of the implications of such high stresses has led to modified designs which address the effects of tailings consolidation and the risks associated with buried pipelines and appurtenant structures. The decant design must therefore seek to mitigate all risks arising from the configuration and operation, and address the following:



Critical stress locations:

1. **Vertical section of decant crushed due to loading imparted by consolidating tailings.**
2. **Horizontal portion fails in shear due to vertical thrust imposed by vertical section.**
3. **Horizontal pipeline fails in tension due to spreading of embankment foundations.**

Fig. 5.15 Critical structural considerations for the buried section of a vertical decant tower (Cambridge 2015)

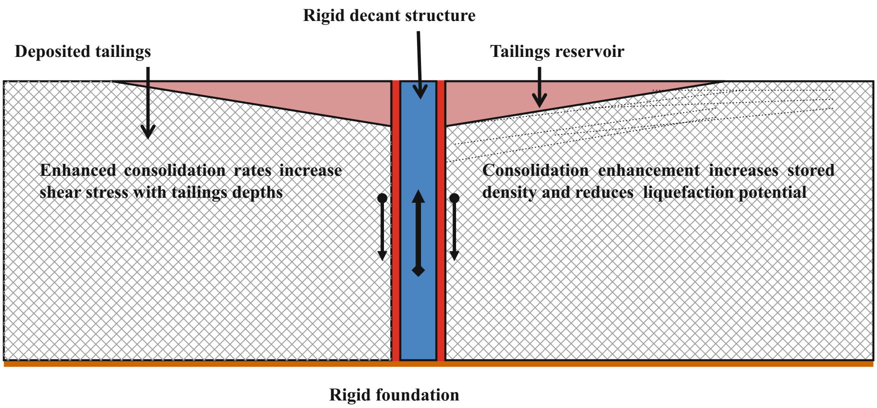


Fig. 5.16 Critical structural considerations for a vertical decant tower (Cambridge 2015)

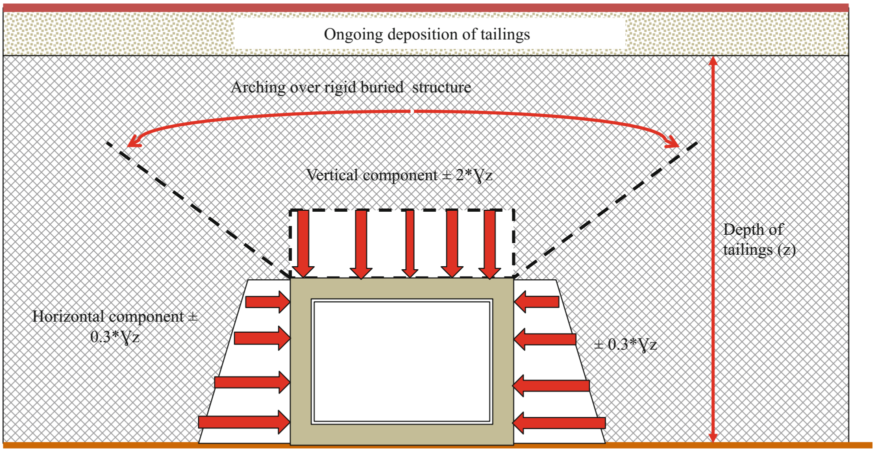


Fig. 5.17 Critical stress concentrations on a buried culvert (Cambridge 2015)

(i) adequate hydraulic capacity to meet all process flows and flood criteria;
(ii) robust construction to meet both short- and long-term loadings;
(iii) ease of access and operation, enabling the accommodation of successive raises;
(iv) full function under all emergency conditions;
(v) the design to mitigate any adverse structural or functional effects arising from adverse water quality or geochemistry of the hydraulic fill;
(vi) the particular requirements of inspection and monitoring.

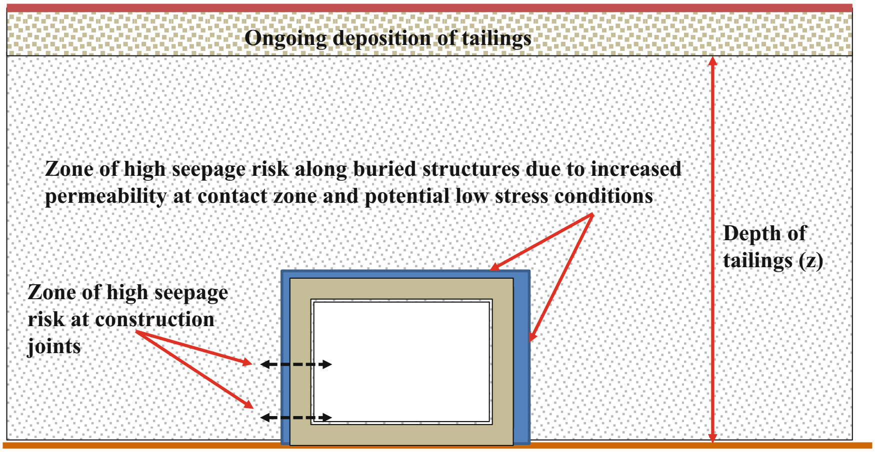


Fig. 5.18 Zones of potential high/preferential seepage (Cambridge 2015)

5.6 Emergency Planning

5.6.1 *Background*

The EWD requires that emergency planning be an essential design element for all Category A mine waste facilities. Categorisation therefore requires assessment of the hazardous nature of the hydraulic fill and of the risk posed by the storage of this waste, and is a two-stage process (Fig. 5.19). The characterisation process for

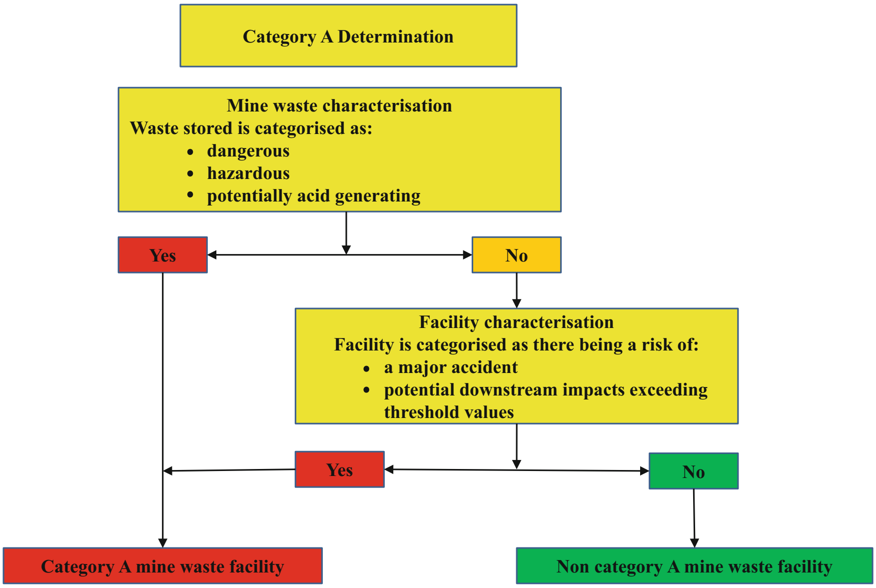


Fig. 5.19 Facility characterisation for emergency planning

determining whether a mine waste facility is to be classified as either Category A or Non Category A is based on the following:

- whether the contained material is hazardous/non-hazardous or dangerous/non-dangerous;
- whether the potential downstream impacts arising from a failure exceed the threshold values of depth and velocity of flow after a breach has occurred.

Regardless, therefore, of whether the mine waste characterisation determines the MWF as Non Category A, the facility may, by virtue of potential downstream impacts exceeding the specified threshold values, still be classified as Category A. Emergency planning is therefore required for the majority of MWFs in Europe in order to assess the downstream impacts arising from a failure, to determine the extent and severity of any social and environmental effects and to develop both mitigating measures and the off-site action plan.

Emergency planning requires the testing of the design and construction system to assess the most likely (credible) failure mode for the MWF. The adopted most likely credible mode needs to be developed rationally and the failure modelled in order to provide an indication of the downstream risks, if any, and the magnitude of the hazard posed by the facility. Though the development of the critical failure mode and the subsequent modelling may be undertaken by sophisticated computational methods, this can be an expensive process and in many cases may not be cost-effective, noting that the model is only required to provide an order of magnitude assessment of the downstream impacts rather than precise numbers of people and properties at risk. On the basis of the principle of design risk (Fig. 5.20) an alternative methodology using a more pragmatic approach to failure can be adopted

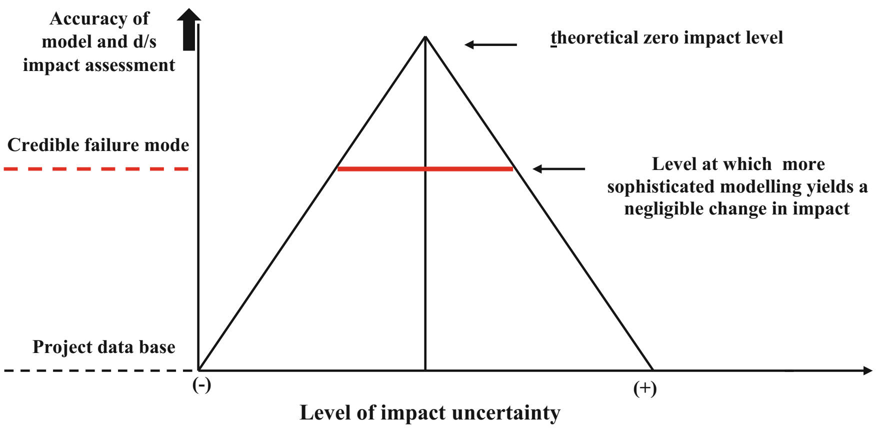


Fig. 5.20 Defining inundation model parameters based on relative impact downstream (Cambridge 2013)

in many instances and may prove adequate in establishing the extent of any downstream impacts and for emergency planning. This methodology is briefly described below in the knowledge that national guidelines may determine the approach to emergency planning.

5.6.2 Development of a MWF Failure Model

The design process for a mine waste facility should involve the identification of all potential hazards, not only during operation but post closure as well, as previously described. The key risks to be addressed should include a full evaluation of both short- and long-term risks to life and to the environment downstream and the final design stage include a detailed risk assessment of the stability of the confining embankment under all anticipated conditions. Therefore, for a correctly designed and operated facility, the initiation of failure leading to a breach is considered to be extremely unlikely since:

- the confining embankment should have a design factor of safety under both normal operating and extreme conditions which exceeds the minimum recommendations published in national and international guidelines;
- the embankment construction programme should ensure a crest height significantly in advance of both tailings and reservoir impoundment, thus ensuring that freeboard levels exceed minimum flood requirements at all times and that there is a very low probability of overtopping during an extreme event;
- the inspection and monitoring of the facility, the instrumentation and the embankment performance data should ensure that any untoward issues are rapidly identified and suitable mitigating measures adopted;
- annual, at minimum, independent inspection should confirm ongoing stability and correct operation and management of the facility, and identify any measures required in the interests of safety which need to be addressed in order to prevent the occurrence of future untoward incidents.

The failure of properly designed and operated mine waste facilities is recognised as having low-probability but high and serious consequence. It is mandatory within the EU for all Category A facilities to be assessed in order to determine the hazard potential which would arise should the embankment fail in such a manner that a breach were to develop and lead to an uncontrolled outflow of the contained liquid and solids. The purpose of failure modelling is to establish the worst credible event which could lead to the development of a dam breach, and to determine the extent of any subsequent downstream inundation and risk to life and the environment using the source-pathway-receptor approach. Such an assessment enables emergency planning by the operator and requires, at minimum, the identification of the following (Cambridge et al. 2014):

(i) Tier 1 assessment—to identify all potential and credible failure models and to establish the critical mode;
(ii) source—determination of the volume of solids and liquids disturbed and potentially released during the critical failure;
(iii) pathway—determination of the release mechanism for the material from the designed position towards a potential receptor;
(iv) Tier 2 assessment—establishment of the probability rankings for the credible failure modes and the identification of the critical mode to be modelled for emergency planning;
(v) receptor—assessment of the extent of inundation of the downstream catchment and of any centres of population or river and estuarine systems.

Establishing the credible failure modes may follow accepted national methodologies, which are generally based on failures of water supply reservoirs confined by embankment dams for which the critical condition is often assumed to be overtopping. The critical failure model for such reservoirs assumes a full-depth breach developing to near foundation level, with the basin emptying rapidly in a Teton-type failure (Snorteland 2013) and there are well-documented hydrodynamic models available for establishing the resulting inundation extent. For these reservoirs the rate of release is dictated by hydrodynamics and therefore no Tier 1 assessment is necessary (Fig. 5.21).

However, a failure in a MWF containing both water and settled fine particulate materials may, dependent on the characteristics of the depository, result in a partial breach through the dam wall and the rapid evacuation of the fluid portion and of only the more mobile fraction of the mine waste. The result is a Kolontar-type failure (Javor 2011) with the release dictated by both geotechnical and hydrodynamic characteristics (Fig. 5.22).

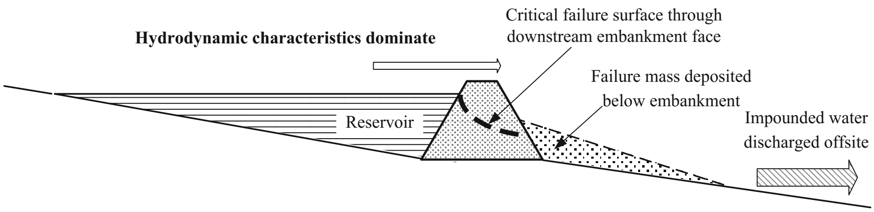


Fig. 5.21 Single-phase hydrodynamic model for a water supply reservoir

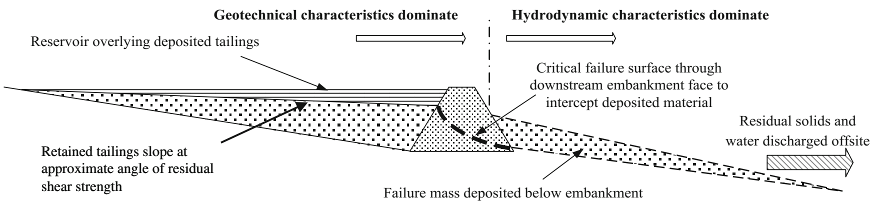


Fig. 5.22 Two-phase model for a stage constructed MWF

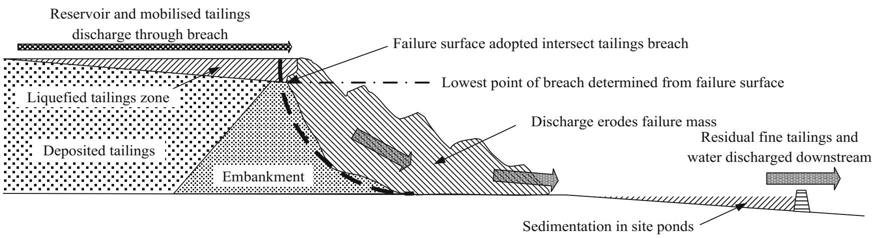


Fig. 5.23 Critical failure mode for a MWF

The initial Tier 1 risk assessment to determine the worst-case critical breach scenario for such a MWF should reference previous dam failure studies (ICOLD 2011) since a review of historical failures indicates that two-phase breach models are appropriate as a means of both determining the failure mode and predicting the event outcome (Cambridge et al. 2014). The model is predicated on the volume of free water stored on the facility at failure and separates the event into upstream and downstream phases. The failure characteristics, as outlined in Fig. 5.23, are determined as being geotechnical upstream of the embankment toe of the initiating failure surface and hydrodynamic downstream. A two-phase model enables a realistic assessment of the volumes of both solid and liquid waste involved in the failure, and the development of the breach mode permits conventional hydraulic models, such as those adopted for water supply reservoirs, to be used for preparing downstream catchment inundation maps and for determining sediment deposition.

Though the failure of a correctly designed and constructed MWF is considered unlikely, it is necessary to assess which modes should be addressed in developing a critical state for use in a breach analysis. Paradoxically, failure of a stable confining dam has to be considered in order to allow an emergency off-site plan to be prepared and the potential downstream impacts to be identified. The necessary engineering studies, requiring the use of basic risk assessment methods in order to identify and model the most likely failure mode and outcome, are summarised in Table 5.11.

5.6.2.1 Geotechnical Phase

Though the design should incorporate measures which, if implemented, would mitigate against failure of the facility at all stages, the identification of critical failure modes should be based on the least well-defined parameters. The critical states which, under realistic worst-case conditions, might precipitate a failure of the MWF should therefore consider, in particular, the following:

- local geological unknowns;
- inadequate construction and material control;
- poor operation and management of the facility.

This combination of parameters, no matter how unlikely where strict statutory controls on both design and construction are imposed, must be considered in the

Table 5.11 Staged approach to basic MWF breach modelling (Cambridge 2013)

Stage	Geotechnical phase	Basis
1	Critical failure modes	Identification of all potential hazards Identification of initiating event
2	Critical failure model	Identification of most-credible failure models Definition of critical location Definition of critical climatic effect (sunny- or rainy-day failure)
3	Critical failure mechanism	Development of failure progression Identification of breach extent Definition of solid and liquid volumes implicated in critical failure
Stage	Hydrodynamic phase	Basis
4	Discharge hydrograph	Development of breach hydrograph [Froelich equation, (Froelich 1995)]
5	Inundation modelling	Development of inundation mapping using standard hydrological models Preparation of inundation maps (in terms of extent, depth and velocity of flow) Assessment of attenuating elements in downstream catchment Definition of sedimentation of solid fraction within catchment based on flood velocities Definition of residual volumes carried downstream
6	Final assessment	Review of inundation extent against location of at-risk properties Review of depth and velocity profiles at at-risk properties using EWD criteria Determination of Category A/Non Category A status on the basis of breach model Preparation of input to both on- and off-site emergency plans

Tier 1 assessment in order to identify the range of credible failure modes which are considered most likely to result in embankment or structural instability (Table 5.12). Review of these modes should enable definition of the critical locations for the development of the breach, of the anticipated configuration of the failure surface and therefore of the volume of embankment fill involved. The definition of the failure surface will enable the breach height to be determined and this will lead to an assessment of the volume of the contained fine mine waste likely to liquefy, flow and be released. This volume can conservatively be based on a conical surface defined by the residual shear strength of the hydraulic fill.

Table 5.12 Example of critical failure mode assessment (Cambridge 2013)

Initiating event	Typical mitigation in design	Credible/non-credible	Failure mode
Waterway design		Cr/NCr	FM01-N
Overtopping	Spillway designed to pass PMF	NCr	
Spillway blockage	Robust storage volume with no catchment debris	NCr	
Erosion of spillway	Construction quality control	Cr	
Decant failure	Floating pump station	NCr	
Embankment design			
Seismicity	Rockfill dam stable under dynamic loading	NCr	
Uncontrolled seepage and piping	Factors of safety on filters >10 Construction quality control	Cr	
Erosion of underdrains	Factors of safety on design >10	Cr	
Untoward settlement	Construction quality control	Cr	
Foundation competence	Underlying geology and construction quality control	Cr	
Abutment competence	Underlying geology and construction quality control	Cr	
Old mine workings	Foundation preparation and structural mitigation measures	NCr	

5.6.2.2 Hydrodynamic Phase

The development of the breach configuration enables the release discharge hydrograph to be established and incorporated into a standard (national) flood attenuation model from which the peak discharge velocities and flow depths throughout the downstream catchment can be determined. These data enable an assessment of impact against the critical threshold values included in the EWD, which are defined as follows:

- depth of water or slurry exceeding 0.7 m above ground;
- velocities of water or slurry exceeding 0.5 m/s.

For a MWF, the velocity mapping also enables an assessment of the proportion of the hydraulic fill and the fine eroded debris which will settle-out in the catchment as a result of sedimentation. The peak flows throughout the inundation area can be used to assess the minimum settling velocity and the equivalent particle size (Leeder 1982). On this basis the material to be retained in the upstream catchment can be defined and a realistic calculation made of the tonnage of solids eventually released into the downstream catchment. Using this method it may be proved that only the finest particle sizes will be released through the breach into the downstream catchment. The proportion of this material should represent a reasonable upper-bound estimate of the total volume likely to be involved in the event. It should be recognised that, due to the shape of the outflow hydrograph, the peak velocity is transient and therefore the solid fraction released may be considered to be extremely conservative.

The results of the inundation mapping can be used to determine the areas of flooding and the velocity and maximum depths at each part of the catchment assessed. The locations at which high velocity flows will be confined to the existing channel should be evaluated, together with a broad indication of the areas where properties might be at risk. The extent to which out-of-channel flow occurs and exceeds the EWD thresholds for risk to life and property must be identified. The main area of environmental impact arising as a result of the deposition of the silt can also be identified, noting that evidence from the review of historic failures indicates that the maximum impact may involve the settlement of only a thin (less than 25 mm) veneer of silt and fine tailings over the flood plain or inundation area, with the major depth being restricted to close proximity to the facility.

5.6.3 Emergency Planning

The EWD requires the following to be completed for each Category A MWF:

- identification of the major accident hazards;
- preparation of a major accident prevention policy;
- preparation and implementation of an internal (on-site) emergency plan;
- preparation of an external (off-site) emergency plan.

The operator is therefore required to identify the major accident hazards and to incorporate the features necessary "to prevent such accidents and to limit their consequences for human health and the environment" into the design, construction and operation. As part of the design, therefore, a major accident prevention policy must be prepared and an on-site emergency plan developed. This plan should be based on the following:

- the development of a realistic failure scenario;
- the assessment of the volumes of solids and liquids which would potentially be released during a breach;
- the assessment of the risk to life and properties;
- the assessment of the downstream environmental impacts arising as a result of deposition of any silt carried downstream with the discharge.

These data should enable the operator to develop the on-site emergency plan, specifying the actions to be taken on-site in the event of an accident. The Competent Authority is required to generate the off-site emergency plan, which specifies the actions to be taken off-site in the event of a major accident. This plan should be based on the information supplied in the emergency on-site plan, which must provide all information required to minimise the consequences of a major accident for human health and to assess and minimise the extent, actual or potential, of any environmental damage. The format for such plans is generally specified in national regulations and guidelines, which should be referenced for content and detail.

5.7 Closure and Rehabilitation

5.7.1 Closure Philosophy

The design of a MWF is determined by its primary function, namely to store the extractive waste in a safe and stable manner. The design process should involve an assessment of environmental and social impact considerations and include both controls and mitigation measures in order to meet regulatory and environmental permitting requirements. This should include closure as an integral part of the design from inception onward ("design for closure") and entail not only closing and rehabilitating the facility but ensuring, to the extent practicable, its long-term re-integration into the biological, cultural and physical landscape. This good practice approach formulates the ultimate closure objectives into an integral part of a design rather than a closure plan being developed at a later stage when the operation of the facility is advanced and which, by necessity, is required to mitigate the impacts and risks resulting from the original design and operation. The closure process and restoration is therefore a major parameter in the design and becomes an integral part of the operational mode. Designing for closure requires a clear set of post-closure objectives for the facility, based on landform and after-use, the environmental setting (landscape and land-use) and long-term stability. Engineered closure involves capping, surface rehabilitation and the development of the final land use, together with the production of the engineering fills and soil-forming materials needed to support this. In addition, the development of the final closure system involves the assessment and mitigation of all short- and long-term geotechnical, geochemical and hydrological risks.

The key elements of the closure plan will therefore comprise the following:

- management and secure placement or treatment of any high-risk materials, such as ARD-inducing wastes, during operations;
- development of an engineered closure cover to mitigate all geotechnical and geochemical risks;
- minimisation, where practicable, of water storage on the surface of the MWF;
- ensuring suitable site drainage, flood control and water management;
- development of seepage management and control, including the provision for passive or active water treatments for ultimate discharge;

- development of appropriate land-use objectives, including covers, suitable vegetation types and their management and the potential benefits or risks associated with incorporating woodland or deep-rooted shrub species as part of the long-term objective;
- establishment of a clear strategy for future ownership and after-use, including the important functions of site management and transfer of responsibility from the operational company;
- establishment of appropriate financial provisions (as required under the EWD) and of potential income streams.

It is also critical to note that a closure plan is normally required for submission as part of an Environmental and Social Impact Assessment (ESIA) report. As such, the closure plan will be subject to the consultation process required under ESIA procedures and the key elements set out above be subject to both an internal and external consultation process involving a range of stakeholders.

5.7.2 Design for Closure

At the end of the operational life the MWF may comprise a large embankment dam containing some millions of cubic metres of deposited hydraulic fill and a residual industrial water reservoir, together with the saddle dams, pollution control dams, hydraulic structures and associated infrastructure. Such facilities need to be designed and engineered for closure from the outset such that at the initiation of the closure process and decommissioning phase there is a planned transition from operational to post-closure conditions. Further, the extent of additional re-engineering works needs to be minimised so that there is no requirement to compromise on after-use and landscape options. Preparation of a closure plan at the design stage is a strict requirement under both the EWD and EU ESIA Regulations, and there is the added requirement for regular review and updating of both the plan and the supporting engineering and closure strategy. Information and guidance on closure planning, options and procedures is provided in the BREF and in ICOLD bulletins (BREF 2009; ICOLD 2011; ESIA Regulations 2014).

The process of closure planning and implementation both prior to, and during, operations will typically involve:

- preparation of the closure plan and of the decommissioning strategy at permitting stage;
- regular review of the closure plan throughout the operating life, involving external consultation with a range of stakeholders as required by the permit;
- testwork to predict the geotechnical and geochemical behaviour of the confining embankment and its constituent materials, as well as of the hydraulic fill, in order to enable the design to take account of long-term degradation, ARD, residual contamination and erosion potential;

- testwork to assess the suitability of soil-forming materials, as well as to predict their geotechnical and geochemical behaviour;
- initiation of trials to investigate, test and demonstrate rehabilitation solutions both for cover materials and for vegetation;
- progressive rehabilitation of the containment structures and of the disposal areas;
- initiation of engineering works to achieve the final landform prior to cessation of extraction operations on the site.

In summary, the decommissioning and closure objectives should be as follows:

(i) pre-decommissioning—modification of the deposition system to achieve the final landform and, in particular, to minimise, to the extent practicable, potential surface water storage;
(ii) post closure, short-term—immediate stabilisation of all surfaces in order to manage extreme flood events, reduce the potential for wind- and water-erosion, to control infiltration and seepage and to develop the final landscape and after-use;
(iii) post closure, long-term—maintenance of ongoing geotechnical and geochemical stability and the development of an appropriate sustainable after-use requiring minimal intervention.

Designing for closure from project initiation, together with the early identification of a suitable and manageable after-use, will help to ensure that the long-term objectives can be met and will minimise the closure costs and reduce the long-term liabilities. The development of a closure strategy which is regularly updated during the operating life of the facility enables the deposition system to be modified in the period immediately preceding closure. This should permit the final landform to be created to meet the closure objectives and may, by manipulating the plant, enable the initial, or in some cases the final, cover system to be placed hydraulically (CLOTADAM 2003).

Closure planning also requires both the instrumentation of the facility and ongoing testwork in order to obtain the following:

- geotechnical data in order to confirm overall stability at closure and the extent of any necessary buttressing or re-profiling works;
- piezometric and seepage records for the confining embankment and the deposited hydraulic fill in order to confirm the stability of the tailings surface in advance of the implementation of the closure plan;
- geochemical data for all engineered and deposited materials in order to confirm their long-term stability and their resistance to degradation and to enable the design and incorporation of any necessary mitigation or treatment works.

It is essential that the closure plan specify a sustainable after-use which is appropriate for the site location and includes provision for beneficial uses both in terms of livelihoods and the ecosystem. The proposed after-use and land management plan will be subject to external consultation under ESIA Regulations, and need to be compliant with the project permitting requirements. After-uses can range from those with direct economic benefits, such as agriculture, to less tangible but equally valuable services such as biodiversity. A facility comprising the long-term confining system for the storage of the hydraulic fill should be permanent, and be designed to be safe and stable at closure and, effectively, in perpetuity. The design must therefore take account not only of the immediate operational and safety needs, but satisfy the longer-term requirements for:

- integration into the landscape and land-use pattern, with an enduring beneficial use;
- reduction of ongoing liability and of potential for untoward releases in the future;
- anticipation of changes and circumstances over a long time-scale and under a variety of external and internal forces, not all of which will be predictable.

The location and design of a facility must therefore anticipate and incorporate five key long-term factors, together with the necessary considerations and requirements as shown below:

(i) Engineering containment of the hydraulic fill

- geotechnical changes such as physical weathering and alteration of fills, as well as the degradation of liners and geomembranes or geofabrics, which may affect the stability of the retaining structures and the integrity of the containment;
- hydrological changes such as degradation of embankment drainage materials and filter zones, cessation of operation of underdrainage and seepage control systems, as well as the functioning of the surface water management systems;
- geochemical changes in the hydraulic fill, particularly the development of acid rock drainage, the leaching of toxic elements and the chemical weathering of the engineered materials;
- extreme events, both seismological and hydrological, including provision for passing flood events around or through the facility.

(ii) Capping, covering and soil-forming materials

- in many cases the hydraulic fill will be benign and will comprise a good soil-forming material without the need for additional growth media;
- where the fill material is expected to be physically or geochemically active, or contains leachable contaminants, a capping layer or barrier may be required to isolate it from the overlying cover and vegetation system. Such barriers may take the form of low-permeability materials comprising geological or synthetic covers, or high-permeability capillary breaks. Regardless of the cover system adopted it will need to be robust against long-term disruption or deterioration and to include drainage provisions for control, diversion and management of incident rainfall and runoff and the reduction of seepage and infiltration;

- the soil-forming materials (SFM) such as overburden, screened waste rock with appropriate particle size distribution and other waste materials to be used for final restoration cover and amelioration should be identified and stockpiled during operations. Topsoil is rarely available in sufficient quantities and is not always appropriate for the required land use.

(iii) Land cover and vegetation

- all sites will ultimately be required to support a suitable land cover, comprising a functioning soil-plant system, for both visual and after-use reasons;
- vegetation is an important part of the long-term integrity of the facility due to:
  - beneficial effects of run-off modification, surface protection, erosion control and, in some circumstances, soil reinforcement with roots and buttressing of slopes;
  - negative effects, including increasing water infiltration, surface loading (trees) and rotational forces which can compromise structural integrity;
  - associated biota such as grazing or burrowing animals which, though potentially beneficial in discouraging tree development, may lead to increased erosion and to void creation.
- vegetation is dynamic, is subject to natural successional and ecological changes over time, and is influenced by the degree of management. In temperate climates the successional change is typically from ruderal herbaceous and grass vegetation through increasing scrub and woody vegetation to woodland. The development of deep-rooted shrubs and trees on the cover system may have long-term detrimental effects, including root penetration of liners and capillary breaks, thus reducing their effectiveness. This may lead to untoward deterioration of the after-use plans and necessitate the provision of long-term vegetation control systems.

(iv) Landform

- visual and landscape considerations are equally important aspects of the long-term after-use and function of the facility. Engineered, angular or regular slope profiles may require modification in order to create a suitable landform but must be designed such that the function of the confining system is not impaired and leads to reduced stability;
- the final landform, including slopes, perimeter and surface drainage, soil type and exposure, is also critical to the ability of the closure system to achieve and support a beneficial after-use.

(v) Responsibility and long-term management

- establishment of a maintenance, monitoring and management programme for the facility after closure is required, including allowance for the necessary independent inspections and reporting together with ensuring both ongoing financial provision and defined responsibility. This can best be achieved by linking it to a beneficial after-use and economic activity, whereby management is not a burden but is a normal part of the land use and livelihood pattern.

The design of the MWF should include a strategy for operation and management during the immediate pre-decommissioning period towards the end of the life of the facility, which will typically include:

- anticipation of the proposed closure landform by developing the disposal of the hydraulic fill during the final years of operation to minimise post-closure engineering works on the surface of the MWF;
- decommissioning of the hydraulic filling reticulation system and other infrastructure, including staged removal of pipelines, pumps and other structures, noting that the decant and/or emergency spillway may need to be retained, together with seepage control systems and provision for water treatment;
- engineering changes to the landform and to both surface and internal drainage, though these must not compromise the long-term geotechnical stability or the hydraulic fill containment system;
- stabilisation of the surface of the hydraulic fill to enable the safe installation of the proposed capping system, soil cover and the post-closure rehabilitation and aftercare;
- long-term maintenance and management to ensure that the depository remains stable and that the revegetation and after-use (and the ecosystem functions) are sustainable in order to minimise both ongoing maintenance and inspection requirements.

5.7.3 Post-closure Inspection and Monitoring

The size and environmental significance of the MWF will require that the inspection and monitoring system be retained in the immediate period after cessation of disposal operations. As the rehabilitation works near completion, the frequency and intensity of these routines can be reduced but will need to be continued, albeit at a lower intensity. Post closure, there is therefore a requirement for an ongoing programme of monitoring, instrumentation and of inspection, both locally and by a competent independent external expert (Sect. 7.2). The continuation of this programme is consistent with statutory requirements in Europe for long-term inspection of embankment dams and tailings depositories, and it is essential that arrangements for ongoing responsibility and financial provision be put in place to account for this cost (Table 7.10). Finally, the system of inspection may need to extend for a period of years after closure and should only cease once the IIE has signed-off on the facility, declaring that it no longer represents a risk to life or to the environment.

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Chapter 6
The Development of a Mine Waste Facility

Mike Cambridge, Gavin Ferguson, Nick Coppin, Ciaran Molloy and Kris Czajewski

Mine waste storage facilities are often large and complex structures whose design, construction, operation and closure must be closely regulated in the EU. As previously indicated, at cessation of operation they constitute the most visible legacy of a mining project and, after closure and rehabilitation, are required to remain safe and stable and to produce no detrimental effects on the environment, effectively in perpetuity. It is evident, therefore, that a poorly designed or managed waste facility will lead to increased closure costs, on-going impacts to the environment and perpetual risk to public health and safety. Mining companies therefore face the challenge of effectively and efficiently managing extractive waste facilities throughout the life-cycle from initial site selection and design throughout construction and operation to eventual decommissioning and closure. Current regulations require that the facility be designed by competent personnel and inspected and audited for compliance throughout the operating life and beyond.

This Chapter details each stage in the physical development of a MWF from the construction of the pre-deposition works to closure. The elements addressed include the options for the configuration of the facility, for construction of the confining wall and the appurtenant structures, for the selection and operation of the hydraulic fill placement system and for an appropriate method of closure and rehabilitation to meet both corporate and regulatory objectives.

6.1 Configuration of the Facility

Mine waste facilities are designed to perform the following specific functions:

- permanent containment of the hydraulically deposited extractive waste;
- permanent containment by precipitation and stabilisation of potential contaminants such as hydroxide and oxide materials;

M. Cambridge (ed.), *The Hydraulic Transport and Storage of Extractive Waste*,
Professional Practice in Earth Sciences,
https://doi.org/10.1007/978-3-319-69248-7_6

- storage, recycle and management, both quantitative and qualitative, of process water;
- control and management of runoff and of extreme flood events;
- effective rehabilitation at closure.

The location of the project will determine the options for extractive waste storage and, through the site selection process, the optimum configuration of the depository. This will in turn determine the most cost-effective cross-section for the confining embankment and layout of the depository in order to maximise safe storage and minimise negative impact. The optimum configuration for the facility will depend on the physical and environmental characteristics of the chosen site, on economic considerations, on the preferred construction system and finally on the location of the facility in relation to the process plant. It is generally accepted that there are four principal configurations of MWFs, as illustrated in Fig. 6.1 and described in Table 6.1.

The site selection process described in Sect. 5.3 should involve detailed assessment and characterisation of the location, including identification of realistic closure options. It should also include an assessment of the potential implications of the long-term storage capacity in the event of the discovery and exploitation of additional mineral resources. Further, consideration should be given to the possibility of new mineral resources being discovered beneath or in close proximity to the MWF, the construction of which would effectively prevent their exploitation.

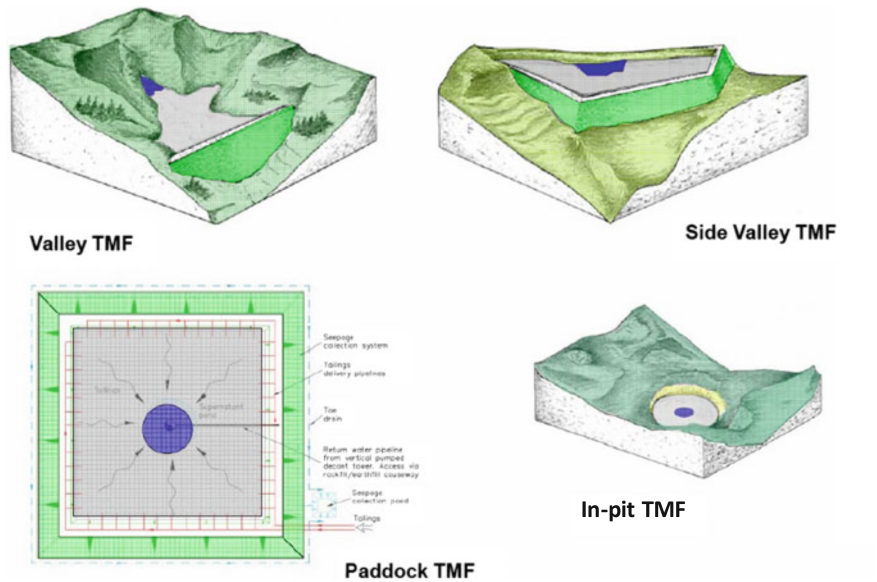

Fig. 6.1 Mine waste facility: typical arrangements

Table 6.1 Configuration options for a MWF

MWF type	Description	Benefits	Disadvantages
Valley	Comprising a confining wall constructed across a river course to form an impoundment on the valley floor	A valley profile generally offers the most cost-effective confining wall/waste storage volume ratio	Storage efficiency may be offset by the cost of flood storage and river diversion
Side valley	Comprising a confining wall constructed to form an impoundment on the valley side, generally above river level	The side-valley impoundment reduces flood storage and river diversion provisions to incident rainfall and runoff from the immediate valley sides	Less cost-effective confining wall/storage volume ratio due to the need to construct confining walls along three sides
Paddock	Comprising the construction of full perimeter confinement and appropriate where the topography provides no natural valleys or side slopes	The paddock impoundment reduces flood storage provisions to incident rainfall only	The least economical option due to the high confining wall/storage volume ratio
In-pit	Utilising existing mine voids or, infrequently, one specifically excavated to contain the hydraulic fill	In-pit storage involves no surface water flood controls as no confining wall is generally required	The cost of installing liners on the high wall, of mitigating seepage to groundwater, higher management input to achieve efficient storage as well as increased risks of inundating underground mine workings and of sterilising future ore bodies

6.2 The Confining Embankment

For each of the configurations described, some form of engineered structure will be required in order to provide confinement of the anticipated volume of hydraulically placed extractive waste to be produced on the site. The confining structure for most surface MWFs generally comprises an embankment dam constructed from mine waste, rockfill or earthfill, a concrete structure or indeed a combination of these dam types. The confining structure is likely to be stage-raised, and will thus entail on-going construction input throughout the extraction operation. An in-pit facility may also need internal embankments to segregate storage areas or to enable perimeter lining but, due to the generally lower structural risks, a homogeneous embankment may be adequate and will not require the same level of engineering input as other configurations. This section primarily addresses the engineered confining embankments associated with surface MWFs, and does not address either concrete confining structures or in-pit facilities, though it is noted that many of the characterisation and design guidelines are common to all. It is further noted that the use of concrete structures for containment is extremely uncommon within the EU and the design and construction requirements are well-addressed in other standards and guidelines.

Ultimately, the embankment cross-section for the MWF will be dictated not only by topography but by the availability of suitable construction materials, local geology, seismicity, hydrology and the economics of mine waste storage, an assessment of which will have been undertaken during the site screening and optimisation stage (see Chap. 5). The confining dam structures usually have three main segments, namely upstream, capable of retaining the waste without excessive fines penetration or erosion, a low-permeability zone which manages all seepage release rates in a controlled manner, and the downstream section which provides strength and stability (EC 2009). For smaller volume facilities the confining embankment may be constructed to full height prior to initiation of deposition (e.g. the Galmoy, Tara and Lisheen MWFs in Ireland). Most MWFs, however, and particularly on those sites where the mine waste is used for construction, will be staged-raised and be developed to full height over the life of the mine.

A zoned confining embankment will typically include the following elements:

- a lower-permeability upstream zone comprising a barrier against uncontrolled flow through the dam wall and involving a central core, an upstream face of conventionally placed clayey fill and/or a geomembrane liner. Where the hydraulic fill contains a suitable proportion of fines, this upstream barrier may consist of hydraulically-placed mine waste deposited to effectively separate the main structural wall from the tailings pond and reservoir. This zone, dependent on the configuration, will be supported by an upstream shoulder comprising conventionally placed rockfill or earthfill as appropriate;
- the main downstream structural section, constructed from engineered earthfill and rockfill placed to an appropriate specification to suit the properties of the construction materials. Hydraulically-placed tailings may be included in the section where the characteristics of the extractive waste permit, with placement relying on deposition and drainage to achieve a suitable density and strength. In some cases the hydraulic fill may require reshaping and be compacted using conventional earthworks equipment, as at Titania in Norway (ICOLD 2015);
- the necessary engineered filter zones, underdrains and seepage collection system to control pore pressures and the lateral movement of interstitial water through the embankment. The seepage control zones, comprising granular materials, control the piezometric conditions and enable all releases to be collected, controlled and recycled back to the main reservoir, often via pump and return systems.

The confining embankments for the storage of extractive waste have historically incorporated a significant volume of the hydraulic fill into the dam cross-section and the characteristics and quantities of this material have subsequently become integral to both design and construction methodology. Traditionally, "tailings dams" were categorised by four simple cross-sections which were used to extend the construction of the confining embankment beyond the initial, pre-deposition, starter dam (Vick 1990) and were identified as upstream, downstream, centreline and water retaining types, as shown in Fig. 6.2.

The advent of improved engineering techniques, the changing economics of mineral extraction operations and the need for the development of larger storage facilities, particularly the extension of existing structures to accommodate increased volumes and modified processes, have led to the differences between the basic confining embankment cross-sections becoming less distinct. Many MWFs have composite cross-sections exhibiting the properties of each construction method, as exemplified by the Clemows Valley Tailings Dam in Cornwall, UK (Fig. 6.3). In reality, site configuration, economics and local geology will determine the construction method and it is noted that, within the EU in particular, as suitable locations for a MWF are more limited, the cross–sections are more likely to be complex.

A synoptic description of embankment types is provided below with particular reference to MWFs within Europe.

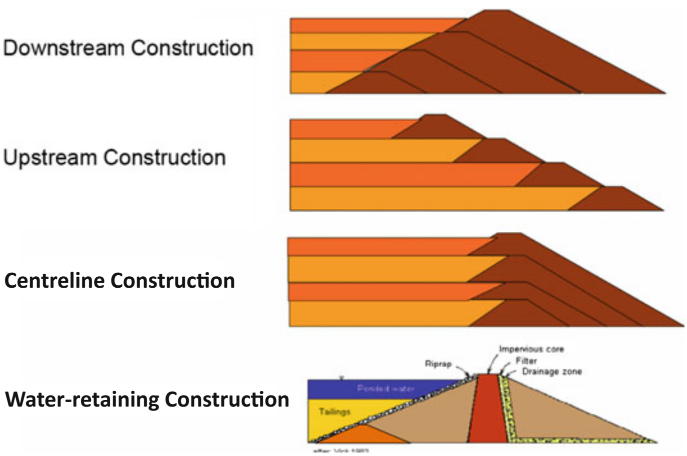

Fig. 6.2 Basic confining embankment cross-sections

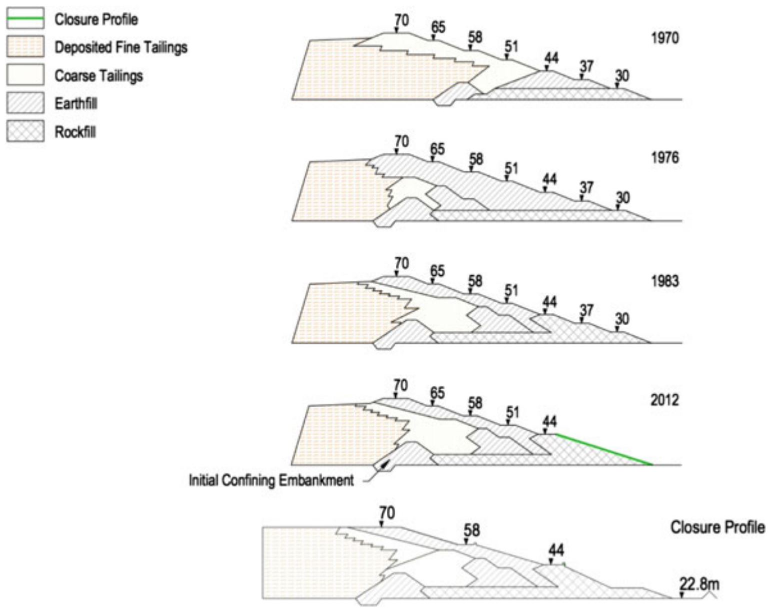

Fig. 6.3 Example of changes in confining wall profile at Wheal Jane, UK (Cambridge and Haile 1991)

6.2.1 *Homogeneous Embankments*

The simplest confining embankments comprise unzoned earthfill structures constructed from engineered local fill, and are often of limited height. These dams are the predominant form of confinement for silt lagoons in quarries, are often constructed within the excavation area (Fig. 6.4) and thus pose limited risk to third parties and of untoward discharges off-site. The stability is often reliant on the hydraulic head across the structure being restricted by the maintenance of a hydraulic fill beach along the upstream face and a limited depth of water on the silt surface. However, the water circuit and, in particular, the settling characteristics of

Fig. 6.4 Examples of in-pit hydraulic fill confining embankments

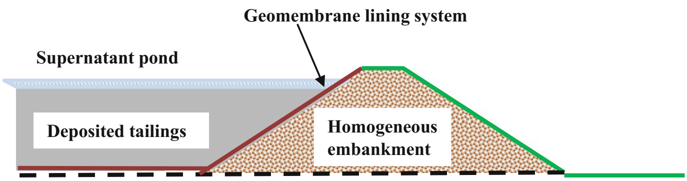

Fig. 6.5 Example of a lined homogeneous embankment at Galmoy MWF, Ireland

Fig. 6.6 Pre-deposition lining system at Galmoy MWF, Ireland

the silt residues at such sites, may require the construction of a succession of lagoons. Each of these will be designed to improve clarity of the return water, and thus the final lagoon/s in the circuit may provide clarification only and impound a continuous depth of water. In these circumstance the issues of seepage are often ignored (Fig. 6.4) and the retrofitting of a protective filter zone may be necessary after some years of operation in order to prevent instability in the downstream face.

Such embankments have also been employed for mining projects where the MWF is to confine a limited volume of tailings or where there are height restrictions on the development. These low-height homogeneous embankments (Fig. 6.5) have been adopted for the paddock-type facilities associated with the base metal operations in Ireland where the entire facility has been lined with a geomembrane (Fig. 6.6).

6.2.2 Stage-Raised Confining Embankments

For the majority of mineral projects it is not cost-effective to construct the confining embankment in a single phase and therefore most MWFs are stage-raised throughout the life of the project. Stage-raising can be programmed to suit deposition requirements and/or financial constraints and to optimise capital and operational expenditure. Initial construction will commence with a pre-deposition starter

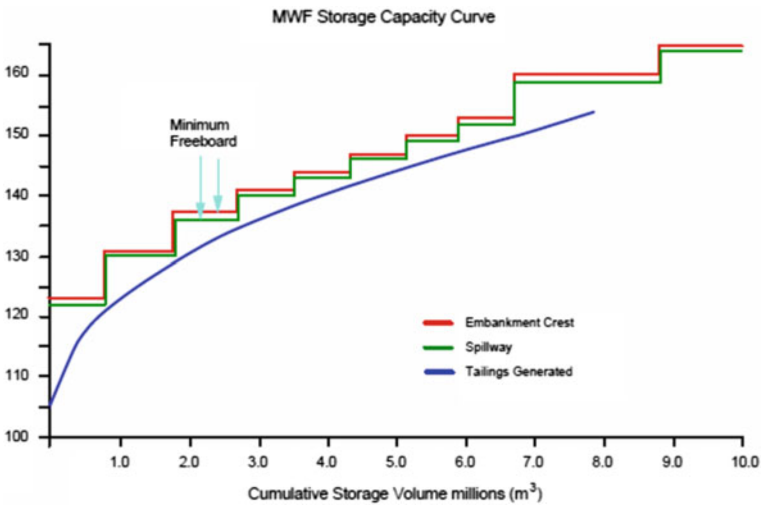

Fig. 6.7 Depth capacity curve and predicted embankment crest level for a stage-raised MWF

dam built prior to any mineral processing on the site. This starter dam will be sized to impound the initial period of production of plant output together with flood inflows and process water storage requirements. The advantages of the stage-raised approach are the potential to utilise extractive waste subject to suitable strength and competence, to fund construction from operational rather than capital costs and, in addition, to enable the cross-section to be modified to suit changes in process technology, mill throughput or ore mineralogy. The disadvantages of staged-raising are the need for greater attention to scheduling, construction CQA and ongoing stability, together with a larger operational management input and the potential for design responsibility to change. The stage-raising may extend over numerous cycles and a graphical representation showing the staged-raising of a MWF with hydraulic fill storage requirements and indicating the elevations at which emergency spillways are planned is shown in Fig. 6.7.

The principal construction methods adopted during each phase of a stage-raised MWF confining embankment are described below.

6.2.2.1 Pre-deposition Starter Dam

The pre-deposition embankment or starter dam is designed to store the initial tailings production and is the common element to all MWF confining embankments. The embankment forms a principal element of the pre-deposition works and, being constructed prior to process plant start-up, precedes the availability of plant-processed waste. The starter dam cross-section and the construction materials closely mirror those of a water-retaining dam and are generally constructed using conventional embankment techniques and, dependent on the location and on material availability, may as a result comprise any of the following embankment types:

- homogeneous earthfill for low dams;
- clay-cored rockfill;
- geomembrane-faced earthfill or rockfill;
- asphaltic-cored or concrete faced-rockfill dams;
- concrete.

The starter dam is often subsumed by subsequent raises and thus the embankment section may be designed to incorporate coarse mine waste from the initial development of the mine or open pit, subject to availability and, crucially, to mineralogy. It may be feasible, dependent on the future dam section and design seepage regime, to incorporate potentially acid-generating rockfill in the starter dam. However, all subsequent oxidation products need to be fully contained by future embankment construction and a stability assessment be undertaken to ensure that any degradation in material properties cannot negatively impact on long-term dam stability.

6.2.2.2 Water-Retaining Embankments

These structures are similar to conventional water supply reservoir embankments and are constructed using locally available engineered fill materials with the potential to incorporate mine waste rock as structural fill and tailings in filter zones subject to mine phasing and to geotechnical and geochemical suitability. Such dams are prevalent where the total mine waste volume is moderate, the tailings have unsuitable or deleterious content or there is a permitting requirement as a result of facility risk categorisation. Subject to suitable fine (low permeability) fill not being available locally, the cross-section may require the installation of a geomembrane liner. The inclusion of a HDPE or similar geomaterial will require specific design and construction considerations and, in particular, the need to incorporate bedding material below the liner both as a protective zone but also to act as a filtration layer in the event of geomembrane failure.

Conventional embankment techniques are appropriate subject to close attention being paid to long-term deterioration of any local fill materials (Cambridge and Oliveira 2006) and to seepage control and capture. A conventional embankment of this type (Fig. 6.8) poses the least risk in terms of operation and management, but imposes the highest unit disposal costs on the project.

Staged construction of such a conventional dam has become more common in Europe with, over the last twenty years, many of these dams becoming composite downstream constructions, as at the Minas de Neves Corvo in Portugal (Fig. 6.9). This MWF was designed as a conventional water-retaining embankment but was raised by downstream construction using engineered mine waste as the project

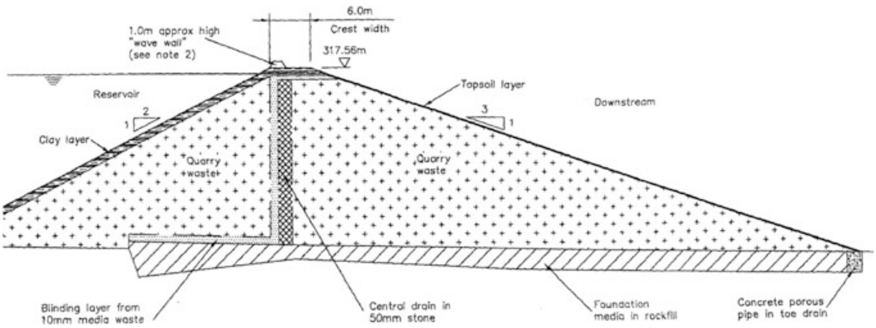

Fig. 6.8 Water-retaining embankment, Blakedon Hollow TMF, UK (Cambridge 2010)

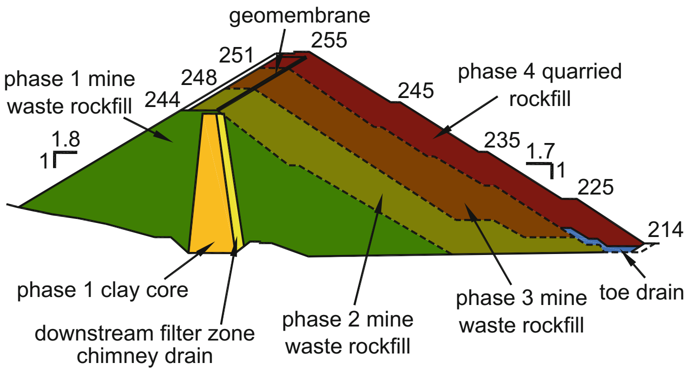

Fig. 6.9 Staged construction using mine waste rock (Oliveira and Cambridge 2006)

progressed. Stage-raising of a conventional embankment permits more efficient cash flow, spreads capital costs more evenly over the period of deposition and is not dependent on the properties of the extractive waste from the mine.

Conventional water-retaining-type cross-sections for hydraulic fill confinement are often used when:

- sub-aqueous deposition of the hydraulic fill is a permitting requirement;
- the MWF impounds a significant catchment and is required to contain runoff resulting from a range of extreme flood events;
- the water balance requires significant storage capacity associated with process water chemistry, climatic effects (high evaporation rates or seasonal water releases) or low recirculation potential;
- retention of water is needed over an extended period for the degradation of a toxic element (e.g. cyanide or process reagents);
- the extractive wastes are not generally suited for dam construction;
- the MWF is in a remote or inaccessible location and water return is not possible.

6.2.2.3 Upstream Construction

This method involves the crest progressing in an upstream direction as tailings deposition develops, maximising the use of suitably-graded hydraulic fill for construction and thus reducing construction costs. Each embankment raise is constructed over previously-deposited tailings, as at Zelazny Most in Poland (Fig. 6.10) and at the Garpenberg project in Sweden (Fig. 6.11). The rate of rise, and thus the available storage, is dependent on process plant production as well as on stability and drainage provisions and is therefore dictated by the characteristics and production rates for the mine waste. Stability is generally reliant on maintaining the tailings pond or reservoir at a safe distance from the embankment by ensuring a good beach length at all times so that the embankment face remains fully drained. For stability reasons, therefore, this section may not be suitable in high rainfall or seismically active areas and is considered inappropriate if there is inadequate management and operational experience to maintain the levels of control and management supervision required. MWFs with such cross-sections have been associated with a number of failures (Dobry and Alvares 1967), particularly due to seismic disturbance, and in many jurisdictions upstream construction has since been

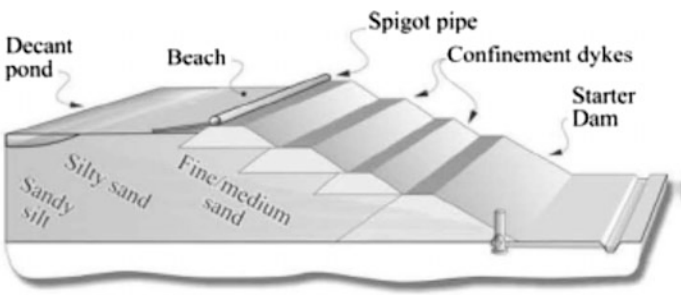

Fig. 6.10 Example of upstream construction method, Zelazny Most TMF, Poland (Jamiolkowski 2014)

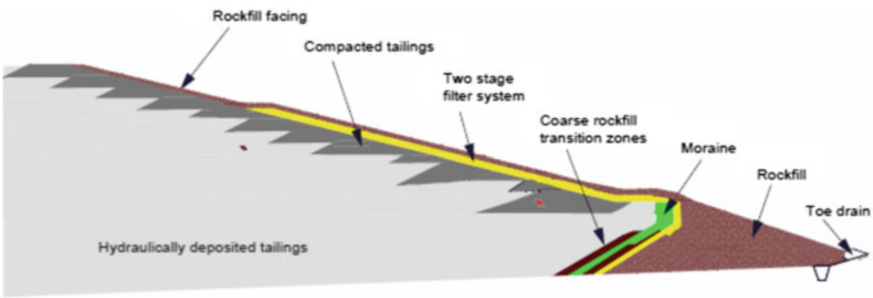

Fig. 6.11 Cross-section through the Garpenberg MWF, Sweden (Cross-section courtesy of SWECO)

extremely difficult to permit on the basis of enhanced risk perception. However, as a majority of these failures have resulted from poor operation and management (ICOLD 2011) it is evident that, with appropriate design input and close control of disposal and construction, the section may be proved to be viable where hydrological and seismic risks are not extreme.

The adoption of an upstream cross-section may therefore be limited to specific project conditions where the following parameters can be guaranteed:

- control of phreatic surface in the downstream face to maintain embankment stability, including prevention of piping failure;
- management of the supernatant pond at a suitable distance from the confining embankment to create a beach above water level as a first line of defence against piping failure;
- tailings deposition to ensure particle segregation in order to achieve both stability and suitable drainage of the containment embankment;
- management of deposition to prevent slimes negatively affecting the competence of the upstream foundation zone;
- creation of a liquefaction-resistant embankment structure;
- provision being made for extreme flood and seismic events.

However, as for most confining embankment cross-sections, the upstream system may be modified to create a composite design. The inclusion of suitable underdrainage within the downstream face in order to maintain the phreatic surface drawn down, the use of conventional compaction equipment on the downstream face to provide improved face stability and the adoption of flatter slopes in line with closure requirements may provide an economical, as well as stable, construction. In many facilities the changes in storage requirements, project economics or waste properties have resulted in such adaptations and an upstream approach being adopted, as at Tara in Ireland (Fig. 6.12) and at Titania in Norway (Fig. 6.13). In these examples the deposited tailings form the foundation for the raise, necessitating attention to both the strength and consistency of the formation as well as to the underlying drainage. With proper attention to the engineering and liquefaction potential this method can prove suitable for a limited vertical extension of the confining embankment.

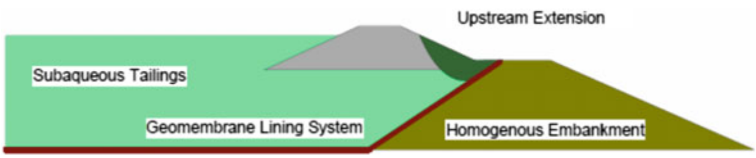

Fig. 6.12 Upstream extension at Tara MWF, Ireland

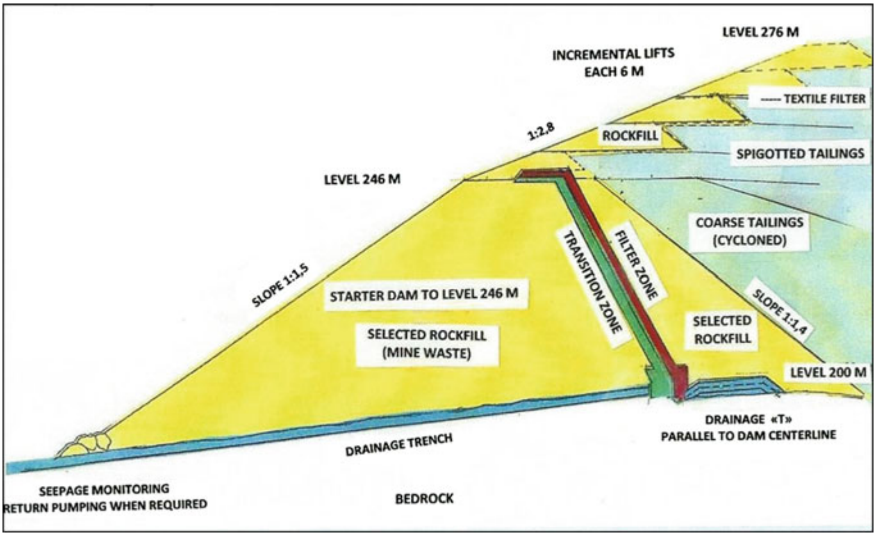

Fig. 6.13 Upstream extension at Titania MWF, Norway (ICOLD 2015)

6.2.2.4 Centreline Construction

Centreline construction involves raising the crest on the same centreline as the starter dam, as shown in Figs. 6.14 and 6.15. The dam structure relies on the hydraulic fill being placed against successive conventionally-placed low-height earth or rockfill embankments in order to provide competent foundations for

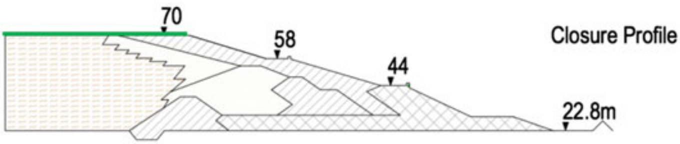

Fig. 6.14 Centreline construction method at CVTD, UK

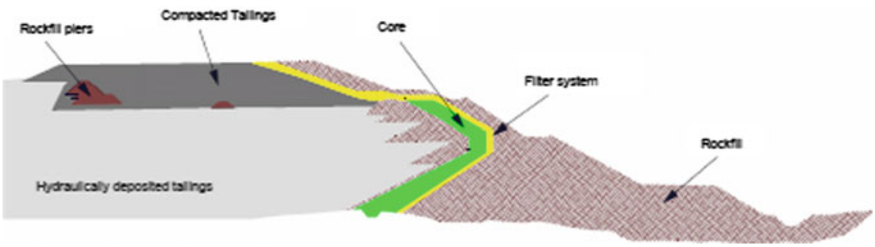

Fig. 6.15 Centreline construction at Zinkgruvan MWF, Sweden (Cross-section courtesy of SWECO)

subsequent lifts. The stability of the section is reliant on the structural competence of the starter dam but also, more importantly, on the characteristics of the tailings deposited against the upstream face. The as-placed hydraulic fill needs to have suitable geotechnical characteristics to form a stable foundation zone for subsequent conventionally-constructed lifts. Drainage and seepage control through the embankment section are crucial and there will generally be an increased management element to ensure that a good beach length is retained to prevent inundation of the foundation zone. The volume of fill required for a given height lies between that for the downstream and upstream construction methods, thus resulting in intermediate costs. Centreline designs are preferred when the seismic risk is low, and where upstream stability may be an issue.

The cross-section can comprise either conventionally-placed construction fill or, as in the example shown in Fig. 6.14, be reliant on the competence of cycloned hydraulic fill. Similar constraints on this approach apply as described above, particularly with respect to the cyclone split, the strength of both overflow and underflow products and their liquefaction resistance. However, the advantage over the downstream system is the ability to minimise conventional embankment fill volumes and to supplement any shortfall in underflow material with imported fill. Indeed, the most cost-effective seismic-resistant section may incorporate a stage-raised downstream rockfill toe with a suitable upstream filter zone which provides both a drainage medium and a former for the underflow.

6.2.2.5 Downstream or Modified Downstream Construction

Downstream construction, as the name implies, results in the embankment centreline progressing downstream from the starter dam with increasing height and may therefore be reliant on the hydraulic fill as a structural material. This method involves staged construction using either conventional fill placement (Fig. 6.16) or selected hydraulic filling as shown in Fig. 6.17.

This dam type, when constructed using conventional embankment techniques (Fig. 6.16) is the most expensive as large volumes of engineered fill are required,

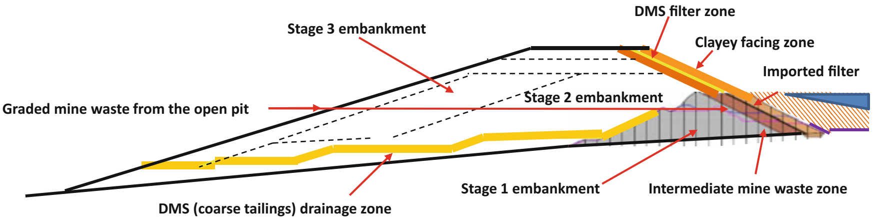

Fig. 6.16 Downstream construction at Hemerdon MWF, UK [Cambridge (2018) (Cross-section courtesy of Wolf Minerals Ltd)]

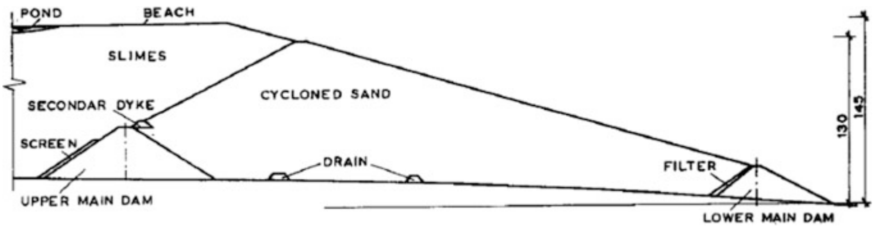

Fig. 6.17 Downstream construction method, Elatzite TMF, Bulgaria (Abadjiev and Karadimov 1991)

and the embankment footprint increases as deposition progresses. Such embankment sections are inherently stable and, if properly constructed from competent fill materials, should be "liquefaction-resistant" and can thus be used in areas of high seismicity. This cross-section is also appropriate where the longer-term or permanent storage of large depths of water against the upstream face cannot be avoided. In this case the crest of the starter dam may have to be widened to accommodate a clay core for final elevation of the containment dam or, as at the Minas de Neves Corvo, involve composite construction and the installation of an upstream clay or geomembrane liner.

However, the downstream method has historically been employed where suitably graded hydraulic fill is available to be incorporated into the downstream face. In the 1970s the development of portable cyclones for hydraulic fill enabled the separation of the coarser fraction (underflow) which was then placed to form the downstream structural shoulder of the confining embankment, the overflow being used to create a beach and an upstream buffer zone against impounded water. The cross-section in Fig. 6.17 shows deposition of underflow from an upstream starter dam against a rockfill toe, thus forming a fully-drained downstream shoulder. Drainage control is through this toe, and is often supplemented by formal drains which underlie the downstream face, ensuring that the phreatic surface is drawn down and stability is assured. The cross-section efficiently utilises the coarser fraction of the waste to construct the embankment and thus reduces the cost of imported materials. However, the disadvantages are the reliance on a consistent volume of suitably graded underflow, the high management costs of operating the cyclones and the maintenance of a fully-drained downstream shoulder. There may also be issues in proving to the Regulators that the cross-section will remain fully drained, with a suitably low phreatic surface, and will be liquefaction-resistant under seismic loading.

However, in addition to the above stability risks, disposal management and, in particular, the failure to achieve suitable cyclone efficiency or to provide adequate volumes of coarse material to maintain the rate of rise, may require rapid and often dramatic design changes. This may in turn result in a radical modification of the cross-section, with the resulting development of a composite dam section, as at the Clemows Valley Tailings Dam.

6.3 Embankment Construction

The construction of a MWF confining embankment depends on numerous factors, including:

- availability of construction materials, both coarse mine waste and from local borrow sources;
- geotechnical characteristics of the mine waste (hydraulic fill);
- geochemical characteristics of the mine waste and of the process water;
- seepage control;
- climatic conditions;
- project water balance;
- regulatory environment and permit conditions.

The construction of a confining embankment for a MWF may, unlike a conventional water supply embankment, be undertaken as a series of civil engineering contracts. Invariably the construction of the pre-deposition embankment will form part of the mine development works and may comprise an integral part of project construction, often on mine sites under an EPCM contract. A specialist earthworks contractor may be engaged specifically for the embankment and appurtenant structures. Post-start-up, however, each subsequent raise may be undertaken as a series of smaller contracts let on a batch process either by the owner's own fleet or by a local contractor. Whatever the contract arrangements, the procedures, the design CQA and approval processes should be similar, as indicated in Table 6.2.

Table 6.2 Construction procedures for a MWF embankment

Design phases	Construction phases	Independent engineer
Pre-deposition		
Submission of final design Receipt of regulatory approval Issue of design drawings and specification Approval of works Preparation of CQA summary and pre-deposition construction report Completion of a detailed construction record and a full set of as-built drawings Receipt of regulatory approval to commence deposition to predefined safe storage level	Appointment of contractor Approval of contractor's CQA system Ongoing construction supervision Submission of CQA data files	Independent design review Site inspection to review works and CQA data files Preparation of pre-deposition approval report

(continued)

Table 6.2 (continued)

Design phases	Construction phases	Independent engineer
Operation—Stage 1 raise		
Appointment of Stage 1 designer Submission of final Stage 1 design Receipt of regulatory approval Issue of design drawings and specification Approval of works Preparation of CQA summary and Stage 1 construction report Completion of a detailed construction record and a full set of as-built drawings Receipt of Stage 1 regulatory approval to continue deposition to predefined safe storage level	Appointment of Stage 1 contractor Approval of contractor's CQA system Ongoing construction supervision Submission of CQA data files	Independent design review Site inspection to review works and CQA data files Preparation of Stage 1 approval report
Operation—Stage 2 raise		
Appointment of Stage 2 designer Submission of final Stage 2 design Receipt of regulatory approval Issue of design drawings and specification Approval of works Preparation of CQA summary and Stage 2 construction report Completion of a detailed construction record and a full set of as-built drawings Receipt of Stage 2 regulatory approval to continue deposition to predefined safe storage level	Appointment of Stage 2 contractor Approval of contractor's CQA system Ongoing construction supervision Submission of CQA data files	Independent design review Site inspection to review works and CQA data files Preparation of Stage 2 approval report
Operation—Stage 3 raise		
Subsequent phases to continue along similar lines		

The final design for each construction stage should include not only detailed design drawings but also a specification for the works, including a description of the means of quality control, i.e. method- or results-based assessment. The contract arrangements should state clearly not only the system for earthworks approval but also the contractual responsibilities of the owner, designer, contractor and, where appropriate, IIE to ensure that at each stage of the works there is appropriate quality control and reporting. The CQA process is described in more detail in Sect. 7.1.

The means of construction of each type of embankment is summarised in Table 6.3:

Table 6.3 Construction methods for a MWF embankment

Embankment type	Description	Construction options	Fig. No.
Homogeneous			
Quarry silt lagoon	Generally low-height earthfill dam	Conventional earthworks contract and placement equipment	6.4
Lined MWF	Earthfill dam with geomembrane facing	Conventional earthworks contract and placement equipment and specialist geomembrane installation contractor	6.6
Water-retaining			
MWF	Zoned embankment dam	Conventional earthworks contract and placement equipment Note that stage-raising and material availability may result in the section being modified during subsequent raises	6.9
Upstream			
Downstream toe	Low-height pre-deposition starter dam	Conventional earthworks construction and placement equipment	6.13
Downstream face	Hydraulic fill embankment	Constructed by cyclone separation to achieve suitably-graded underflow for downstream stability or hydraulically placed material excavated from the beach and placed and compacted conventionally	
Upstream face foundation/ beach	Hydraulic fill deposit	Cyclone overflow or hydraulic placement by spigot or spray-bar to achieve suitable foundations, maintain beach length and separation of reservoir Hydraulic placement supplemented by conventional compaction where appropriate	
Centreline			
Starter dam	Low-height pre-deposition starter dam	Conventional earthworks construction and placement equipment	6.15
Downstream toe	Rockfill toe for stability and drainage control	Conventional construction and placement equipment	
Downstream face	Earth/rockfill structural section	Conventional earthworks construction and placement equipment	
Upstream face	Hydraulically-placed fill embankment/ beach	Cyclone overflow or hydraulic placement by spigot or spray-bar to achieve suitable foundations, maintain beach length and separation of reservoir Hydraulic placement supplemented by conventional compaction as appropriate	

(continued)

Table 6.3 (continued)

Embankment type	Description	Construction options	Fig. No.
Downstream			
Downstream (pre-deposition) toe	Rockfill toe for stability and drainage control	Conventionally constructed downstream toe for drainage control	6.17
Structural embankment	Hydraulic fill embankment	Cyclone separation to achieve suitably-graded underflow for downstream stability	
Upstream protective beach	Hydraulic placement	Cyclone overflow or spigotting of secondary tailings to maintain beach length and separation of reservoir	

6.4 Hydraulic Placement

Hydraulic placement systems involve both the transportation of the hydraulic fill to the MWF, often over many kilometres, as well as the distribution of the slurry around the facility and its efficient placement in the storage area. The elements of hydraulic placement are generally separated into two primary engineering facets, namely:

- the hydraulic transportation system, including the reticulation arrangement between the process plant and the MWF together with the necessary pumps, valves and environmental controls;
- the hydraulic deposition system, including the distribution pipework, the deposition equipment such as cyclones, spigots and spray-bars, and a further set of valves and environmental controls.

6.4.1 Hydraulic Transport

Solids concentration at the point at which hydraulic fill leaves the process plant (often referred to generically as the "tailings box") drives both the transport and the disposal system. The diverse characteristics of an extractive waste in terms of particle size and shape, and physical, chemical and rheological properties, as well as of water quality and quantity, require the development of an understanding of the slurry parameters in order to be able to engineer the design of an efficient disposal system. The development of improved design models for both slurry transport and pipe hydraulics, together with better knowledge of the rheological properties of hydraulic fills, has enabled a wider range of pulp densities to be pumped efficiently over greater distances. The hydraulic transport system for the extractive waste, which involves the design of the pipeline and pumping system, needs to consider the following issues:

(i) mine waste production, including both upper- and lower-bound tonnages, with a view to ensuring that the design of the hydraulic transport system is fit for purpose;
(ii) process flow sheet, with respect to slurry density, water demand and the potential benefits of recovering water in the plant by thickening rather than by double-pumping a proportion of the return water;
(iii) physical properties of the process waste, including particle size, specific gravity, abrasiveness and settling characteristics in order to optimise transport velocity, pipe wear and unit head loss;
(iv) chemistry of the transport media (process waters) and the implications for accelerated or hindered settlement or for the precipitation of salts. The issue of gypsum precipitation in transport pipelines can be significant and can increase pipe maintenance costs and plant down-time if not addressed in the design;
(v) specialist laboratory testing, such as accelerated settlement tests, rheology and loop testing in order to optimise design and calculate head loss in the system.

In addition, the design of the reticulation system should consider the potential range of return water volumes and quality based on the MWF water balance under all extreme conditions. This should consider both prolonged wet and dry periods as well as the implications of climatic conditions such as extremes of temperature and wind for return water volume and quality from the MWF. It is noted that prolonged icing of the facility may impose additional water burdens on the return system and that fine sediments may be disturbed by wind shear, increasing solids contents in the return. It should therefore also be confirmed in the design that:

(i) recycling water from the MWF will not have a detrimental impact on metal recoveries, noting that residual reagent volumes in the return water may, with time, build up and exert a negative impact on process efficiency;
(ii) should contaminants in the MWF potentially exceed permitted water quality criteria, consideration would be given to modifying the process flow sheet to remove such compounds—e.g. cyanide removal in a gold plant to prevent untoward levels and a breach of permit conditions;
(iii) solids concentration in the tailings streams has been optimised in order to minimise pumping volumes and thus costs.

For the lower range of pulp densities, i.e. low-to-medium density slurries with the potential for a gravity feed to the MWF, the design process may involve standard hydraulic systems for optimising open channel flow, pipeline size and pumping capacity. However, for complex hydraulic transport and disposal projects, particularly those involving long pumping distances, higher densities and thickened tailings, more sophisticated computer models will be required in order to optimise slurry pipelines. The design approach should follow internationally recognised practice or else be quality-assured via peer review to ensure that the hydraulic transport system is robust and that the risk of pipe failure under all anticipated operating conditions is minimised. For long transport corridors or where routing through complex topography is necessary, GIS-based software may be necessary in order to locate the pipelines in a manner which fully addresses constructability, operation and maintenance, security, environmental stewardship and land ownership. Such systems should optimise route selection and generate the most cost-effective alignment, pipeline layout and pumping arrangement. However, regardless of the complexity of the design it must not neglect the important issues of maintenance, inspection, pipeline exposure and the risk of untoward leakage on the environment. Each hydraulic fill project and MWF site will require a different emphasis in the design but should, at minimum, include consideration of the following issues:

(i) impact of climatic conditions on pipeline performance, considering both freezing and thermal expansion;
(ii) leak detection and automatic shut-down systems;
(iii) water hammer;
(iv) potential for sedimentation and precipitation at topographic low spots where velocities, either during operation or at shut-down, are less than critical;
(v) location of pipeline bleed points and washout locations;
(vi) the need for pollution protection bunds or embankments to control any untoward releases, pipebursts, and uncontrolled maintenance discharges and to protect the downstream environment;
(vii) security devices on all valves and connections where third-party damage or random vandalism is a potential issue.

6.4.2 Hydraulic Deposition

Hydraulic placement of fine extractive waste and the configuration of the internal deposition system should be arranged to achieve maximum density and efficient disposal. The hydraulic fill should be discharged into the MWF to ensure, where appropriate:

(i) clarified supernatant water for return to the process plant;
(ii) that deposited densities are maximised;
(iii) that effective consolidation takes place;
(iv) that the disposal method adopted encourages the development of a laminated deposit, enhancing horizontal/vertical permeability ratios and lateral drainage through the extractive waste;
(v) cost-effective operation of the depository and disposal efficiency;
(vi) achievement of a surface which meets the long-term closure objectives.

This process requires exploitation of the properties of the hydraulic fill, the configuration of the depository, the production process and the climate to enable cost-effective and environmentally-appropriate disposal. As the extractive waste itself may vary considerably in grain size, mineralogy and pulp density at the point of disposal into the MWF, a key function of the operation is to deposit in such a

Table 6.4 Relative advantages and disadvantages of hydraulic placement systems

Thickened	Sub-aerial	Sub-aqueous
High density and efficient storage High cost Intensive management input Good storage and disposal control Reduced ARD and airborne potential Additional water storage costs Lowest closure cost Lowest risk and long-term liability	High density and efficient storage Intermediate cost Intensive management input Good storage and control Increased ARD and airborne potential Requires reservoir management Low closure cost Lower risk and long-term liability	Poor storage density and inefficient storage Low cost Low management input Poor disposal control Assured short-term ARD and airborne performance High closure cost High risk and long-term liability

way that maximises sedimentation and minimises solids return to the plant in the recycle water. The minimum settling velocity of the tailings will determine the minimum operating area of the surface water pond to achieve clarity (Sect. 4.3.2.2) except where an ultrafine/clay fraction or use of flocculants necessitate that the criteria be based on the quality of the water return and not on a minimum pond size.

The disposal system may involve hydraulic transport and disposal via open channels, pipelines, spigots, cyclones and thickeners or transport and placement of filtered tailings using conveyors and conventional earthmoving equipment. The relative advantages and disadvantages of the principal systems as described below are shown in Table 6.4.

The configuration of the depository, the slurry density and, occasionally, permit conditions will dictate the dominant deposition mode, i.e. sub-aqueous or sub-aerial, as defined below.

Sub-aqueous Deposition

Sub-aqueous deposition involves placement of the hydraulic fill, predominantly underwater, with minimal beaching of the deposit and a comparatively large supernatant pond. Extractive waste deposited underwater generally exhibits particle segregation and lower in situ densities, and thus requires greater storage volume. Sub-aqueous slopes are steeper and thus efficient deposition and use of available capacity requires a significant operating input with frequent moving of disposal points or with multiple inlets in order to maximise storage. The application of sub-aqueous techniques may be imposed for environmental reasons, particularly for tailings containing high levels of sulfides which are likely to oxidise, mobilise metals and produce acid. Restricting oxygen to the tailings by permanently placing them underwater inhibits oxidation and minimises the environmental problems associated with acid mine drainage. However, the resulting depository will be likely to incur higher costs at closure and consideration should be given to other methods of controlling the environmental impact of high sulfide levels.

It is often assumed that sub-aqueous tailings deposits are homogeneous and that they display isotropism. However, in addition to the cross-bedding resulting from the disposal system, chemical changes in sub-aqueously deposited tailings may be induced by precipitation of chemical residues, such as carbonates and salts, as a result of the quality of the process waters and, in particular, the saturation level of key constituent elements. Following sedimentation of the tailings, chemical reactions within the pore spaces may lead to the accumulation of gypsum and halite precipitates over time. These may occur as discrete localised lenses throughout the deposit or, dependent upon the deposition environment, as extensive sub-horizontal layers. In both instances the presence of these precipitates will impact on the characteristics of the deposit, increasing the degree of anisotropy in the tailings as well as reducing overall vertical permeability. The deposit may subsequently be characterised by alternating hard and soft layers and, resulting from the overall reduction in the rate of vertical drainage in the deposit, by reduced tailings consolidation rates.

Sub-aerial Deposition

Sub-aerial deposition involves disposal above the water level and results in the development of a beach sloping gently towards the supernatant pond or the location of the decant. Sub-aerial techniques invariably involve an element of sub-aqueous deposition, with the finer fraction reporting directly to the supernatant pond. For highly-thickened tailings the extent of the supernatant pond is often limited, dependent on pulp density and climatic factors (runoff). The advantages of sub-aerial deposition, all of which contrive to reduce long-term seepage and closure costs, are:

- sedimentation of an unsorted deposit across the beach;
- the inherently higher settled density;
- the ability, with operational control, to use climate to desiccate and partially consolidate the deposit;
- the saturation state which lends liquefaction resistance.

The deposition system ideally needs to be flexible such that the operators can exploit the natural tendency of hydraulically placed fills to develop a cross-bedded, laminated deposit and an elevated horizontal-to-vertical permeability ratio. This promotes horizontal drainage through the confining embankment, maximising lateral seepage, reducing saturation levels, increasing rates of consolidation and thus storage density. The embankment filter zones enable the majority of this seepage to be captured and directed into a downstream collection and return system. The extent to which this can be achieved is dependent on the properties of the extractive waste and the internal drainage provisions within the embankment. Thus the basic geotechnical characterisation forms a fundamental part of the design process and its importance in defining ongoing stability and closure should not be underestimated. Increasing consolidation and decreasing levels of saturation lead to a progressive improvement in overall stability as a result of the decrease in pore pressures and the corresponding rise in effective stress. The desaturation of the extractive waste also leads to the reduction of risk, both of liquefaction and of the potential for mobilisation on disturbance. The geotechnical data for the hydraulic fill and the disposal and internal drainage systems should be fully integrated at each design stage in order to maximise consolidation, increase stability and enable early restoration, rehabilitation and landscaping at closure.

However, seepage is restricted where a basal liner has been installed on the internal embankment faces and without additional drainage provision consolidation rates in the deposited waste will be low and the storage efficiency impaired. Underdrains installed over the foundations and which feed into the embankment drainage system may enhance these rates, though the high k_h/k_v ratio of the hydraulic fill will limit the life of these drains and thus seepage capture. The drains can be supplemented by inclined collectors on the upstream embankment face but these may be limited in efficacy or expensive if installed throughout the perimeter.

The MWF should be managed throughout its life, and a disposal strategy adopted which meets the following primary objectives:

(i) controlled deposition to encourage consolidation;
(ii) maximisation of available storage capacity by optimising sub-aerial deposition;
(iii) maximisation of consolidation via air drying and the development of desiccation cracking;
(iv) maximisation of consolidation via the under-drainage system;
(v) effective control of the size and location of the supernatant pond;
(vi) minimisation of the potential for airborne pollutants;
(vii) maximisation of seepage collection and recycling;
(viii) minimisation of operating costs;
(ix) facilitation of early access to permit implementation of the closure strategy.

The facility should be fully instrumented to ensure that the performance of the embankment and the appurtenant structures can be monitored appropriately and that the MWF performs in accordance with the design parameters at all stages of operation and closure. The operating manual should include disposal, operation, maintenance, monitoring and recording practices as well as emergency protocols.

The options for discharging the extractive waste slurry into the depository are described in brief below:

6.4.2.1 Floating Pipeline

For sub-aqueously deposited tailings the conventional system is to discharge the hydraulic fill from floating pipelines, either from a series of discharge points from a perimeter ring main system or from longer, floating lines, into the centre of the depository (Fig. 6.18). The system requires storage behind a water-retaining-type embankment and, as described above, is the least efficient in terms of both stored density and use of storage capacity. Such a disposal system has often been proscribed for environmental protection reasons, particularly for extractive waste with adverse geochemical characteristics. Such prescriptive permit conditions have required that the operator maintain a minimum depth of water-cover over the

Fig. 6.18 Floating tailings delivery pipeline

Fig. 6.19 Exposed tailings surface during sub-aqueous disposal

deposit which, due to the steepness of the underwater slopes, may be extremely difficult to maintain (Fig. 6.19). Management of such a system requires a significant operating input, with regular movement of discharge points essential in order to overcome the difficulties of achieving a uniform surface. It is noted that sub-aqueous deposits result in less efficient storage density than sub-aerial disposal and, though geochemical alteration may be depressed, closure is inevitably restricted to a wet system and thus may only be suitable in wetter climates. Finally, such wet closure systems raise additional concerns regarding long-term liability for the owner as well as increasing risk with respect to the stability of the confining embankment and the ongoing provision of flood management.

6.4.2.2 Single Point Discharge (Launder, Leat or Single Pipeline)

The tailings are discharged under gravity in an open, sometimes lined, natural channel (leat), a concrete channel (launder) which may be capped for protective purposes, or using a single pipeline (Figs. 6.20 and 6.21). This discharge system is generally only applicable to low pulp density slurry and is not considered suitable for high density thickened tailings due to rheological properties. On some projects where the process produces both a fine and a coarse hydraulic fill, the finer fraction may be discharged via such a system whilst the coarser material is delivered to the confining embankment for structural purposes. The method is common in quarry

Fig. 6.20 Open channel flow

Fig. 6.21 Concrete tailings launder with multiple channels

silt lagoons where thickening is less common and gravity feed predominates. In addition, it is used for low-throughput projects where deposition is undertaken sequentially into a series of small paddocks.

For such gravity-fed discharges the inlet to the MWF is generally through natural ground and the disposal is effectively single-point discharge. The deposit creates a delta at the inlet, which forms a bird's foot feature with the development of successive levees and channels. The resulting beach is likely to grade towards the pond though, due to the lack of control on discharge velocity, significant erosion and re-deposition occurs, resulting in a highly-sorted deposit with variable degrees of lamination. This deposition technique is potentially low-cost and low-maintenance, but offers a less efficient method of mine waste storage and the deposit is unlikely to achieve optimum in situ density. This system would, under most circumstances, preclude the use of the hydraulic fill as a structural element and thus is likely to be prevalent where the confining structure takes the form of a water-retaining embankment.

6.4.2.3 Multiple-Point Discharge (Spigots or Spray-bars)

Sub-aerial deposition involves the tailings slurry being pumped from the process plant, generally via a dedicated pipeline, for discharge into the MWF above reservoir level. Sub-aerial deposition is the most common technique for disposal of hydraulic fill and may involve a wide range of slurry pulp densities, generally from >20% to <50%. At lower solids content the pulp is often gravity fed but requires more sophisticated pumping with increasing density. To achieve the most cost-effective disposal system the deposition points need to be arrayed around the perimeter of the facility using a manifold system. This enables rotation of the disposal point and the development of good beaches. This form of deposition is often undertaken from the crest of the main confining embankment and thus may, if properly managed, be used to form a beach for either an upstream or centreline extension. In their simplest form the actual discharge points may comprise regularly-spaced valved pipe outlets, known as "spigots", from a ring main or manifold (Figs. 6.22 and 6.23). These spigots are generally evenly spaced on the main distribution pipeline, usually at a distance of between one and two pipe lengths, in order to facilitate sequential deposition of the hydraulic fill in thin layers. Sequential deposition encourages efficient beaching, desiccation and densification, and reduces the occurrence of gullying, erosion and re-deposition of the eroded fraction into the pond. With good management the beach length can be controlled, providing a degree of flexibility in the cross-section of the confining embankment. The spigots are often installed on the embankment face and include outlets at regularly-spaced vertical intervals, thus precluding the need for moving or replacing outlets. The velocity on to the beach can be controlled by manipulating the diameter of each spigot to reduce erosion and effect efficient beaching.

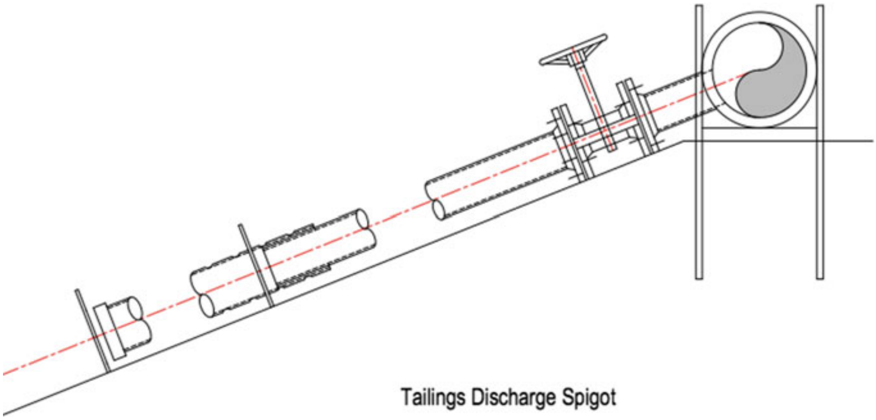

Fig. 6.22 Typical spigot detail

Fig. 6.23 Example of spigotting

A refined development of the spigot system is the use of spray-bars, which comprise similarly-spaced valved feed pipes off a perimeter ring main. Each pipeline is fitted with a tee bar which has a series of small-diameter outlet holes in its invert (Figs. 6.24 and 6.25). The diameter and number of these outlets is designed to limit outlet velocity and create laminar flow across the beach. A general guide to the limit of outlet velocity is considered to be between 0.5 and 1 m/s, and this has been shown with most metal tailings to generate laminar flow and to enable the development of a uniform beach with limited erosion and re-deposition. Such a system requires a greater management input but the resulting beach is likely to achieve higher density and should thus be suitable for subsequent embankment construction.

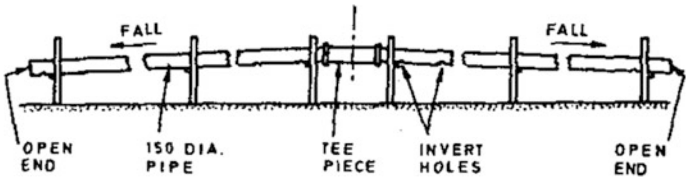

Fig. 6.24 Typical spray-bar detail (Cambridge and Coulton 1990)

Fig. 6.25 Trial spray-bar set-up

6.4.2.4 Cycloned Tailings

The use of hydrocyclones within the mine waste sector was initiated in the 1950s and has progressed since to form a key tool in the efficient use of mining waste for embankment construction. Though cyclones were in use in process plants for ore separation throughout the twentieth century these were static facilities, whereas those required for embankment construction need to be moved on a regular basis. "The primary objectives are to produce from mine waste tailings a free draining material of good grading for the structural zone of the dam" (Cooper, undated). The cyclones provide an efficient means of separating the hydraulic fill into the underflow, a coarse (wall-building) fraction, and the overflow, a fine fraction used for beach development. The adoption of cyclones rather than more conventional embankment construction methods is dependent firstly on the grading of the hydraulic fill and secondly on the ability of the cyclone to produce sufficient quantities of free-draining underflow product. Modification of the process flow sheet is often required on projects where cyclones have been adopted for embankment construction, with primary cyclones being introduced into the plant to improve the feed to the secondary (embankment) cyclones (Fig. 6.26). The design of a cyclone embankment raise must take into consideration the potential for the feed from the process plant to vary considerably with time, as issues such as inconsistent grading, pulp density and inlet pressure will affect both the size and number of cyclones required as well as the proportion of wall-building material

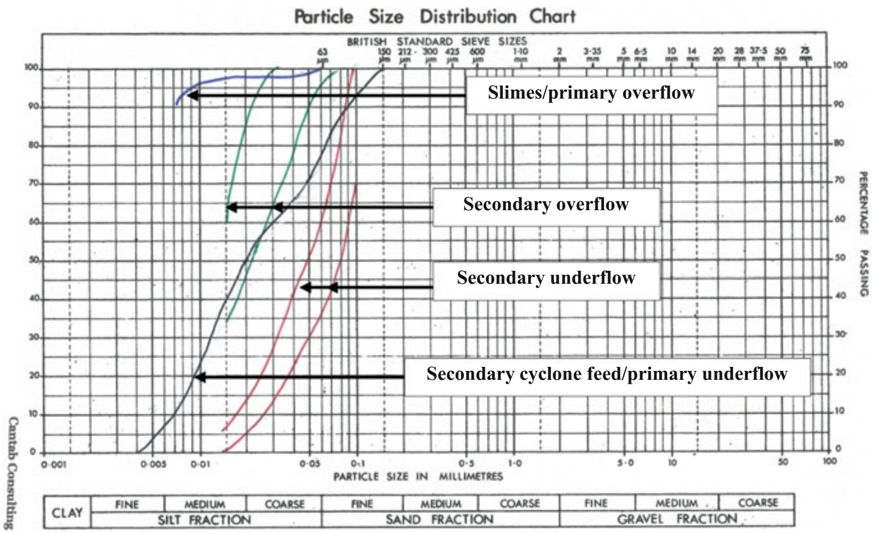

Fig. 6.26 Cyclone PSDs for CVTD MWF, UK

produced. The cross-section and designed rate of rise must therefore be robust against process changes and alternative sources of fill may need to be available to supplement any shortfall in embankment construction materials. The number and size of cyclones will also be a determining factor as the logistics of moving a significant number of large cyclones regularly to suit embankment construction requirements may prevent consideration of hydrocycloning.

The design of hydrocyclones for embankment construction and the means of adjusting the inlet and outlet parameters in order to achieve a consistent product capable of meeting wall-building requirements are well documented. It is evident that the use of cyclones is not suitable for all hydraulic fills, particularly those exhibiting either a very broad grading or containing a significant clay fraction. A target of <10% finer than 30–40 μm for the underflow product and a permeability of 10^{-5} m/s has been quoted (Cooper, undated) and there are numerous examples of facilities constructed in this fashion, though the number within Europe is limited. A typical arrangement of cyclones on a Bulgarian MWF is shown in Fig. 6.27 for downstream construction and in Fig. 6.28 for the upstream method at Salsigne mine site in France.

The advantages of cyclone construction are the efficient use of the coarser mine waste in the confining embankment, the potential lower construction costs and, with a suitable overflow/underflow split, the creation of a protective beach to prevent the reservoir from ponding against the embankment face and the development of higher seepage flows. Cycloned tailings have been adopted with success in the cross-sections of upstream, centre line and downstream dams. However, against this should be set the additional operating costs required to move the cyclones for each embankment lift, the potential for erosion and dusting and the risk from extreme hydrological and seismic events.

Fig. 6.27 Downstream construction using hydrocyclones, Bulgaria

Fig. 6.28 Upstream construction using hydrocyclones, France

6.4.2.5 Thickened Tailings Disposal

Thickened tailings disposal involves the installation of high-density thickeners on the hydraulic fill feed and the provision of a pumping system capable of transporting and distributing the mine waste around the facility. The product may have a pulp density of up to 75% and typically flows without segregation, the slope angle being controlled by the degree of thickening. With proper management the thickened product will exhibit sheet flow, with water release restricted to bleedwater only. A key design factor is the provision of suitable deposition points and surface area to enable flow and efficient control of runoff and bleedwater (Figs. 6.29 and 6.30). As with all sub-aerial disposal, rotational deposition enables exposure of successive

Fig. 6.29 Typical thickened discharge

Fig. 6.30 Sheet flow development

layers to desiccation and consolidation, thus achieving higher density and in situ strength (Jewell and Fourie 2006). Typical slope angles of 1°–3.5° can be achieved to form a self-draining, easily reclaimable shape (ICOLD 2001, Williams 2011). The reduced water content of the hydraulic fill provides a wide range of options for disposal, from an upstream raise to central deposition. Modification of the tailings properties by the addition of binders may be used to increase both static and dynamic stability and reduce the likelihood of surface erosion.

At a number of older MWFs, thickened discharge has been adopted by retro-fitting an additional tailings circuit to the process, enabling increased storage capacity without extending the MWF footprint. At the Minas de Neves Corvo site in Portugal the facility is being extended upstream by depositing the thickened hydraulic fill over the pre-existing sub-aqueous/sub-aerial deposit (Fig. 6.31). Deposition has been modified from a mono- to a multi-cellular approach, with disposal behind low-height rockfill berms creating a layered, wedding-cake-type surface arrangement. At the other extreme, thickened disposal from riser towers or central ramps (ICOLD 2001) has been adopted at some sites to create a self-supporting conical pile against a low-height perimeter confining embankment, as at the bauxite operation at Aughinish, Ireland (Figs. 6.32 and 6.33).

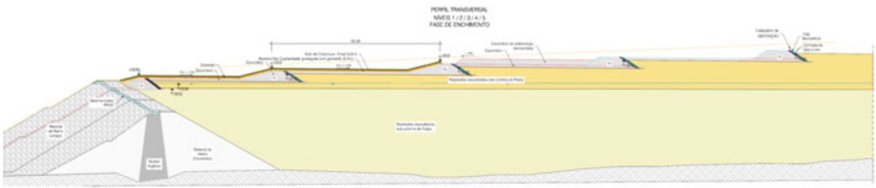

Fig. 6.31 Cross-section through thickened tailings confining embankment, IRCL MWF (Cross-section courtesy of Knight Piésold Limited), Portugal

Fig. 6.32 Thickened deposition, Aughinish MWF, Ireland

Fig. 6.33 Deposition against rockfill toe, Aughinish MWF, Ireland

Thickened tailings systems generally require specific delivery equipment, such as positive displacement pumps and high-pressure pipelines. The costs of these elements, together with those of the high-density thickeners and additional reagent usage, need to be balanced against the cost-saving on embankment fill, land-take and closure costs. Environmental problems such as seepage, spillage of process water and the potential for water to act as a transport medium for hydraulic fill flows (e.g. embankment breach) are significantly reduced. Proponents would also claim that the potential for oxidation and acid generation is reduced, though it is considered that the same benefits can be achieved with properly-managed sub-aerial disposal without the additional costs of high-density thickeners and positive displacement pumps.

Sustainable water use in the mining industry is becoming increasingly important, the potential for recovering high volumes of water at the plant eliminating the losses associated with the transport and storage of water at either the hydraulic fill facility or in holding ponds. Though a benefit of thickened disposal is the reduced volume of supernatant water emanating from the deposit, this may be offset by the need for a major modification of the water circuit as the overflow from the thickener continues to require recycling, necessitating enhanced industrial water storage. Runoff control as well as flood management will continue to be required and the lack of capacity in such a MWF necessitate an additional flood storage facility, involving the construction of a separate water-retaining embankment dam and storage basin at further cost (Tavares 2015) (Figs. 6.34 and 6.35).

Thickened disposal may permit phased closure and early restoration of the surface of the facility. However, ongoing provision will be required for slope runoff both during operation and post closure and will need to continue until the water can be proved to be benign. Management of deposited slopes to enable perimeter

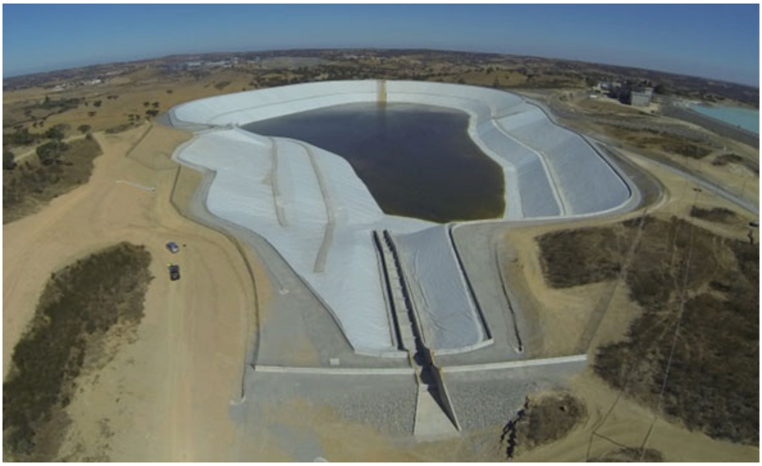

Fig. 6.34 Industrial water supply reservoir at Minas de Neves Corvo, Portugal

Fig. 6.35 Industrial water supply reservoir at Almagrera, Spain

control necessitates increased operating and management input and may require additional pumping or treatment costs. Finally, as runoff is often collected in peripheral drains against the perimeter confining embankments, attention to ongoing seepage issues and to crest stability is essential.

The advantages and disadvantages of a thickened disposal scheme are summarised in Table 6.5.

Table 6.5 Comparative assessment of thickened tailings

Advantages	Disadvantages
Little or no solid/liquid separation results in lower oxygen ingress, reducing oxidation rates thus inhibiting acid generation (Welch 2003) Pre-deposition works for the MWF may be reduced as the water storage capacity may be significantly lower, thus reducing capital costs Enhanced storage capacity for most non-clay hydraulic fills Reduced susceptibility to liquefaction and higher seismic resistance Minimal surface water storage, limiting potential seepage volumes Reduced return water pumping costs Avoidance of large decants and associated buried pipelines Reduced closure costs with potential early implementation of the surface rehabilitation works Reduced cost of maintenance post closure	High pre-deposition costs associated with additional deep-bed thickeners in the process plant High energy costs associated with hydraulic transport of thickened hydraulic fill, together with cost of high pressure pipelines Additional water supply reservoir may be required to ensure ongoing process supply Dust may become an environmental issue due to desiccation of the surface of depository, requiring irrigation Collection of surface water runoff and slope drainage remains necessary throughout the life of the facility and beyond, with potential additional water treatment costs Thickened disposal is not applicable where the hydraulic fill is very fine (less than 15% < 20 μm)(Verburg 2010) or for very coarse tailings or for waste with a high acid-forming potential Density achieved by deposition of thickened tailings, and thus storage efficiency, may not be significantly greater, if at all, than for a correctly configured and operated sub-aerial depository

6.4.2.6 Paddock Deposition

The use of paddock systems constructed on the surface of an existing MWF is well-documented and frequently results from a need to increase the life-span of a facility, as at the Minas de Neves Corvo (Fig. 6.36), or to store a radically different waste product, as at Wheal Jane (Fig. 6.37). The construction of a dividing bund on low-density hydraulic fill deposits, often placed sub-aqueously, is now well-proven and can be undertaken with confidence providing that an appropriate risk assessment and strict construction method statement is prepared in advance. The methodology requires dumping and dozing from pre-placed rockfill berms so that the machines always operate on stable roadways. The act of placement of the waste rock on to the surface of the hydraulic fill increases the stiffness of the upper layers due to the penetration of the coarse rock particles, enabling the rock bunds to be driven across the depository. The development of localised shear failures in the tailings surface, together with large settlements, is to be expected and will require the placement of further rock to level the surface together with an ongoing assessment of the stability of the roadways.

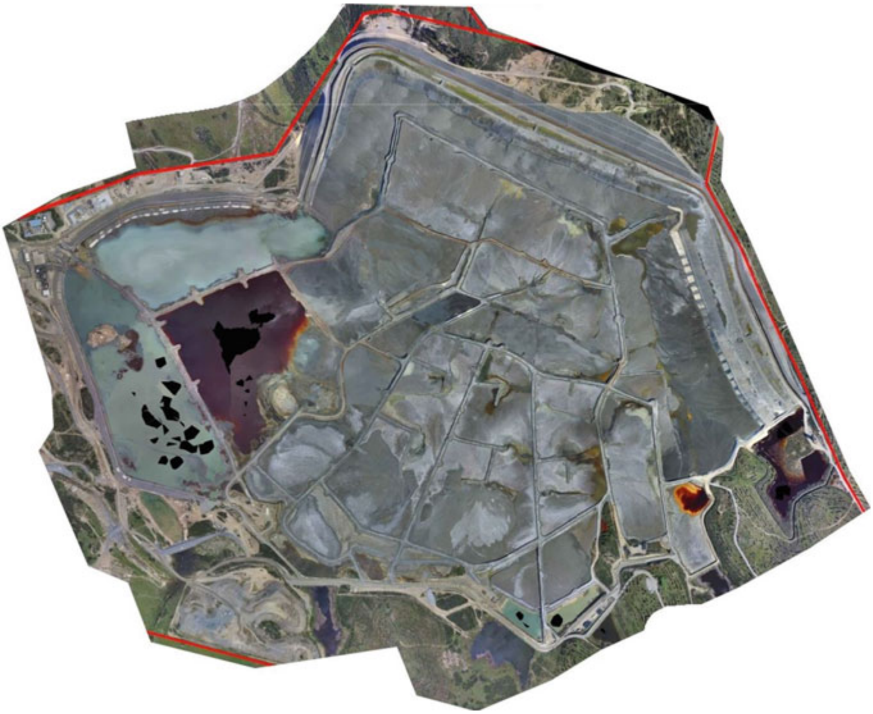

Fig. 6.36 Aerial view showing paddock system at IRCL, Portugal (Photograph courtesy of Lundin Mining plc)

Fig. 6.37 Paddock system for storage of minewater treatment residues at CVTD, UK (Photograph courtesy of Wheal Jane Ltd)

The construction of surface paddocks at both Wheal Jane and at the Minas de Neves Corvo has, in the first instance, enabled the storage of very low-density minewater sludges and, in the second, the conversion of a sub-aqueous depository into a thickened discharge facility. The creation of smaller deposition zones together with alternating deposition and desiccation cycles provides benefits of improved density and thus of storage capacity (Figs. 6.38, 6.39, 6.40 and 6.41).

Fig. 6.38 Operating paddock for minewater sludge on surface of CVTD, UK

Fig. 6.39 Desiccating paddock minewater sludge on CVTD, UK

Fig. 6.40 Paddock system for tailings disposal on IRCL, Portugal

Fig. 6.41 Tailings disposal into paddock on IRCL, Portugal

6.4.2.7 Co-disposal with Waste Rock

The concept of co-disposal of tailings with mine waste rock is suitable for countries with a predominantly arid climate and for projects which manage extensive open pit mining operations. Starter wall embankments are essentially reduced in size and the mine waste rock can be sequentially dumped with the hydraulic fill. The numerous methods of co-disposal are highlighted in Table 6.6 and are differentiated by the degrees of mixing and the method of placement.

Disposal can be effected onto the crest of a waste rock dump by constructing paddocks which are then filled with spigotted thickened hydraulic fill. The disposal system involves alternating deposition and desiccation cycles, maximising storage and enabling either placement of further layers or early capping with waste rock prior to closure and rehabilitation (Fig. 6.42). The ratio of the waste rock to thickened hydraulic fill will be dependent on mine production (Wickland et al. 2006). Careful management of this type of facility is required to ensure that it remains stable. If the thickened hydraulic fill is placed too quickly, subsequent loading with waste rock will lead to a build-up of excess pore pressure which may result in localised slope or layer failure. To evaluate the feasibility of co-disposal, the physical characteristics of hydraulic fill and of the waste rock need to be assessed, the strength of the co-disposed materials being dependent on the blend ratio. For a co-disposed material which predominantly comprises waste rock, the interstitial voids are only partially filled with hydraulic fill and the shear strength of the waste rock predominates. However, such an approach in Europe would require extensive and expensive control and mitigation measures for reasons of climate, emissions control and environmental regulations, as well as of stability.

Table 6.6 Methods of co-disposal (Wickland et al. 2006)

Description	
Homogeneous mixtures: waste rock and tailings are blended to form a homogeneous mass (placement method unknown)	Increasing degree of mixing ↑
Pumped co-disposal: coarse and fine materials are pumped to impoundments for disposal (segregation occurs)	
Layered co-mingling: alternating layers of waste rock and tailings	
Waste rock is added to a tailings impoundment	
Tailings are added to a waste rock dump	
Waste rock and tailings are disposed in the same depression	
Separate disposal: waste rock in dumps and tailings in impoundments	

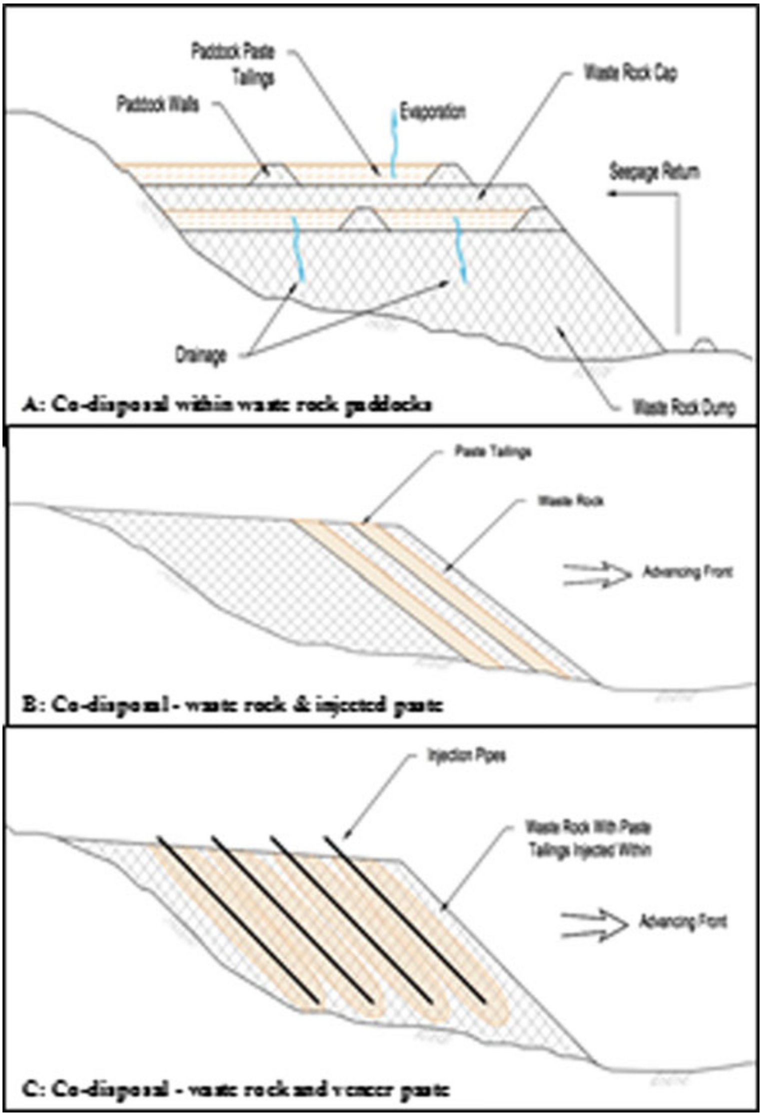

Fig. 6.42 Options for co-disposal with waste rock

6.4.2.8 Pressed Filtered Hydraulic Fill

As the water content decreases, the thickened tailings slurry becomes less mobile and ultimately, with the use of belt or vacuum filters, emerges as a non-pumpable cake with a water content of typically <20%. The disposal of a mine waste cake requires a different approach in terms of deposition techniques, as the tailings will either be trucked or transported by conveyors to the disposal area and be deposited and compacted by a conventional earthmoving fleet. Such a thickened product may remain close to saturation and still require to be placed in a secure and stable MWF, either in a dedicated facility or by co-disposal with waste rock. Similar investigation, design and operating procedures, as described in these guidelines, still apply to such facilities, which will also be subject to the requirements of the EWD and of compliance with good engineering standards.

This method does not use hydraulic processes for transport or disposal and is not therefore within the scope of these guidelines. However, as with thickened tailings, the benefit of cake disposal is the reduced volume of supernatant water emanating from the deposit which, again, needs to be offset against a major modification of the water circuit and the provision of enhanced industrial water storage. Additionally, an unmanaged surface stack can quickly become inaccessible to traffic in wetter environments, thus resulting in the need for significant re-working and in increased operating costs. Runoff control and water management in extreme weather conditions will continue to be required with regard to erosion control, physical and chemical weathering and local stability. The technique is of merit in both extreme dry and cold regions where water conservation is an important issue and also in seismic regions where earthquakes make it necessary to reduce water content in hydraulic fill for stability purposes. Though it has been recommended as the ultimate panacea by various environmental authorities due to its apparent stability and low risk, filtering and stacking of caked hydraulic fills are at the high end of unit disposal costs due to energy input in the process plant and the costs of bunding, lining, water management and long-term (post-closure) stability.

6.4.2.9 Dust Management

A key facet of the hydraulic deposition of any extractive waste is the control and management of airborne emissions. Figures 6.43 and 6.44 indicate the environmental impact of airborne particulates and the need to manage hydraulic deposition to mitigate such risks. Dusting is generally related to the development of long or otherwise extensive beaches which remain exposed to drying and desiccation over time. As surface moisture content reduces, soil particle interaction decreases and surface material can be readily lifted and blown by wind forces.

Dust is not just a permitting or compliance issue. In particular, where the hydraulic fill contains potential contaminants and phytotoxic elements, wind-blown emissions may lead to degradation of previously-landscaped areas on the mine site or of surrounding agricultural or amenity land. Such dusting problems resulting from an exposed hydraulic fill surface are not restricted to warmer climatic conditions, occurring during cold dry spells with equal frequency. Airborne emissions from an exposed tailings surface can be controlled through either surface moisture management or chemical processes. Dust is inhibited by maintaining higher water

Fig. 6.43 Exposed tailings beach

Fig. 6.44 Resulting dust issues

contents and agricultural sprays are often used to enhance moisture levels, with chemical additives such as admixtures and biodegradable oils being used to reduce evaporation or to bind surface particles. Control of moisture content in the extractive waste deposit can also be achieved using rotational sub-aerial disposal techniques which can be managed to ensure that a surface at or close to critical water content is immediately covered by fresh hydraulic fill. This can be achieved by monitoring the desiccation process since the development of surface cracking is a good indication of the critical soil moisture condition. A regulated cyclic disposal system can ensure a degree of control but, inevitably, emergency protocols to inhibit dusting during extreme weather conditions, prolonged shutdowns or periods of reduced production are essential. Such protocols often involve intensive irrigation systems requiring a robust reticulation and distribution arrangement together with a guaranteed water supply. However, the ultimate physical control of dust emissions from a hydraulic fill surface remains sub-aqueous deposition.

A further control on dust emissions derives from the geochemical properties of the extractive waste and the subsequent potential for chemical reactions inducing physical changes in the surface of a deposit. This characteristic has the potential to modify the geotechnical properties of the tailings and to inhibit surface emissions. In sub-aerial deposits even moderate levels of sulfides or salts in the hydraulic fill may lead to the development of a thin chemical crust across exposed surfaces where oxidation or selective precipitation occurs under atmospheric conditions. Such crusts are generally thin and have limited competence where the chemical content is nominal and, if left undisturbed, often result in increased runoff rates as well as acting as a very effective dust suppressant. However, the competence of these chemical crusts is, under most circumstances, fragile and the surface is readily destroyed by vehicles and operators accessing the surface, thus negating any beneficial effects. In extreme cold weather the development of ice lenses in the tailings surface and the subsequent expansion of the surficial layer will have a similar effect in destroying the competence of the crust.

6.4.3 Storage Optimisation

The key issues in ensuring efficiency of operation and mine waste storage within a MWF are the control and management of the disposal operations in order to maximise the following:

- density of stored tailings;
- percentage water recycle to the plant;
- sedimentation in the reservoir;
- control of all emissions.

However, the depository must also be managed to achieve the end-point defined in the most up-to-date closure plan and the deposition configured to maximise consolidation, to reduce surface ponding and thus seepage and to ensure surface stability. Finally, towards the end of mine life the disposal method needs to be modified so that a sustainable landform consistent with the closure objectives is achieved and early access to the surface for rehabilitation works is facilitated. Storage optimisation therefore requires management in phases, as shown in Table 6.7.

Table 6.7 Phases of disposal planning

Deposition phase	Disposal strategy
Post start-up	Establishment of disposal layout, including deposition points and cycle times Development of systems for operating and disposal management, reservoir control and recycle Preliminary CQA on hydraulic fill and return water quality Ongoing testing of hydraulic fill and return water to further optimise deposition system Development of instrumentation and monitoring system for the deposit
Operating	Ongoing geotechnical monitoring to optimise disposal characteristics and stored density Refining of deposition cycle time to maximise climatic influences, particularly desiccation and desaturation cycles, without increasing risk of dusting Ongoing geochemical monitoring to optimise return water quality and minimise any negative impacts on the process and mineral recoveries Ongoing geotechnical and geochemical waste characterisation Active management of all potential releases to air and water
Pre-closure	Modification of disposal and water management system to achieve final landform Consideration of hydraulic placement of final cover materials, both inert base-soil and seed bed Geotechnical and geochemical assessment to confirm closure parameters Stability assessment of surface of depository to ensure early access for final closure works
Closure	Stabilisation of deposition surface and installation of final surface works, including cover system Development of long-term hydraulic management system for extreme hydrological events Landscape and after-use development
Post-closure	Ongoing monitoring of deposition surface and after-use

6.5 Water Management

The MWF requires adequate capacity to store not only the hydraulic fill but also process waters and direct rainfall falling within the catchment and impoundment area. The confining embankment therefore needs to be sited to ensure adequate water storage capacity, and the associated waterways designed to enable the release of excess waters in a controlled manner in order to prevent damage or long-term deterioration of the embankment and an untoward release of the waste product or of the contained process water. The overall design approach for the containment is to provide sufficient storage to enable water management during operations such that no process water is released directly from the MWF into the environment other than in accordance with the permit. The standard to be applied will determine the storage volume for the design event and the emergency requirement for the extreme flood.

The hydrological assessment for the MWF and all associated water bodies will need to comply with this flood standard and the approved methodology for defining the design storm and runoff will enable definition of strict freeboard criteria at each stage of construction, together with the size of any associated waterways, emergency spillways, decants, stream diversions and pollution control dams.

6.5.1 Emergency Spillways

As previously described, the flood standard to be applied to the MWF will require that the facility remain robust and intact under the extreme event throughout its life, either by discharging in a controlled manner via a spillway or by retention without breaching freeboard criteria. Provision for the extreme event often imposes a significant financial burden and may result in uneconomic construction costs at some facilities due to the flood volume to be retained. The adoption of flexible flood management standards, such as retaining all floods arising from storm events up to and including the 1:1000-year without spilling but passing in safety those arising from greater storms up to and including the PMF, has significant cost and operational benefits without the need to compromise on safety or on environmental criteria (Cambridge 2010). For such MWFs the provision of an emergency spillway will be required at each construction stage and be designed to pass in safety the PMF without breaching freeboard criteria since overtopping of the confining embankment is rarely permissible and any untoward release is likely to give rise to degradation of water courses and of the downstream catchment. Flood control measures for a MWF therefore require both environmental controls during operation as well as safe designs against extreme events. Such measures are complicated by the construction method commonly adopted for these confining structures. Staged construction with successive, often annual, raises over a period of many years to meet the demands of process and mine life requires a succession of emergency spillways, as shown in Figs. 6.45, 6.46 and 6.47 in order to comply with the following:

- being capable of flood management at every stage of construction, and thus needing to incorporate a series of control structures throughout its operational life;
- providing a robust water supply as the majority of the water used during mineral processing is derived by recycling that discharged into the storage reservoir with the hydraulic fill;
- complying with strict regulation of any discharge into local water courses, or indeed accommodating zero controlled-release where there are overriding environmental concerns.

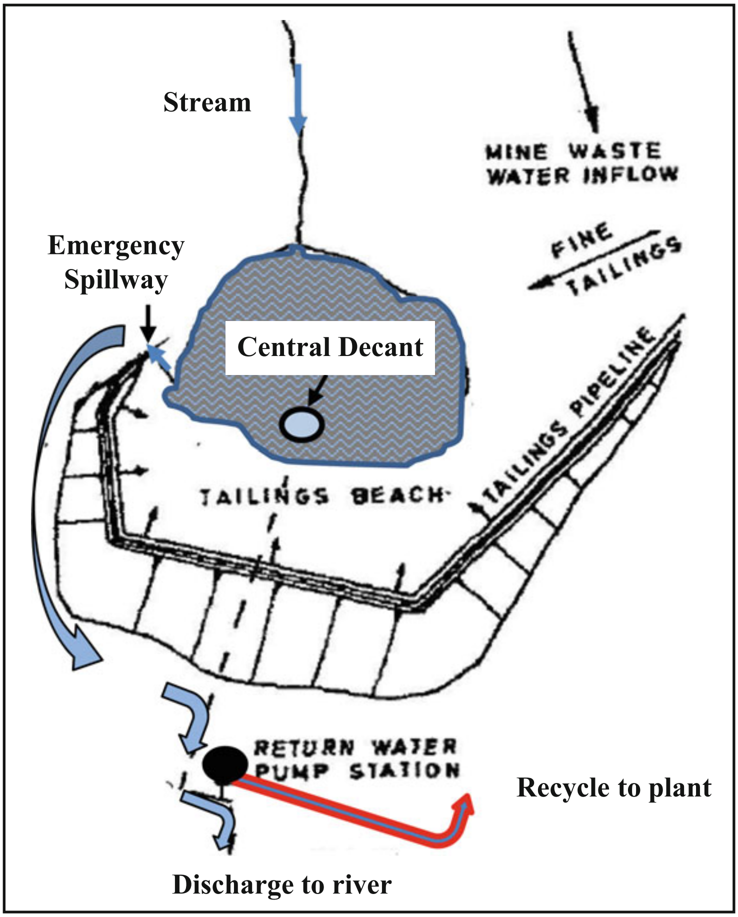

Fig. 6.45 General arrangements of the CVTD throughout its life showing flood/decant provision—central decant

The configuration of the MWF will determine the arrangement of the emergency spillway and be a function of the size of catchment confined, as summarised below:

- paddock dam—designed to cater for the flow arising from the incident rainfall only;
- side valley dam—designed to cater for runoff from incident rainfall and from the residual local catchment;
- valley dam—designed for flood runoff from the full catchment unless a significant diversion system has been installed.

Figure 6.45 shows the spillway requirements for the Clemows Valley Tailings Dam as it developed from a valley dam, through a side valley to a paddock facility. This facility was raised on an annual basis throughout the operational life and

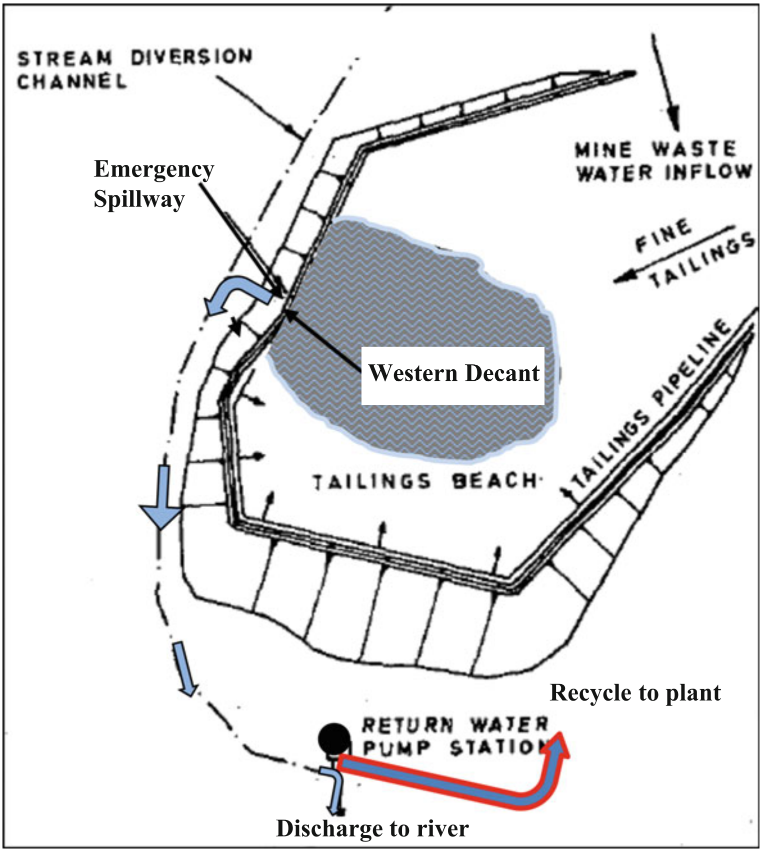

Fig. 6.46 General arrangements of the CVTD throughout its life showing flood/decant provision—western decant

required a series of emergency spillways and decant facilities as well as a stream diversion system. This system was designed to cater for the catchment runoff resulting from a PMF event and to divert this flow in a channel around the facility without endangering the confining embankment. The flood provision for this facility epitomises the hydraulic arrangements often required for a stage-raised MWF, as summarised below:

(i) Initial deposition phase—development of a valley facility:

- central decant designed for both recycle and a portion of the extreme flood event;
- succession of emergency right-bank spillways capable of passing the residual PMF.

(ii) Construction of the upstream confining embankment—development of the side valley facility:

- central decant designed to cater for both recycle and for the flood event from runoff from the local catchment;
- diversion system designed to cater for the catchment runoff resulting from a PMF event and to pass this flow in a channel around the facility without endangering the confining embankments.

(iii) Failure of the central decant (Forbes et al. 1991):

- combined emergency right-bank spillway and decant structure constructed in the western embankment;
- spillway capable of passing the PMF and diverting it into diversion channel.

(iv) Final deposition phase—development of a paddock facility after cessation of mining operations:

- emergency left-bank spillway located on the valley side and constructed in the eastern embankment;
- spillway and flume capable of passing the PMF and of controlling emergency discharges from the minewater treatment plant.

Examples of emergency spillways are shown in Figs. 6.48 and 6.49.

Key elements in the design of such emergency spillways and associated waterways are as follows:

(i) capable of passing the extreme flood event under all operating conditions, including provision for all potential inflows such as mine dewatering, hydraulic fill and potential contaminated site run-off;
(ii) maximum flood surcharge, to include wave allowance below minimum crest level;
(iii) spillway outlet designed to protect confining embankment toe from erosion at all times;
(iv) spillway inlet, outlet and downstream channel to be maintained clear of obstructions, including vegetation, at all times;
(v) flood criteria and wave provision to be regularly reviewed by a suitably qualified civil engineer throughout the life of the facility;
(vi) development of any flood diversion system around a MWF, ensuring that such diversions cater for extreme events without causing erosion or damage to any part of the facility or inducing failure.

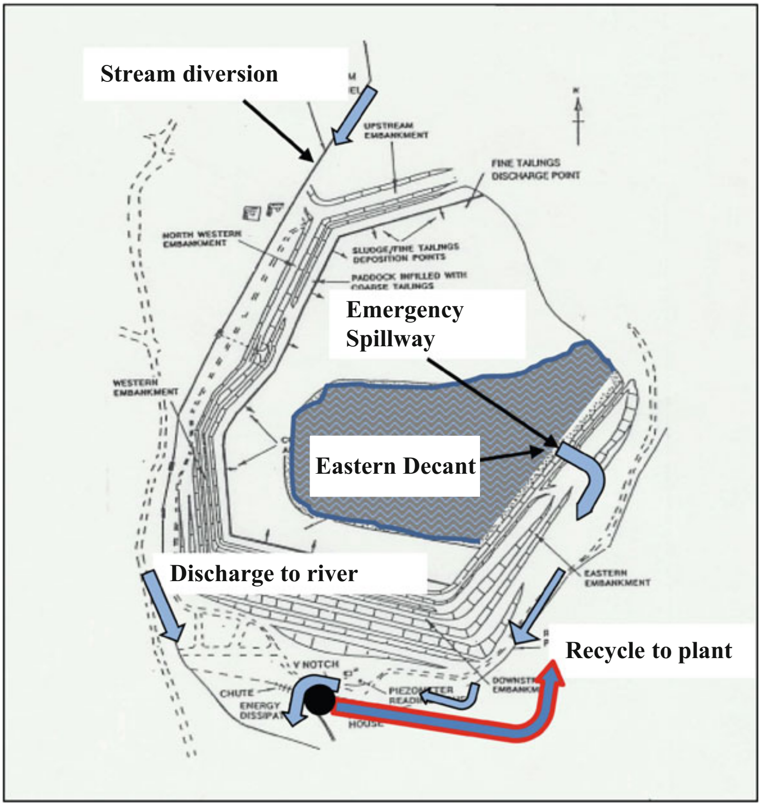

Fig. 6.47 General arrangements of the CVTD throughout its life showing flood/decant provision—eastern decant

Fig. 6.48 Emergency spillway at IRCL, Portugal

Fig. 6.49 Emergency spillway at CVTD, UK

6.5.2 Decant Structures

The design of the decant is, as previously discussed (see Chap. 5), a function of both configuration of the depository and the water balance, the primary aim of this structure being to control reservoir level whilst ensuring that adequate water volumes are returned for re-use in the process circuit. For a stage-raised facility the decant needs to have in-built flexibility in order to enable the level of abstraction to rise with the waste deposit. For a single-stage MWF the options for decanting are limited as the structures are fixed and do not vary over project life. As with all hydraulic structures, the type and structural considerations need to be balanced against the operational and closure risks, as detailed in Sect. 5.5.5. The design should recognise all potential failure modes and ensure that both structural and operational risks are fully mitigated, and therefore address the following:

(i) for buried sections, the full range of potential imposed stresses, including asymmetric loading under all embankment and deposition conditions;
(ii) design of the segmental raising system to prevent uncontrolled leakage, particularly of hydraulic fill, through both horizontal and vertical sections, where this may lead to enhanced asymmetric loading;
(iii) location to enable optimisation of reservoir area and thus of sedimentation, noting that this may require construction of a number of decants throughout the life of mine;
(iv) optimisation of energy usage in the return system;
(v) effective separation of flood and process water where the decant has both a return water and an emergency spill function;
(vi) development of robust emergency protocols.

The range of options is shown in Table 6.8, with examples given in Figs. 6.50 and 6.51.

Table 6.8 Summary of decanting options

Decant Type	Decant structure	Benefits	Risks
Gravity	Central vertical tower with long horizontal outlet	Good control of reservoir and perimeter beaches Maintains reservoir at a distance from embankments	Difficult access for raising inlet level Potentially high stresses on both horizontal and vertical structures Tailings ingress into joints leading to asymmetric loading
	Peripheral inclined chute	Lower structural risk Easy access for raising inlet level Sequential outlets at discrete vertical intervals limit potentially high stresses to horizontal structures only	Maintains reservoir against perimeter embankment Reduces deposition flexibility Potentially high stresses on both horizontal and vertical structures
Siphon	Installed on embankment with discharge over crest in fixed feedline	Lower structural risk Easy access for raising inlet level Sequential outlets at discrete vertical intervals limit potentially high stresses to horizontal structures only	Maintains reservoir against perimeter embankment Reduces deposition flexibility Erosion and failure resulting from pipeburst on the embankment Requires managed emergency control
	Installed on embankment with discharge into gravity chute	Lower structural risk Easy access for raising inlet level Sequential outlets at discrete vertical intervals limit potentially high stresses to horizontal structures only	Maintains reservoir against perimeter embankment Reduces deposition flexibility Potentially high stresses on horizontal structures Requires managed emergency control

(continued)

Table 6.8 (continued)

Decant Type	Decant structure	Benefits	Risks
Pump	Floating barge	Lowest structural risk Automatic inlet level control	Maintains reservoir against perimeter embankment Reduces deposition flexibility Erosion and failure resulting from pipeburst on the embankment Requires managed emergency control
	Fixed installation in inclined chute	Lower structural risk Easy access for raising inlet level Sequential outlets at discrete vertical intervals limit potentially high stresses to horizontal structures only	Maintains reservoir against perimeter embankment Reduces deposition flexibility Potentially high stresses on horizontal structures

Fig. 6.50 Floating barge pump at IRCL, Portugal

Fig. 6.51 Central decant tower at Baia Mare, Romania

6.5.3 Pollution Control Structures

The mineral processing operations on mine sites often require the construction of a series of water clarification and pollution control facilities. These generally comprise small reservoirs or lagoons impounded by low-height embankment dams, and generally contain a solid portion which would be classified as extractive waste and thus be subject to the provisions of the EWD. These structures can be grouped into three categories, namely:

(i) water treatment lagoons designed to treat minewater, sewage effluent from the site and other potentially contaminated waters such as site runoff, either for subsequent recycle to the plant or, subject to permit, for discharge into the environment;
(ii) contaminated water ponds which impound potentially-contaminated materials emanating from the wider mineral processing site;
(iii) pollution control dams constructed to prevent the off-site discharge of contaminated runoff arising either from leakage along the hydraulic transport pipelines or from pipe-bursts.

These structures may comprise small lagoons, often constructed in series which, due to their size, are confined by natural ground with low confining embankments or, subject to topography, are located partially below natural ground level in excavations. These lagoons may have only a seasonal role where the majority of site waters are recycled but, often during wetter winter periods, the volume of flood runoff may require intensive management and careful operation if untoward discharges off-site are to be avoided. It is noted that the contents of these small lagoons may be discharged into the MWF during normal operations, assuming that the facility has the storage capacity to cater for the relevant water volumes. However, as indicated, this may not be feasible under storm conditions and flood provision will be required. The generally small embankment height and storage capacity often result in limited attention being paid to their design and construction which, during operation, leads to the necessity for significant management effort in order to prevent failure and effect any remediation. The embankments are often unzoned, with the result that winter storage leads to seepage and both internal and external erosion which, if permitted to continue uncontrolled, will lead to embankment failure. Further, where these facilities store low pH waters, the seepage may lead to oxidation of the embankment fill and to precipitation of metals in the outlet downstream.

Experience indicates that these structures need to be incorporated into the overall water balance and risk management strategy for the extractive waste site. This requires that attention be paid to the design of these low-height embankments and their overflow facilities. An appropriate assessment of flood risk is required, with the spillway being designed to prevent overtopping under an extreme event on the basis that any breach in such a structure may result in severe negative impacts on the downstream environment. It is evident that good design and an appropriate level of construction quality control, together with a suitable programme of operation, maintenance and inspection, will lead to more efficient operation and reduce management costs in the long term.

6.6 Closure and Rehabilitation

This section considers the geotechnical, geochemical and rehabilitation aspects of hydraulic fill and how they interact with the process of optimising long-term storage and achieving cost-effective closure. These factors relate primarily to the method of placement of the hydraulic fill and to the structural confinement of the extractive waste (Table 6.9).

Table 6.9 Stability considerations for long-term storage and closure

Parameters	Primary factors influencing closure parameters for elements of the MWF	
	Hydraulic fill	Confining structure
Geotechnical stability	Physical properties of the hydraulic fill Hydraulic placement system Drainage and consolidation Surface water management	Construction materials and techniques Effective mitigation of long-term risks through design Potential for changes in geotechnical properties over time Geotechnical stability and longevity of internal drainage systems

(continued)

Table 6.9 (continued)

Parameters	Primary factors influencing closure parameters for elements of the MWF	
	Hydraulic fill	Confining structure
Geochemical stability	Geochemical properties of the hydraulic fill Hydraulic placement system Effective containment by drainage and consolidation Oxidation state of deposited hydraulic fill Surface water management	Potential for changes in geochemical properties over time Geochemical stability and longevity of internal drainage systems Interaction between geochemical and geotechnical properties
Storage optimisation	Management of hydraulic deposition system to maximise density and minimise water content at closure Flexibility in the disposal system to effect surface stabilisation and, to the extent practicable, the agreed landform during final stages of deposition	Mitigation of all storage risks through design and operational management Ongoing monitoring and updating of disposal system
Land-use stability	Flexibility in the disposal system to effect agreed landform during final stages of deposition and facilitate early surface rehabilitation Hydraulic placement to effect long-term geochemical and geotechnical stability and to minimise risks to after-use Development of a suitable land-use which is not destabilised by the imposed ecosystem or agrisystem	Modification of outer faces of confining embankments without loss of stability or drainage function Integration of embankment into final landforms without increasing erosion or long-term degradation risk Development of long-term after-use, vegetation and management system to maintain structural integrity, effectively in perpetuity

6.6.1 Stability of the Closed MWF

The stability of a MWF is defined by the geotechnical and geochemical characteristics of the facility in terms of material properties of both the confining structure and the hydraulic fill, and also the setting of the depository, i.e. climatic, topographic, hydrological and seismological. The drivers for the closure plan are the development of a closed facility which achieves a state of equilibrium in its environmental setting, has benign emissions and a sustainable after-use.

6.6.1.1 Geotechnical Stability

Long-term geotechnical and erosional stability of the confining embankments, the surface of the depository and of the contained hydraulic fill must be ensured in the scope of the closure plan. This is developed throughout the “operational” phase through both the design and construction of the containment and the control and

Table 6.10 Recommended factors of safety

Load case	Minimum factor of safety	Analytical method	Soil Parameters
Static stability			
Long-term static (post-closure)	1.5	Limit equilibrium	Consolidated undrained
Short-term static (operational)	1.3	Limit equilibrium	Consolidated undrained
Rapid drawdown on upstream slope (operational)	Site specific but never less than 1.1	Limit equilibrium	Unconsolidated undrained
Dynamic stability			
Non-liquefiable soils under maximum design earthquake or MCE conditions only	1.1	Pseudo-static–subject to applicability: (Sect. 5.3.4.2)	Consolidated undrained
Liquefiable soils under maximum design earthquake or MCE conditions only	Site specific but never less than 1.1	Residual shear strength analysis Deformation analysis Finite element analysis	

management of the hydraulic placement system. The stability of the confining embankments should conform with the factors of safety shown in Table 6.10 which are based on European, CDA and ANCOLD guidelines modified to provide good practice guide.

Static and dynamic analyses should be undertaken in order to confirm that the as-built structure and its foundations comply with the international norms (Table 6.10) and meet the requirements of the closure strategy. As previously indicated, all embankment cross-sections should be modelled using strength parameters based on the material database compiled during construction and operation of the facility and should comply with national and European Standards as well as with good practice. The piezometric data used in the stability model should be based on the data derived from the installed instrumentation for which an extensive continuous record should be available. The analyses should take into account the potential for long-term deterioration of the embankment materials as well as of the potential for seepage and drainage conditions to degrade and potentially cease to function due to natural weathering, geochemical influences or poor management practices. In order to comply with international standards for closure (ICOLD 2011) these analyses, or indeed regulatory requirements, may necessitate additional stabilising measures, such as:

(i) buttressing or flattening of external slopes;
(ii) improving drainage to depress the phreatic surface within the external slopes;
(iii) minimising or eliminating any ponded water on the surface of the facility;
(iv) modifying flood control and surface water runoff systems to prevent erosion of surfaces;

(v) modifying the properties of the hydraulic fill in order to reduce the risk of liquefaction and flow in the unlikely event of a breach, noting that such waste stabilisation measures should have been achieved by design during the operational phase.

An important part of the stability of the MWF is resistance to surface erosion caused by atmospheric conditions such as wind or water. The elements of such a design should include a suitable closure strategy and be specified in the permit application and the approved closure plan with respect to the final land-use. The erosional stability of the facility should be addressed by the following:

(i) design of the final cover for all slopes and exposed surfaces in order to maximise runoff and to minimise velocity by the inclusion of a suitable vegetation cover, slope armouring or provision for traffic access where such is permitted by the specified end use;
(ii) design of a sustainable runoff control and drainage scheme, including the formation of open channels which are fully compatible with the final landform;
(iii) development of a sustainable flood management scheme which passes or diverts extreme events in safety either through, or around, the MWF without leading to deterioration;
(iv) design of the cover system to inhibit the ARD potential and to be sustainable in respect of the agreed land-use, taking account of root penetration, animal damage and human intervention such as deep ploughing or untoward excavations;
(v) placement of limitation on the final land-use and ensuring appropriate stewardship and land management, effectively in perpetuity.

6.6.1.2 Geochemical Stability

The geochemically dynamic system which is a MWF will react both to the physical characteristics of the materials incorporated and to the disposal method adopted. Geochemical stability is to a greater extent defined by emissions and in particular by seepage, the quality of which will be a function of the composition of the hydraulic fill (both solid and liquid phases), method of deposition, drainage conditions and geotechnical stability both of the deposited extractive waste and of the confining structures.

The principal issues with respect to the long-term geochemical stability of a MWF are therefore the quality and quantity of seepages and the potential for other releases from the facility resulting from long-term chemical weathering of the hydraulic fill and embankment materials. The rate of geochemical alteration, the quality and quantity of the seepage, together with the predicted rate of decline in the volumes released, will determine the extent to which active and passive treatment systems are required. In addition, an assessment of seasonal impacts will determine under what conditions seepages can be discharged to the environment. The prediction of long-term emissions from a closed facility should be generated during the final design of the closure system and should be based on the geochemical database established during operation using a suitable model. This should be developed during operation so that it can be validated pre-closure in order to confirm closure design parameters and to define the accompanying specification for the rehabilitation works. The prediction of the extent of both active and passive treatment is important as it will underwrite a significant element of the post-closure operating costs and thus form part of the financial guarantee required for the permitting of all Category A facilities.

6.6.2 Rehabilitation Techniques

The guiding principles for mine site closure and rehabilitation, regardless of conservation issues, apply to both existing and historic sites. These principles are enshrined in the Directive and require the following to be achieved:

- Safety—physical and environmental
- Stability—physical and chemical
- Sustainability—socio-economic and environmental, effectively in perpetuity.

As can be seen from the qualitative assessment of liabilities for an extractive waste project shown in Table 6.11 the MWF represents a significant potential liability in terms of costs of closure and aftercare.

Table 6.11 Qualitative assessment of mine closure liabilities

	Timescale	Cost implications	
		Short-term	Long-term
Mine site	Short-term	Low-to-medium	Low
Mine buildings	Short-term	Minimal	Zero
Waste rock	Short-to-medium-term	Medium	Very low
Ore stockpiles	Short-term	Minimal-to-medium	Very low
MWF	Medium-to-long-term	Potentially high	Low-to-medium
Minewater	Long-term	Medium	Low-to-medium but potentially infinite

6.6.2.1 Initial Considerations for Rehabilitation

There are a number of considerations which will affect the scope and method of rehabilitation, as shown in Table 6.12.

Table 6.12 Summary of closure options

Parameter		Closure options
Closure technique	Wet closure	Wet closure may be prescribed in order to effect control of ARD and dust. It may be feasible on sites where there is a positive water balance both seasonally and through all predicted climatic extremes. It is noted that once installed the water cover must be maintained, effectively in perpetuity. In addition, as previously described, wet closure increases the risks relating to the confining structures, to maintaining emergency flood provisions and the management both of seepages and of the aquatic environment
	Dry closure	Dry closure is generally the preferred option as it can provide long-term stability and reduced risk if suitable provision is made for drainage of the embankment and of the hydraulic fill, that surface ponding is limited and that infiltration is inhibited
Geochemical stability	Sulfidic waste	For hydraulic fill containing high sulfides with ARD potential or with leachable toxic elements, closure requires both some form of containment (capping or cover) to prevent infiltration by oxygen and water, and the development of a sustainable surface and after-use
	Inert or non-inert non-ARD-generating waste	For benign hydraulic fill, establishment of vegetation directly on the surface of the depository may be possible, supplemented by fertilisers, organic matter and soil-forming materials
Geotechnical stability	Surface instability	For undrained hydraulic fill or that with low strength, surface stabilisation under atmospheric conditions may take years. Therefore if suitable bearing capacity has not been achieved at closure, thus preventing machinery access for rehabilitation, installation of a stabilising cover layer may be required
	Surface stability	Where the final landform has been achieved at closure and the surface stabilised, early rehabilitation should be feasible and few, if any, additional stabilising works required
Final landform	Depositional	The placement of the final fill layers may, in some cases, achieve the overall landform for the surface, requiring minimal additional works other than for the establishment of a vegetative cover or other after-use
	Post-depositional	Generally, the properties of the hydraulic fill surface will need to be modified post closure and imported fill material placed to achieve surface drainage, erosion-resistant slope angles and to provide gradual transitions between the embankment and natural ground surface

6.6.2.2 Progressive and Staged Rehabilitation

Progressive rehabilitation of a MWF should be undertaken in stages wherever possible, with restoration undertaken throughout the operational phase subject to any extension of the footprint, modification of production or a change in the disposal system. Where deposition cycles are complete, such as for cellular or paddock disposal systems, or where the outer faces of the confining embankments achieve their final form at an early stage, rehabilitation pre-closure may be feasible. This permits closure to be funded, in part, out of operating rather than capital budgets, with substantial cost savings. On most sites, however, such early-stage rehabilitation works are likely to be limited in extent, and the major closure works required to be undertaken post decommissioning of the plant.

During the closure period the MWF transitions from decommissioning to post-closure phase, which would normally be programmed for up to five years. However, for more aggressive hydraulic fills a longer period of up to ten years may be necessary. A staged approach is likely to be required, as follows:

(i) Decommissioning and initial rehabilitation:

- removal of infrastructure, regrading of embankment and other surfaces, capping and establishment of vegetation;
- inspection and monitoring of the MWF with particular regard to embankment instrumentation;
- extension of the geotechnical and geochemical database, with ongoing collection of drainage and seepage waters;
- control of both air- and water-borne emissions;
- installation of long-term flood provisions;
- ongoing containment of out-of-consent seepage or drainage waters, or treatment to ensure that all discharges meet emission-quality standards.

(ii) Second decommissioning stage:

- removal of all retained infrastructure or facilities;
- completion of final long-term drainage and seepage collection arrangements;
- ongoing water treatment;
- installation of passive water treatment facilities where appropriate;
- establishment of long-term inspection, monitoring and data collection regime.

(iii) Active care period:

- intensive aftercare of vegetation and final landform;
- dust, seepage and drainage management and control;
- ongoing water treatment and quality testing as appropriate;
- frequent inspection, monitoring and data collection to confirm closure parameters.

(iv) Passive care:

- minimal direct intervention to embankment and depository surfaces;
- initialisation of long-term site management arrangements;
- ongoing maintenance of site drainage, soil stability, land-use, vegetation and flood provisions;
- ongoing water sampling until emissions are proved to be benign;
- ongoing inspection and monitoring until the IIE reports that the MWF no longer poses a risk to life, to health or to the downstream environment.

6.6.3 Modification of Landform

The embankment slopes may require the addition of material in order to provide buttressing to increase stability, reduce slope angle to achieve a sustainable non-erosional surface or the agreed post-closure landform. The transition between the outer embankment and the surface of the hydraulic fill will require modification of the embankment crest to soften its angular profile. However, if the surface is to continue to involve regular or seasonal flooding, sufficient freeboard will need to be maintained in order to prevent overtopping. If the hydraulic fill is contained by an artificial liner then it will be essential to ensure that the edges of this are covered and not exposed to long-term degradation. The hydraulic fill may also require modification, involving final profiling with placement of imported materials in order to achieve a convex surface rather than the concave or flattened landform associated with such deposits. In addition, internal divisions or separate paddocks may need to be created by the construction of low-height berms in order to partition the facility for long-term use, to suit internal drainage requirements or to make 'field' boundaries.

6.6.4 Surface Drainage

As part of the long-term drainage arrangements an understanding is required of the post-closure water balance in order to assess the seasonal effects of the following:

(i) net infiltration leading to basal seepage;
(ii) net runoff leading to surface drainage;
(iii) availability of water for vegetation growth.

Properly designed embankment and internal drainage systems supported by competent CQA should be sustainable and be capable of long-term seepage control, subject to any internal or external degradation forces. It is therefore vital that any changes to landform do not compromise the long-term integrity of the embankment and deposition drainage systems and that emphasis be placed on the geochemical and geotechnical suitability and compatibility of all drainage media during construction. However, it is noted that the associated water management structures such as the decant and return water system are rarely suitable for inclusion in the long-term rehabilitation scheme. These structures, including any buried pipelines, should therefore be fully decommissioned by sealing with a suitable grouting system or by demolition and removal.

A passive scheme for long-term drainage control should be targeted, with an open channel gravity system being adopted with no buried pipelines, culverts or pump chambers in order to simplify long-term maintenance and monitoring. The final drainage arrangements should ensure that rainfall is collected, removed from the surface of the depository and safely conveyed to a suitable outfall beyond the toe of the embankment. Provision should be made to prevent the runoff from causing erosional damage to the external slopes of the confining embankments. In addition, regular sampling and quality testing of all drainage waters should be undertaken in order to confirm their suitability for direct discharge into the downstream environment. In the short term, some form of active water treatment may be required until the rehabilitation works have stabilised with, in the long term, attenuation and polishing through a pond or passive wetland as necessary.

6.6.5 Cover and Capping Systems

The objectives for a cover or capping layer over the surface of the depository may include one, or a combination, of the following:

- isolation of geochemically active fill and prevention of upward migration of contaminants to the surface;
- reduction of infiltration in order to prevent leaching of contaminants through the fill, thus reducing seepage to groundwater and through the toe of the dam;
- prevention of wind-or water-erosion of the fill surface;
- isolation of the root zone of vegetation from potentially-contaminated fill;
- provision of an adequate substrate or soil profile (soil-forming material) for the required vegetation.

The most widely-used components of cover and capping systems are summarised in Table 6.13. These may be used either singly or in combination as a composite system, depending on the circumstances and considerations such as availability of material, toxicity of fill, water balance (net water deficit or net percolation), vegetation requirements, risk of wind-and water-erosion and cost.

There are no ‘standard’ systems and each has to be designed to suit the setting of the MWF, the properties, particularly the geochemistry, of the hydraulic fill and the planned after-use. However, Table 6.14 below indicates the example options based on toxicity and geochemical stability of the hydraulic fill.

Table 6.13 Summary of functions, benefits and disadvantages of cover systems for hydraulic fill rehabilitation

Cover or cap system	Engineering details	Benefits and disadvantages
Synthetic liner	LDPE or HDPE liner, over protective sand layer placed to suitable specification with full placement CQA Cover layer comprising a further sand layer or capillary break with an overlying soil profile comprising subsoil and SFM for vegetation establishment Textured liner combined with geogrid or geotextile for soil layers on slopes	Low permeability liner effectively isolates and encapsulates ARD-generating or hazardous fill material, prevents ingress of air and water and thus upward migration and percolation Expensive to install and to maintain sufficient depth of SFM Liner not suitable on slopes as soil layer may slough or erode, especially in wet conditions Cover system design life unknown Liner liable to root penetration and other damage with extended exposure
Clay cap	Geological barrier comprising local clay fill, sand/bentonite or a combination to achieve required permeability criteria Barrier placed and compacted in accordance with suitable specification and with full placement CQA Cover layer comprising further sand layer or capillary break with an overlying soil profile comprising subsoil and SFM for vegetation establishment	Low permeability geological barrier effectively isolates and encapsulates ARD-generating or hazardous fill material, prevents ingress of air and water and thus upward migration and percolation Cheaper than synthetic liner, especially if locally available Integrity is dependent on installation and consistency of material Resistant to erosion and accidental damage but prone to animal damage Permeability may increase over the long term with weathering
Capillary break layer	A layer of coarse rock material as part of a composite cover system. Capillary break may be combined with a filter fabric to prevent blinding by sedimentation A synthetic drainage layer comprising a composite geogrid within a geotextile envelope forming a capillary break	Prevents upward migration of contaminants from the hydraulic fill into the surface layers and reduces root or other biotic penetration Allows downward percolation of rainfall into the hydraulic fill, thus reducing surface water accumulation and improving drainage. However, downward percolation may enhance oxidation rates Resistant to erosion and damage and very robust even if surface soil covers are compromised Will not support vegetation without SFM cover Potentially susceptible to animal damage
Simple cover layer	A cover of locally available, suitably graded crushed rock, overburden or general fill material	Isolates hydraulic fill by depth of cover, limiting upward and downward water movement and air ingress, depending on permeability

(continued)

Table 6.13 (continued)

Cover or cap system	Engineering details	Benefits and disadvantages
	Can be included as part of a layered soil profile with a surface SFM	Increasing depth theoretically gives greater protection from ARD subject to rate of oxidation of extractive waste and therefore may not be suitable for high-sulfide wastes Provides stable surface for machinery access Erosion- and damage-resistant, being very robust and not easily compromised in the long term Inexpensive, if suitable material is available locally Susceptible to animal damage
Crusting agents	Synthetic crusting agents (e.g. PVA, bio-oils) in solution or emulsion with water, sprayed on to the surface and curing to form a crust Additives such as cement, bentonite or crushed rock to final hydraulic fill layers. Thickness dependent on economics and quality of hydraulic fill Cover layer may comprise further sand layer or capillary break with an overlying soil profile of subsoil and SFM for vegetation establishment	Temporary erosion-control measure only Easily damaged and does not usually survive vehicle tracking or other cover applications May be susceptible to animal damage Low-cost installation due to use of existing hydraulic transport and placement system but requires soil profile for establishment of vegetation Provides potentially stable surface for rapid access at closure for rehabilitation works and may ameliorate ARD by providing additional buffering capacity Will require modelling to provide anticipated longevity and resistance to degradation

Table 6.14 Decision matrix for capping based on geochemical hazard

Relative geochemical toxicity and hazard (ARD, leached metals and salts)	Prevailing seasonal or annual water balance	
	Net infiltration	Net deficit
Benign or low hazard	No capping required Direct re-vegetation or installation of SFM layer	No capping required Direct seeding or installation of SFM layer and re-vegetation with drought-tolerant vegetation
Moderate toxicity and hazard	Low-permeability cap together with SFM	Simple cover layer with SFM
High toxicity and hazard	Geomembrane liner or low-permeability geological barrier of compacted clay/ bentonite, together with capillary break and SFM	Capillary break and SFM

6.6.6 Soil-Forming Material and Amelioration

If the ultimate objective of rehabilitation is a vegetation cover, then consideration should be given to provision of a soil-forming material (SFM). If the hydraulic fill surface is benign then it may be adequate as growth medium for the vegetation cover, but otherwise a suitable soil profile will need to be constructed from available or imported materials including, as appropriate, some form of soil-improver. SFM may comprise locally-derived topsoil from a natural source or that excavated from the facility footprint prior to construction. If such topsoil has been stockpiled in good condition this may be suitable as a soil cover. However, local topsoil may not be available in sufficient quantity or be of adequate quality, and therefore other soil-forming materials should be sought. The selection and placement of SFM should be based on the following criteria (BS3882:2007—Specification for topsoil and requirements for use):

(i) particle size distribution—low gravel and clay content, preferably with a high percentage of silt-sized particles;
(ii) density—without excessive compaction and retaining sufficient porosity to permit root penetration and water infiltration;
(iii) pH—between 5.5 and 7.5;
(iv) water content—sufficient moisture and capacity within the soil profile depth for plant growth;
(v) quality—absence of significant levels of potential contaminants and toxic elements.

The precise requirements of the above will depend on the land-use and vegetation cover specified. For grazing, a better quality SFM will be required than for other non-productive after-uses, such as biodiversity. SFM can be placed in a combination of subsoil and surface horizons to form the final cover profile, the overall depth of which should be determined by the availability of a sufficient volume of soil for vegetation to exploit for water and nutrients. However, the SFM profile would normally be expected to be between 300 mm and 1 m with, for covers including a low-permeability capping layer, a depth at the upper end of this range. It is noted that this specification does not address soil fertility and though, for low-productivity grazing and biodiversity it is less important, for productive after-uses such as intensive grazing and cropping this property will be critical and should be addressed as part of the surface management plan. Soil fertility can be managed and improved by use of the following:

- lime ($CaCO_3$) to raise pH where acid soils are not required;
- compound fertilisers as a balanced source of essential nutrients such as nitrogen, phosphate and potash (N:P:K). Other micro-nutrients such as magnesium and sulfur may also be required, with slow-release formulations being preferable to normal agricultural compounds;
- organic matter such as composted organic waste, organic by-products or digested sewage sludge will provide a combination of nutrients and improve soil conditions.

Ameliorants provide a convenient way of developing soil fertility to the required levels if they continue to be applied as part of a properly-managed aftercare programme.

6.6.6.1 Vegetation Establishment

The choice and establishment of vegetation for the selected after-use is beyond the scope of these guidelines as it requires specialist ecological, agricultural and/or forestry input. The following are therefore presented as general principles for guidance only.

Vegetation types will normally be selected from the following broad categories in temperate climates such as the UK:

(i) pasture grasslands, maintained by grazing or mowing for fodder storage, and comprising a mixture of grasses and legume species;
(ii) high-productivity biomass crops, such as Miscanthus and other grasses;
(iii) species-rich, mainly herbaceous, swards, based on non-pasture grasses and herbs which will require occasional mowing or grazing in order to control succession to woody scrub;
(iv) wetland and marsh where there is a high water-table;
(v) scrub and woody species, between 0.5 and 3 m in height, which will normally have a biodiversity objective, but can include biomass crops such as willow coppice;
(vi) pioneer woodland, comprising short-lived tree- and larger shrub-species such as birch, alder, maple and rowan interspersed with dominant tree species like oak, beech and sycamore.

When left to itself, vegetation naturally undergoes successional changes. Normally this will progress from herbaceous pioneer vegetation through increasingly dense scrub and taller trees to climax woodland. This may take several decades, though the early stages will progress more rapidly. On engineered structures such as a MWF, trees and larger woody species are considered undesirable for a combination of reasons such as:

- deep root penetration into the structure, which encourages:
  - oxygen penetration, potentially enhancing oxidation rates, leading to degradation of fill properties and to poor seepage quality;
  - physical interference with artificial liners, disruption of drainage systems, thus impairing stability and increasing water infiltration.
- wind-loading and toppling, damaging the integrity of the structure, exposing the deeper material and increasing surface erosion rates;
- enhanced surface erosion rates around trunks and root systems.

The beneficial effects of woody vegetation may include the following (Coppin and Richards 1990):

- soil buttressing and stabilisation with high-tensile root mass, increasing shear strength;
- binding and protection of the soil surface as a tensile mat;
- intercepting rainfall and reducing rainfall intensity;
- erosion-protection from wind and water.

However, despite the above benefits the majority of embankment dam engineers would recommend that trees and deep-rooted shrubs be avoided on all embankment surfaces as experience indicates that the negative impacts outweigh the claimed benefits and increase long-term management costs. The selection and subsequent management of the vegetation on different parts of the impoundment structure will therefore be a compromise between maintaining engineering integrity and the cost of resisting the natural successional progression. Maintenance of vegetation by grazing or other forms of cropping may provide the best long-term way of achieving this, whilst providing some return and beneficial land use. Examples of successful long-term re-vegetation of extractive waste sites are shown in Fig. 6.52.

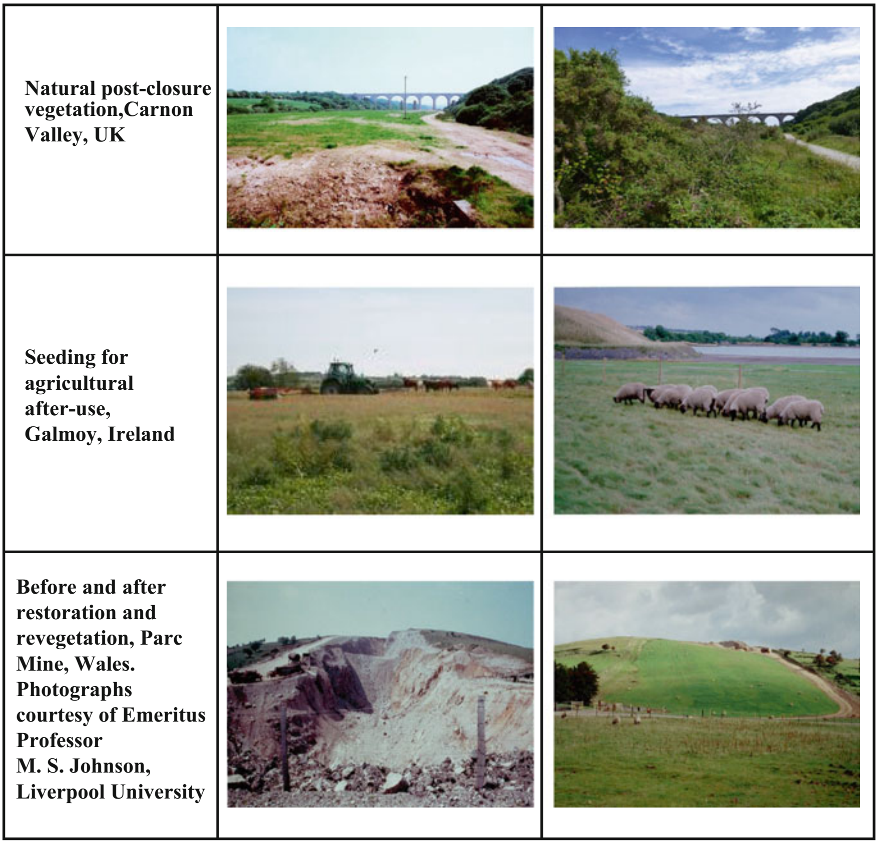

Fig. 6.52 Examples of restored tailings surfaces

6.6.6.2 Long-term Management

The ultimate aim should be to minimise long-term maintenance and management of the decommissioned and rehabilitated facility such that the input is similar to that which is required for any land in similar use.

At some stage, transfer of responsibility for the MWF to a long-term user with an interest in its future as an asset will be required and financial instruments, such as maintenance bonds, may form part of this process in defining ownership obligations. The transfer of responsibility must include provision for the regular inspection and monitoring of the MWF as well as for inspections by the independent engineer and Competent Authority in order to ensure ongoing safety and integrity of the facility as well as its regulatory compliance. As previously indicated, this provision should stay in force until the IIE reports that the MWF is geotechnically and geochemically stable and no longer poses a risk to life, to health or to the downstream environment. Examples of successful long-term after-use are shown in Figs. 6.53 and 6.54.

Fig. 6.53 Rehabilitated coal slurry lagoon, Norton Bog, UK

Fig. 6.54 Rehabilitated lead zinc MWF, Zinkgruvan, Sweden

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Chapter 7
Facility Quality Control, Inspection and Monitoring

Mike Cambridge and Jason Saint

Monitoring of every dam is mandatory because dams change with age and may develop defects. There is no substitute for systematic and intelligent surveillance.
—Ralph Peck, ICOLD, Beijing 2012

The EWD, and good practice, require that a hydraulic fill project be constructed, operated and closed appropriately and that inspection and monitoring plans be prepared to ensure that the ongoing safety and stability of the facility is assured. The Directive established an inspection regime and reporting process involving not only the owner/operator and Competent Authority but, implicitly, an IIE (EC 2012). This mirrors the approach already adopted in some European countries and as good practice by larger mining companies. The overarching inspection and reporting procedures implicit in the Directive are summarised in Fig. 7.1.

The need for instrumentation, monitoring and inspection throughout their operating life and post closure is thus a pre-requisite for all mine waste facilities. The inspection and monitoring parameters should therefore be formulated during the design phase and should be available in the form of the following documents:

(i) The Waste Management Plan, which principally describes the overall waste disposal system, the anticipated depth/storage relationship, the overarching hydrological and geochemical criteria and the closure objectives.
(ii) The Operating and Maintenance Manual (the Manual), which describes the method of confining wall construction, the detailed waste deposition method, all hydrological, geotechnical and geochemical operating criteria, instrumentation installation, maintenance and recording, together with the inspection, monitoring and reporting regimes.

The following sub-sections address all aspects and phases of a MWF construction quality control (CQA) and the inspection and monitoring system as shown in Fig. 7.2 and identify both regulatory requirements and good practice.

M. Cambridge (ed.), *The Hydraulic Transport and Storage of Extractive Waste*,
Professional Practice in Earth Sciences,
https://doi.org/10.1007/978-3-319-69248-7_7

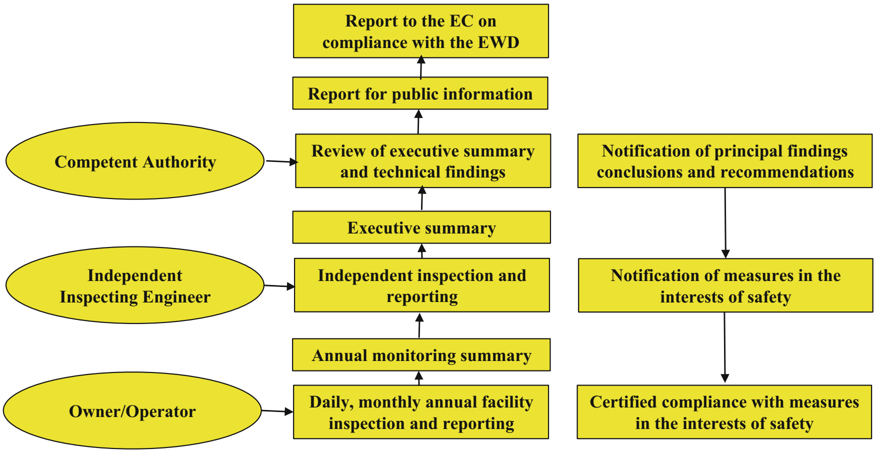


Fig. 7.1 Inspection and reporting procedures within the EU (EC 2012)

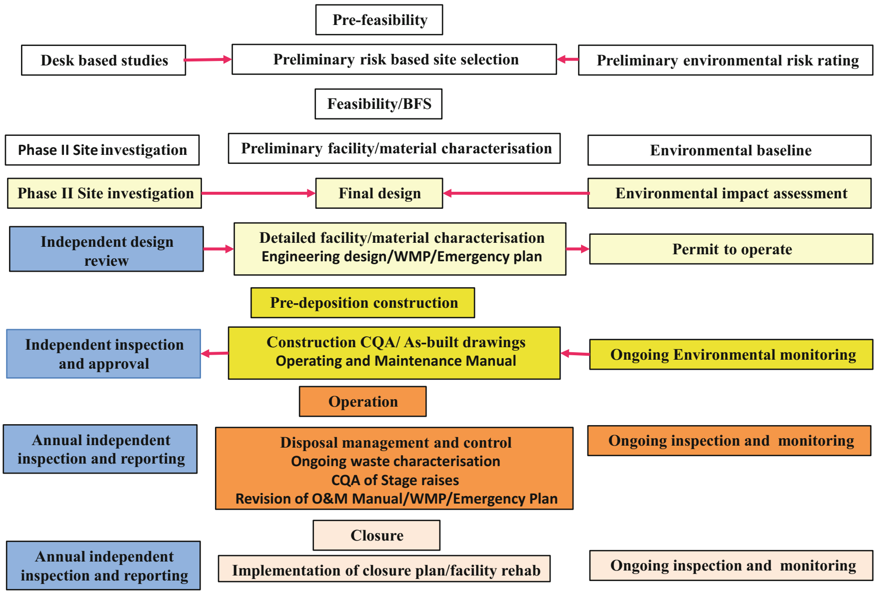


Fig. 7.2 Inspection, reporting and peer review throughout project life

7.1 Facility Construction Quality Assurance

The Waste Management Plan should either make reference to, or contain, a Construction Management Plan (CMP) which includes details of the facility's quality assurance system to be employed during construction. This is usually contained within the Quality Management Plan.

Quality assurance is a set of planned and systematic actions to ensure that the facility complies with pre-defined and specified requirements. It not only involves checking the final construction data to avoid defects, as is the case in normal CQA, but also checking quality in a planned way in all the project delivery stages. It is the development of work and procedures to prevent errors from occurring in the first place, based on planning backed-up by suitable quality manuals and tools.

The quality management system used for construction would normally be ISO9001-certified. The ISO9001 standard specifies requirements for a quality management system where the contractor needs to demonstrate, through its CMP, the ability to consistently provide construction which meets the requirements of clients and applicable regulations. The system should define the need to prepare execution documents, such as work instructions, inspection regimes, procedures, action plans and conformance records. It should include the purpose of procedures, required references to other documents, scope, method and sequence of tests, acceptance and rejection criteria, key control points and time of inspections. In all cases the control of a procedure should be documented in the quality records and filed in the quality log at the construction site.

Technical or administrative procedures can also be part of a quality management system. The Manual should provide a generic description of the owner's/operator's quality system while procedures, whether general or specific, establish what is required to attain the objectives listed. Procedures must link the ISO standards' requirements and the activities of the owner/operator and should include the personnel involved, details of materials and equipment and a description of key activities. Each organisation should decide which processes should be documented on the basis of the nature of its activities, its corporate strategy, together with client and regulatory requirements.

7.1.1 Confining Embankment CQA

The confining structure to a MWF generally takes the form of a large embankment dam and is often of a similar size to those associated with water supply reservoirs. Accordingly both design and construction standards need to be prepared in order to ensure that the embankment is constructed and monitored in accordance with appropriate national or international guidelines. The construction specification and the proposed quality assurance system will form part of the approval process and therefore needs to be fully integrated with the design process. Each material to be incorporated into the embankment section must be fully described in terms of source, geology, geotechnical and geochemical properties as well as volume and rate of supply. The construction documents should specify the excavation and transport methods for each material to be placed in the dam whether it is to be derived from borrow or from extractive waste (open pit or underground).

Fill from borrow needs to be identified pre-construction and the volume available for construction use determined, making an allowance for unsuitable materials and wastage. Where coarse extractive waste is to be incorporated into the embankment cross-section the specification needs to be prepared in co-ordination with the open pit or mine design to ensure that the excavation and blasting process provide material of suitable grading and that the load haul system enable the necessary material selection, stockpiling and conditioning to take place. The engineered fills should be sampled regularly both prior to and post placement in the embankment and tested in accordance with standard protocols (Sect. 4.3). Strict compliance with the specification should be regularly tested and the data fully quality assured throughout construction. The CQA data should therefore be collected, recorded and filed in the quality file with regular summaries produced for independent audit by the IIE during the annual or equivalent inspection visits. Typical CQA compliance tables giving examples of testing frequency for engineered fills, geosynthetic materials and geomembranes are shown in Tables 7.1, 7.2 and 7.3.

7.1.2 *Disposal Quality Control*

The waste management plan should establish the overall criteria for disposal of the hydraulic fill in the MWF and should include the anticipated short- and long-term in situ density in the depository and thus the rate of rise and the ongoing storage requirements. The regular review of hydraulic fill quality is therefore essential in terms of ensuring that suitable storage capacity be available, and the safety margins

Table 7.1 Typical testing frequency for embankment fills and geological barriers

Construction zone	Particle size	Water content & Atterberg limits	In situ density & Proctor optimum	In situ permeability
Clay core	1 per 500 m^3	1 per 500 m^3	1 per 500 m^3	
Basal geological barrier	1 per 250 m^3	1 per 250 m^3	1 per 400 m^3	1 per 1000 m^3
Filter system	1 per 500 m^3	1 per 500 m^3	1 per 500 m^3	
Under-drainage zones	1 per 500 m^3	1 per 500 m^3	1 per 500 m^3	
Zoned earthfill	1 per 1000 m^3	1 per 1000 m^3	1 per 1000 m^3	
Zoned rockfill	1 per 5000 m^3	Grading-specific	1 per 5000 m^3	
Mass rockfill	1 per 5000 m^3	Grading-specific	1 per 5000 m^3	

Table 7.2 Typical testing frequency for geosynthetic liners

Material properties	Test method	Test frequency
Mass per unit area	ASTM D-5993)	One test per five rolls delivered to site. However, more frequent testing will be required if the rolls are not from the same batch or if any rolls are damaged.
Free swell of clay component	(ASTM D-5890)	
Peel strength	(ASTM D-6469)	
Tensile strength	(ASTM D-4632)	
Index flux	(ASTM D-5887)	
Montmorillonite content	(Methylene blue VDG P69)	

Table 7.3 Typical testing frequency for HDPE geomembrane liners

Material properties	Test method	Test frequency
Thickness	(ASTM D-5199)	One test per five rolls delivered to site. However, more frequent testing will be required if the rolls are not from the same batch or if any rolls are damaged. In addition, it is standard practice to vacuum pressure test every weld and to spark test anchorage points and major, and some minor, patches.
Density	(ASTM D-1505)	
Tensile properties	(ASTM D-6693)	
Carbon black dispersion	(ASTM D-5596)	
Notched constant load test	(ASTM D-5397) (single point test)	

and freeboard requirements achieved, at all times. The regular characterisation of the mine waste is therefore not only a regulatory requirement but essential if the facility is to be operated safely and efficiently. Waste characterisation for disposal quality control should take place throughout the operational phase of the project and any variation in mine waste product or properties should be addressed through modifications to design and construction criteria (Table 7.4). This characterisation of the waste facility should be undertaken as outlined in Chap. 4 for each stage of the development of the MWF, as follows:

(i) pre-deposition—determination of baseline design parameters and waste management plan;
(ii) operation—confirmation that deposition parameters meet all design criteria and that the waste management plan remains valid;
(iii) closure—confirmation that the deposited material meets all closure criteria.

7.1.2.1 Pre-deposition

During the pre-deposition stage of a MWF project, preliminary assessment of the properties of the hydraulic fill will need to be obtained from laboratory testing of both exploration core and pilot plant samples. The pre-deposition testing programme will need to be optimised to suit the limited volume of material available

Table 7.4 CQA monitoring of hydraulic fill deposits

Test	Parameter	Function
Jar tests	*Sedimentation data* Minimum settling velocity Overflow water quality	Design of minimum settling (decant) pond area to achieve effective sedimentation and potential return water quality
	Deposition characteristics Minimum settled density (undrained) In situ water content	Calculation of upper-bound hydraulic fill storage requirements Input to water balance
End-of-pipe tests	Geotechnical characteristics (sub-aqueous) Pulp (slurry) density Confirmatory sedimentation data	Ongoing assessment of hydraulic fill/extractive waste Confirmation of materials balance and in situ density data and thus of design and storage parameters
Bathygraphic surveys	Average deposited density (sub-aqueous)	Assessment of **maximum** sub-aqueous storage density Assessment of capacity and predicted rate of rise
Beach sampling	Geotechnical characteristics (sub-aerial)	Assessment of in situ properties of beached deposits (density, grading and particle specific gravity) Input to MWF capacity assessment
Decant water sampling	Return water quality	Regular assessment of sedimentation characteristics and of process (return water) quality
Beach surveys	Tailings slopes	Density and water storage capacity assessment Assessment of ratio of sub-aqueous to sub-aerially deposited hydraulic fill Assessment of predicted rate of rise

and the results should be assessed in the knowledge that material derived from the pilot-scale laboratory tests may exhibit a greater range of characteristics than that obtained from the full-scale process during the operational phase. However, experience of such pre-production testing regimes on numerous sites indicates that the pre-deposition phase can, and has, produced viable data capable of being used to underwrite the design stage for the facility subject to the samples tested being fully representative of the predicted waste.

During this phase, therefore, characterisation should be based on, at minimum, jar settling tests or, where suitable samples and laboratory equipment are available, consolidation tests from minimum settled density (Appendix B2). These tests should be performed on the basis of the feasibility level process flow sheet and be undertaken at the predicted pulp density using process rather than de-aired or de-ionised water. The key geotechnical design parameters for the facility, namely the minimum settled dry density, the in situ water content and the minimum settling velocity, can readily be derived from these simple tests. The minimum density data can then be used to define the upper-bound storage volume required during the early stages of tailings deposition and thus the requisite rate of construction of the confining embankment. When combined with minimum density consolidation testing, the data can be used to provide a more accurate prediction of consolidation rates and thus to predict long-term storage requirements. The jar tests also provide an indication of the settling characteristics of the pulp and of the quality of the overflow. The minimum settling velocity can be used to determine the minimum pond area required to develop a clear supernatant and suitable return water quality, as defined in Sect. 5.4.2. These data are important in the context of the facility water balance and, in particular, in establishing water storage requirements for maintaining supply to the plant and the extent to which deficits or surpluses are likely to occur. The settling data also provide important information for the processing operation as they will indicate whether any constituents, particularly reagents, are likely to be persistent in the return water quality and whether these might be detrimental to either the mineral recovery or, in the case of permitted discharges from the MWF, to the environment. It is important to appreciate during this design phase that pilot plant- or laboratory-derived hydraulic fill samples are an indicator only and that full-scale operation may produce very different results. The developer needs to factor this element into the design.

7.1.2.2 Operation

Jar tests should also be used during the plant commissioning and start-up phases as they can be compared with tests on end-of-pipe samples, enabling confirmation of compliance with initial design criteria. Once the depository has matured, the principal method of quality control will be via assessment of the in situ density of the deposit.

The average in situ density of a sub-aqueously deposited hydraulic fill can be determined from regular bathymetric surveys and from the mine waste tonnages derived from the process plant materials balance. However, during the initial stage in the life of the depository it is accepted that an accurate density assessment using hydrographic means is error-prone due to the inherent difficulties of surveying the sub-aqueous settled surface. On mine sites where this method has been used successfully, such early-stage hydrographic investigations have been proved to overestimate the density due to the volume of tailings which remain in the water column at the time of the survey. However, with time, regular surveys (generally annual) will show the accuracy to increase and the plot of data to become asymptotic to the average value. The accuracy of the plant materials balance is crucial to this assessment as any error in the tonnages deposited or in the delivered pulp density can provide misleading density data and, in an extreme case, lead to inadequate construction rates and a subsequent lack of storage. Comparison with the data provided by the ongoing laboratory testing of hydraulic fill samples should provide assurance that the density estimates are of the correct order of magnitude. With time, the hydraulic fill should consolidate through lateral drainage and the field and laboratory data provide an indication of the longer-term average density for the depository, enabling more effective deposition planning. For sub-aqueously deposited hydraulic fill the consolidation effect will be measurable from the bathymetric surveys and the development of the plant materials balance.

For primarily sub-aerial deposits, testing to derive the average in situ density needs to address not only the difference in density of the beached deposit and the sub-aqueous material but also the disposal split between hydraulic fill deposited above and below the water line. As the extent of the sub-aerial deposit increases, hydrographic methods will need to be supplemented by other land-survey techniques in order to provide a good indication of deposited density for use in future mine planning. Testing of beached deposits by survey and by in situ density testing, supplemented by drained jar tests and laboratory evaporation models, will provide a good indication of average values for use in ongoing deposition planning. Where the beached deposit cannot be accessed in safety there will need to be a reliance on remote survey and laboratory testing. With time, properly-deposited hydraulic fill should consolidate through lateral drainage and climatic input (evaporation) and the field and laboratory data provide an indication of the longer-term average density for the depository, enabling more effective deposition planning.

A programme of ongoing testing of the hydraulic fill product is required throughout the life of the depository in order to improve knowledge of the deposited material and the range of in situ density values being achieved. The testing must be supplemented by regular hydrographic and topographic surveys as the depository develops, and needs to be undertaken over a period of years in order to reduce any error associated with locating the settled surface. The development of an accurate materials balance remains core to the prediction of storage capacity and rate of rise, requiring regular end-of-pipe sampling for slurry density and grading curves as well as a review of the total hydraulic fill produced by the plant and of the metallurgical balance sheet.

7.1.2.3 Closure

Post closure, ongoing testing of the deposited hydraulic fill and of the embankment fill materials is required to confirm compliance with closure parameters and the geotechnical and geochemical stability both of the confining embankment and of the deposit. In addition, ongoing quality testing of surface drainage and seepage will be a continuing requirement, together with regular assessment of flow. Dependent on the configuration of the deposit at closure, testing of decanted water may also be required.

7.2 Inspection and Monitoring of Hydraulic Fill Projects

The EWD requires a MWF to be managed and operated by competent persons and, by inference, that the facility be appropriately inspected and monitored throughout its life from pre-deposition to post closure. Inspection and reporting on the facility should therefore be undertaken by the operator in accordance with an agreed plan, with further overview of the operation to ensure regulatory compliance by, or on behalf of, the relevant Competent Authority at regional or national level. The inspection process is fully described in the EU Guidance Document (EC 2012) and relevant elements of this guidance are summarised in this sub-section. The main parties to the facility inspection process (Fig. 7.3) are as follows:

(i) The Competent Authority—this regulatory body is required to carry out regular inspections to ensure compliance with both the permit and with other applicable legislation, and to confirm the competence of the management and the ongoing safety and stability of the facility. However, an IIE may be appointed as the Competent Person to perform inspections on behalf of the Competent Authority where no suitably qualified personnel are available from internal resources.

(ii) The owner/operator—the operator is implicitly required to initiate and manage the site inspection and monitoring procedures and to report on the results to the Competent Authority on a regular basis or on request.

(iii) The IIE—this Competent Person may, in accordance with recognised good practice, be appointed independently by the owner/operator in order to undertake regular independent inspections of the facility and to prepare a summary report for annual submission to the Competent Authority. Subject to the qualifications and experience of the IIE this summary report may be considered as satisfying the requirements of the National Competent Authority.

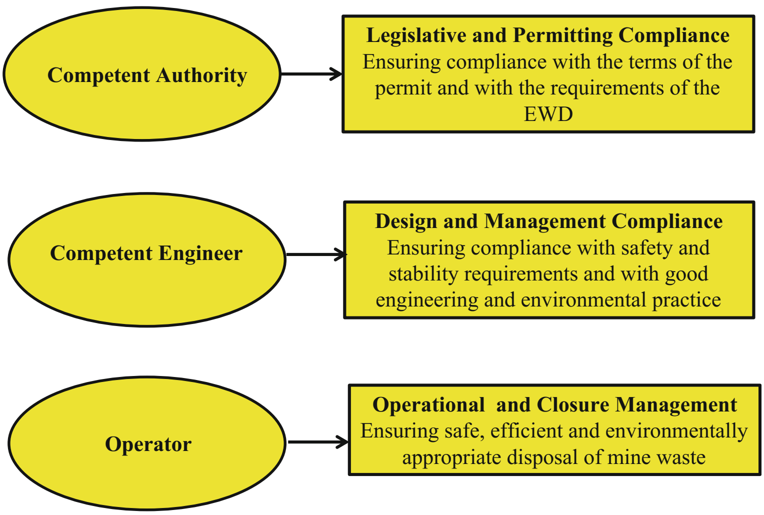


Fig. 7.3 Principal roles of the inspecting parties

7.2.1 Inspection by the Competent Authority

7.2.1.1 Objective

The objective of the regulatory inspection of an extractive waste facility is to ensure safety, stability and environmental compliance and that any untoward signs which may lead to failure or to an uncontrolled discharge can be identified and corrected before any such negative event occurs. The inspection process therefore covers all stages of the facility through inception, feasibility, permitting, design, construction, operation and closure, and is an issue for mine management at all levels from the local operator to the corporate and, for the Regulator, from local authority to the Member State's Competent Authority. As each extractive waste facility is unique the inspection objectives need to comply, initially, with an overall EU-wide framework but, most importantly, must be tailored to suit the individual parameters of the particular extraction operation or site in question. Thus for a complex operation with a range of mine waste facilities (Fig. 7.4) there will be the need for an overall guidance document, which should address both the objectives and the requirements of the inspection process for each MWF on the site. Underlying the overall inspection process is the need for a consistent approach, not only to all inspection and monitoring of extractive waste facilities but also in terms of reporting. Both the Competent Authority and the operator should be cognisant of the overall guidance and ensure that all inspections are undertaken competently.

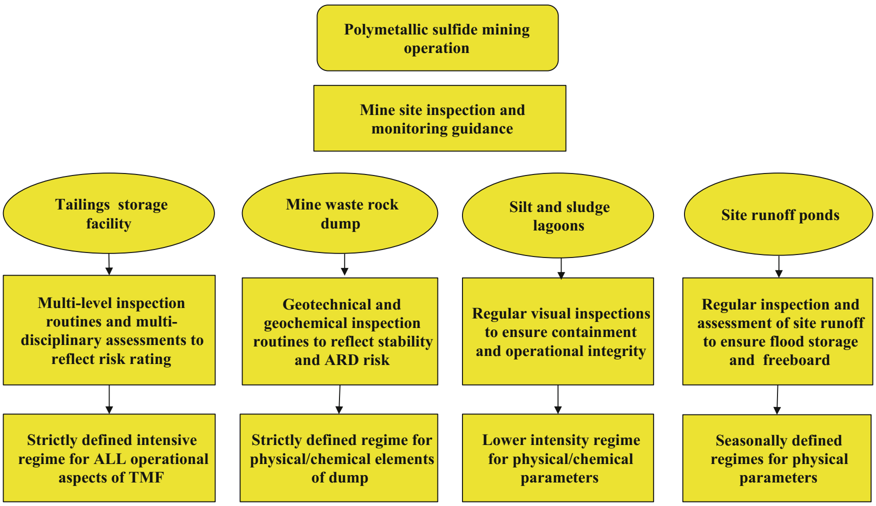


Fig. 7.4 Example of site-specific inspection guidance documentation (EC 2012)

7.2.1.2 Scope

The inspection and reporting undertaken by the Competent Authority should cover all aspects of the MWF operation and include auditing of any inspections undertaken by, or on behalf of, the owner by the operator. Such high-level inspections are intended to confirm the continued compliant operation of a facility throughout its life-cycle to ensure that it is built, operated and closed in a safe and environmentally correct manner according to the permit and to relevant legislation. The objectives of the inspections by the Competent Authority will be site-specific and be focused on the safe and efficient management of the facility. Such inspections may need to be co-ordinated between different inspecting authorities with respect to site visits, access to the site for inspectors and information for the purposes of the inspection. In regions where there is a risk of cross-border impacts, appropriate contacts would need to be made with Competent Authorities in adjacent regions and, where necessary, co-operation be provided in the way of monitoring data or other information exchange.

Inspections should be undertaken prior to the commencement of disposal operations and at regular intervals thereafter, including the post-closure phase. Compliance with the EWD does not reduce the responsibility of the owner/operator but requires that any operating, closed or abandoned extractive waste facility for which inspections are necessary be included in the scope of the reporting by the Competent Authority. It is recommended that all Category A facilities, including those closed and abandoned, be inspected at least annually and that the frequency of the inspections of all other sites be based on the risk posed to human health and to the environment. The inspection reports should be communicated to the operator, and an Executive Summary report be publicly available.

7.2.1.3 Competence

Member States need to ensure that the Competent Authority in charge of inspections has the necessary level of knowledge, experience and competence to carry them out appropriately. For Category A facilities it should be ensured that inspections be carried out by inspectors or a team of inspectors having suitable engineering degrees, and that the leading inspector have a professional qualification with a minimum period of ten years' practical (non-academic) experience in extractive waste facility design, construction, operation and closure. The required level of competence will depend on the type of facility and the related risk, and it is therefore important to ensure that the appropriate engineering skills are available. Where Member States do not have an adequate level of in-house competence, the Competent Authority should initiate a regime of independent inspections carried out by external suitably qualified inspectors on their behalf. In this case, Member States should ensure that the IIE and the associated team, as appropriate, have the required qualifications, and are independent from the operator, designers and construction supervisors responsible for the MWF in question.

In some jurisdictions within Europe, national legislation necessitates the appointment of an IIE who is required to address the overall design and operational parameters with respect to safety and legislative compliance and to report this in summary to the Regulatory Authority (HSE 1999; HMSO 1971; ICE 2000; GRUVRIDAS 2012; EPA 2009). Such an inspection regime is deemed to meet the requirements of the EWD, subject only to the results of the inspections (the Executive Summary) being in the public domain and being included in the regular reporting to the EC (see Table 7.8) for a list of the typical contents of an IIE inspection report. Many owners initiate independent inspections at corporate level to address the risks arising from any aspects of the site design or management, and these may also provide the basis for regulatory reporting.

7.2.1.4 Background Data

As for all technical studies, the completion of the inspection report is highly dependent on the work undertaken in advance. Accordingly, it is important that the inspecting team representing the Competent Authority or the IIE be provided with all relevant information concerning the site setting (social, topographical, environmental, hydrological and seismological amongst others) as well as of the extractive operations associated with the MWF together with a basic description of the design and operational history. The degree of preparation necessary prior to the instigation of the inspection depends on the size, scale, type and complexity of the facility. It is essential that a carefully planned scope for the inspection be prepared in order to ensure that a decision on compliance and on the adequacy of existing site procedures can be made, and any perceived necessary corrective actions identified. The background data need to provide the inspecting team with relevant evidence of a facility's procedures and practices. An inspection plan, to include the proposed itinerary, schedule and any data requirements, should be prepared in advance and a copy be provided to the operator before the visit. An example of the inspection process is given in Fig. 7.5.

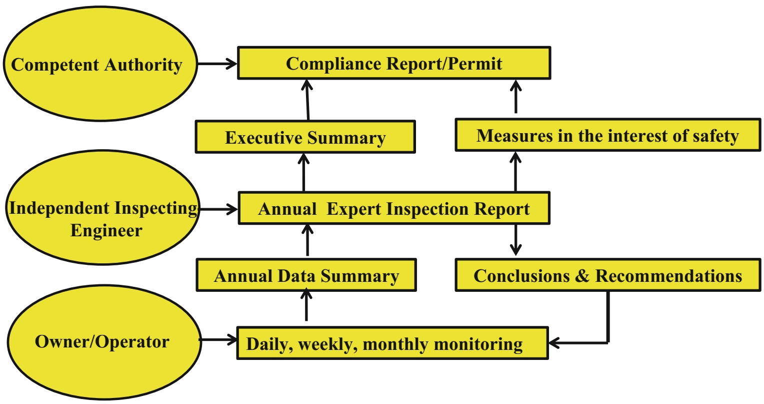


Fig. 7.5 Example of inspection process

Closed and abandoned facilities differ from operating MWFs as reliable data are often limited and there is generally no operator to perform monitoring or regular inspections. In such a case, information should be available from the regulatory inventories compiled by the Competent Authority as required by the EWD.

The principal issues to be addressed by the Competent Authority should cover the following:

(i) review of compliance with relevant permits and legislation;
(ii) review of the interface between the EWD and other legislation (e.g. the Water Framework Directive, Seveso II Directive and IPPC Directive);
(iii) assessment of the competence and completeness of reports regarding technical compliance prepared by the IIE;
(iv) review of inspection report findings, the recommendations and the programme for their implementation;
(v) review of the waste management plan, noting in particular any changes to the original design and water management system;
(vi) assessment of the validity of any progressive closure measures and the adequacy of the closure planning;
(vii) assessment of ongoing and potential environmental impacts from land-use, disturbance and surface operations on groundwater, dust, noise and odour;
(viii) assessment of any potential risks related to other activities on the site with regard to water management and infrastructure;
(ix) assessment of the roles, responsibilities, competence and training of personnel;
(x) identification of any additional inspections which may be required to be undertaken by an Independent Expert.

7.2.1.5 Reporting

After every site visit the Competent Authority should process or store, in identifiable form and in data files, the inspection data and the findings with respect to compliance with legal requirements. Any further action, such as enforcement proceedings, sanctions, the issuing of new or revised authorisation, permits, licences or follow-up inspection activities, including further site visits, should be identified. Reports should be finalised as soon as possible and be properly recorded in print and maintained in a readily accessible future-proofed database. The full reports or, where not practicable, the conclusions of such reports, should be communicated to the operator of the extractive waste facility and a suitably annotated version (executive non-technical summary) be made publicly available.

When an IIE is engaged the resulting inspection report should be properly recorded in print and duly signed, confirming the veracity of the findings, and should include an Executive Summary which, for reasons of commercial sensitivity, should be non-technical in nature. This Executive Summary should include an evaluation of the inspection, the conclusions and recommendations, and details of any measures required to be undertaken in the interests of safety, as well as whether any further action or follow-up inspections are required. The report should conclude with a statement as to the satisfactory nature of the inspection and whether any enforcement proceedings, sanctions or modifications to the permit are necessary. It should then be issued to the Competent Authority and be stored in a readily accessible future-proofed database. The post-inspection reporting procedure, when under the aegis of an IIE, is shown in Fig. 7.5.

The format of the report prepared by the Competent Authority should follow a clear outline and, if an IIE has been engaged, be based on the executive non-technical summary. The structure of the report should be simple and standardised, and include the following:

(i) the scope of the inspection, outlining its purpose and any specific issues such as incidents or complaints from third-parties;
(ii) a list of the documentation reviewed for the inspection;
(iii) a brief description of the inspection visit, including full details and the role of all participants, i.e. the inspector or inspecting team engaged by the Competent Authority, any IIE and the operator's personnel;
(iv) a summary of particular actions taken during the inspection visit, such as physical sampling, details of additional evidence or observations made, together with their chronology;
(v) findings of the inspection, including competence of available documents provided by the operator, results of any sampling and findings of interviews with site operatives and management;
(vi) conclusions, recommendations and corrective measures to be taken;
(vii) the agreed minutes of the final inspection round-up meeting.

7.2.2 Owner/Operator Inspections

> Failure to inspect and monitor may result in the safety of the operations being put at risk. Increased risk leads to increased probability of death or injury to workers or third parties.
>
> Cambridge 2006

Although mining activities are regulated by legal requirements and guidelines, the expectation and opinion of the public will determine the acceptability of the development of new, and the permitting of ongoing, mineral operations. Extractive waste management is an integral part of the extraction process and is often seen as the negative aspect of a mining operation. It is therefore incumbent on the operator to ensure that the necessary standards of operation, management and performance of any MWF are met. The operator therefore has the responsibility for ensuring that such a facility be designed, built, operated and closed in a safe and environmentally-sound manner and that suitable monitoring and inspection regimes are in place. These procedures are crucial elements in confirming that all statutory and specific permitting obligations be fulfilled and are, in addition, an important management tool for ensuring that local operations and performance are compliant with good practice and efficient and safe waste disposal. The scope and extent of the operator's monitoring and inspection regime includes the obligations of all levels of staff at a facility, from the main Board member responsible for corporate health and safety to the excavator-operator or equivalent. The general sections through both a MWF and a silt lagoon, shown in Figs. 7.6 and 7.7, exemplify the range of elements to be inspected and the data recorded.

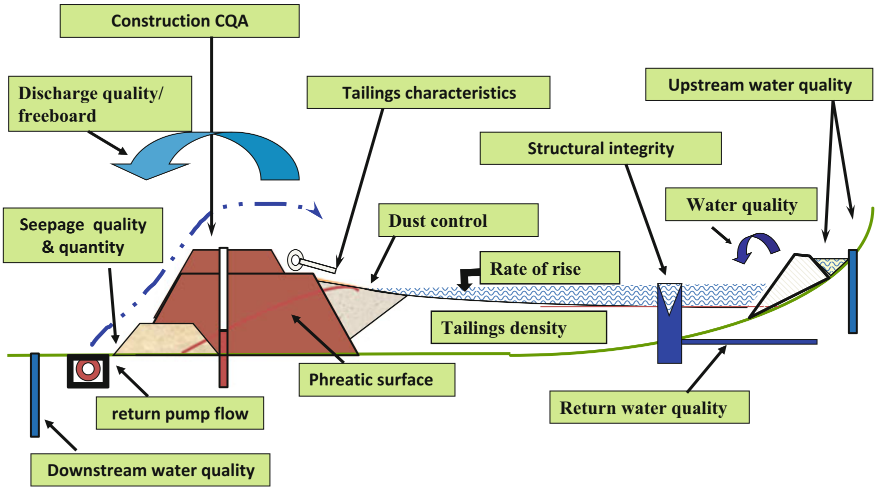


Fig. 7.6 Principal monitoring for a MWF (Cambridge 2012a, b)

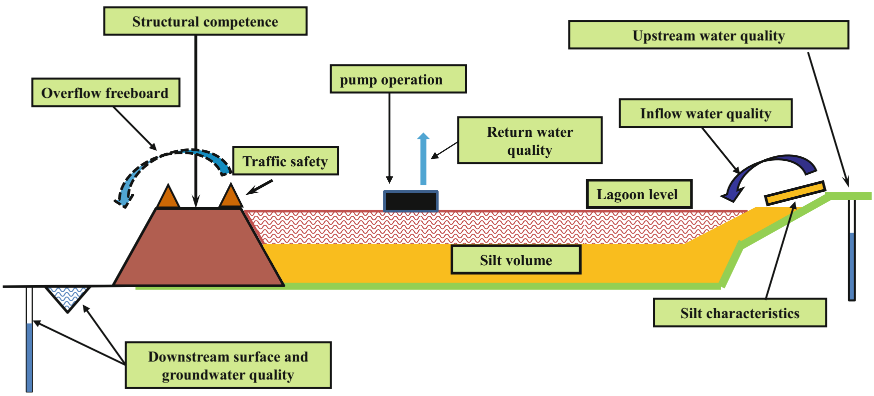


Fig. 7.7 Principal monitoring for a silt lagoon (Cambridge 2012a, b)

7.2.2.1 Objectives

It is important to recognise that extractive waste facilities are engineered structures and thus the overriding objectives for the inspection process are to ensure that:

(i) the engineered structures perform to design;
(ii) the facility is managed and closed properly such that environmental compliance is achieved;
(iii) the management of the facility is in the hands of a competent owner/operator;
(iv) there are suitable plans and arrangements for both regular monitoring and inspection of the waste facility by suitably competent personnel and for taking action in the event of results indicating instability or water and/or soil contamination.

Further, due to the dynamic nature of MWFs, the operating, monitoring and inspection regime, including all record keeping, needs to be regularly reviewed to ensure ongoing efficiency and safety. The operator's inspection regime also provides the supporting framework for the regular reporting to, or by, the Competent Authority. In many environments the extent of this regime is defined by statute, whereas in others it follows best practice or corporate policy. Operators of Category A facilities would be expected to engage an IIE to undertake inspections at regular intervals, to audit the management and operation of the facility against the design parameters and, in particular, to review the adequacy of the inspection and monitoring system. In some European jurisdictions, such as the UK, the role and qualifications of an IIE is required by, and specified in, national legislation as an adjunct to the roles of the Competent Authority and the operator. Similarly, in Austria the Competent Authorities maintain a pool of independent experts with specified relevant qualifications to undertake inspections as needed. The IIE may therefore undertake the auditing role for both the operator and for the Regulatory (Competent) Authority.

An example of the operator's monitoring and inspection regime is illustrated in Fig. 7.8.

7.2.2.2 Competence

The owner/operator should ensure that any MWF is under the management of a competent person. Further, the organisation and the allocation of responsibilities for the inspection of all extractive waste facilities and their associated structures, for ensuring ongoing safety and stability and for environmental monitoring, should be clearly defined and documented. All personnel engaged in operation, surveillance, maintenance, safety preparedness, monitoring and control should have the relevant competences and be advised in writing of their duties and responsibilities. The expertise of all such personnel should be fully documented and include information related to education, training and experience. The operator is responsible for ensuring that the relevant personnel are properly resourced and supported at all times and, in addition, have the appropriate authority and have received the correct

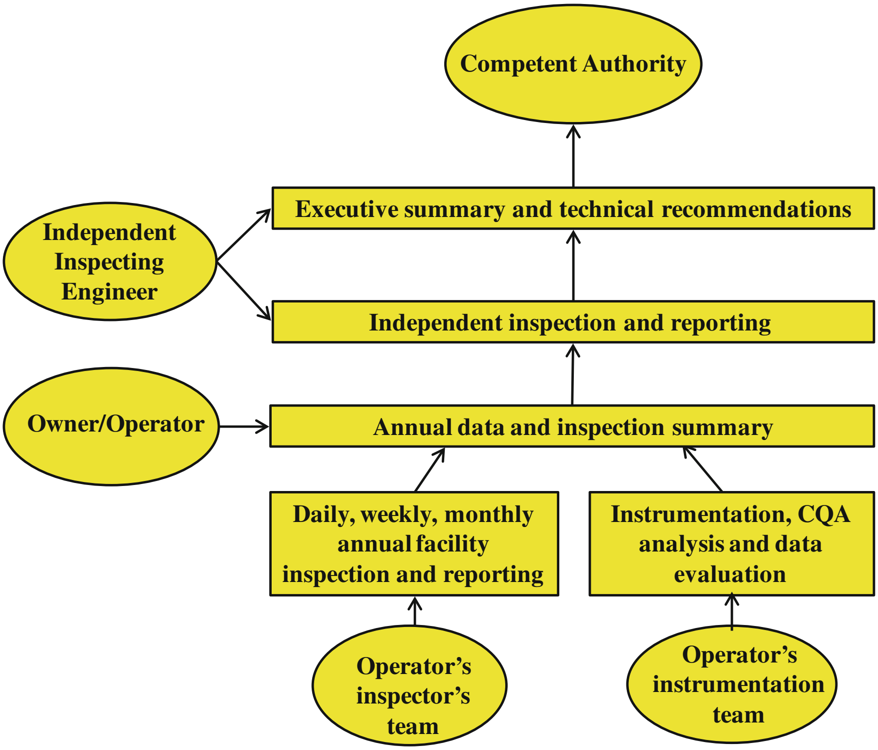


Fig. 7.8 Example of the operator's inspection system

training. It is common practice for the duties and responsibilities of all personnel involved in the inspection and monitoring process to be summarised in the Manual and to cover the following:

- operational monitoring and inspections;
- performance monitoring;
- internal management structure and responsibilities;
- the role of the IIE;
- non-statutory Corporate audits.

7.2.2.3 Inspection Regime

Underwriting the inspection process are the design and operating parameters against which the performance of the facility is to be judged, which for a current operating MWF would be derived from the design and the permit. In the case of an abandoned facility these parameters would need to be derived retrospectively by risk assessment, investigation and back analysis. All operations and maintenance must be undertaken in accordance with these design and operating parameters, which are based on the following principles:

(i) design rules must be followed if the structure is to remain fit for purpose;
(ii) inspection and monitoring is required to ensure safety, stability, design and permit compliance;
(iii) failure to inspect and monitor may result in the safety of the structure being put at risk;
(iv) increased risk leads to the increased probability of death or injury to operators, users and third-parties, and to negative environmental impact.

The need for instrumentation, monitoring and inspection throughout the operating life and post closure is thus a pre-requisite for all mine waste facilities.

7.2.2.4 Operating and Maintenance Manual

This Manual, to be prepared as part of the Waste Management Plan, should be seen as a living document and will thus be subject to revision and amendment as the operation of the MWF progresses. Such modification will often be as a result of the findings of the regulatory inspections. The contents of a typical Manual are:

1 Introduction
2 Project background and history
3 Project description
4 Transport and storage of hydraulic fill
5 Hydrology and seismology
6 Environmental controls
7 Instrumentation
8 Inspection and monitoring routines
9 Figures

Appendices

A Contact details for all (statutory) appointees and inspecting personnel
B Inspection and monitoring record sheets
C Instrumentation maintenance procedures
D Emergency response protocols

The Manual should therefore include:

(i) a description detailing the procedures for the inspection of the various elements of the facility, for recording the key information and for completing the inspection record sheets;
(ii) specific operational instructions in the case of extreme weather conditions and untoward events, together with both normal and emergency reporting routines;
(iii) the primary operating criteria for such elements as freeboard, reservoir level, seepage volumes and other key stability and performance data, together with the necessary reporting and mitigating actions required.

It is therefore necessary for the operator to ensure that the personnel performing such inspections have suitable knowledge of the operation of the facility. The inspection records should be made in writing and be complete, with no sections of the sheets left blank. It is equally important that these records be both accurate and reliable, as they will form the basis of the regular inspection and reporting documentation. Personnel should also be fully cognisant of the importance of the data records with respect to the ongoing safety and stability of the facility. These records should be stored on site and summarised in a future-proof database. Further, it is necessary to ensure that the reporting system be fully functional, with an appropriate communication system established such that suitably competent staff are available at all times to deal with untoward events and to carry out emergency procedures where required.

7.2.2.5 Inspection Procedures

The inspection of any waste or water facility, and the monitoring of the instrumentation, should be undertaken on a regular basis by appropriately-trained operators, facility engineers and departmental managers, with annual safety, stability and compliance audits by the IIE. The objective of monitoring and inspections at the operational level is to ensure the day-to-day performance and function of all elements of the hydraulic fill disposal and containment structures. The principal aim is to ensure that all facets of the operation retain their integrity and function in accordance with design requirements. It is also necessary that all extractive waste disposal operations be undertaken efficiently without undue risk to the operations themselves, to the operators and to the environment or third parties. These inspections should be undertaken regularly and involve a range of frequencies in accordance with the sensitivity of the parameters to be monitored, with certain inspections being required during each shift and others only at monthly intervals.

All inspectors, engineers and appointed operators should be familiar with the operation and the general inspection and monitoring procedures for each structure. Typical inspection requirements should be described in the Manual and record sheets for the regular inspection and monitoring of the facilities be provided. Typical daily and monthly inspection and monitoring record sheets have been included in the Appendix for guidance (Appendix C). The record sheets for each MWF and appurtenant structure should be designed to summarise the safety of the operations and the condition of all embankments and other important structures so that inspections can be undertaken without continual reference to the Manual. All record sheets should require the inspector to record a “yes/no” response or, in some instances, to enter a physical measurement. Tick-boxes are not considered to be appropriate for high-risk structures such as MWFs. Written records of the condition of all facilities need to be maintained throughout their operation. The inspection sheets should be completed conscientiously by the appointed person and filed for future reference. Daily inspection sheets should be submitted for review at the end of each week and be counter-signed weekly by the facility supervisor (as identified in the Manual). The record sheets should be kept up-to-date and be available for review during the monthly inspections, which should be undertaken towards the end of each month by a Senior Operator or Departmental Manager. Any issues raised during the daily inspections should be checked and noted as having been addressed or requiring attention. The monthly inspection reports should be submitted to the owner or his representative without fail on the first day of the following month for review and sign-off. To assist with the annual inspection by the IIE, a summary report on the previous 12 months' records should be prepared in advance. The summary should include reference to any outstanding issues arising from the previous 12 months' inspections.

Typical contents of record sheets are described separately below and include four categories, recording the daily, weekly, monthly and longer-term inspections and data collection.

7.2.2.6 Daily Monitoring

It is important that an inspection of each facility and its operation be carried out on a daily basis. This will provide a continuous record of the condition of the depository so that any malfunction can be detected at an early stage and remedial works undertaken without delay. The facility supervisor should ensure that only suitable responsible personnel undertake the daily inspections and monitor and record the instrumentation. These operators should be fully familiar with the inspection and monitoring requirements, and with the operating criteria described in the Manual. All record sheets should be counter-signed at the end of each week by the facility supervisor. Typical daily monitoring requirements are shown in Table 7.5 with examples of specific inspection elements provided in Fig. 7.9.

7.2.2.7 Weekly Monitoring

It is important that, in addition to the daily inspection of each facility, a weekly inspection by the senior operator or shift supervisor be undertaken. The MWF Manager should identify suitable responsible senior personnel to undertake the weekly inspections and to follow up any contra-indications noted during the daily monitoring. Again, the weekly record sheets should be counter-signed at the end of each month by the facility supervisor or MWF Manager. Typical weekly monitoring requirements are shown in Table 7.6

7.2.2.8 Monthly Inspection

It is important that a monthly inspection by the Senior Operator or MWF Manager be undertaken and, again, the record sheets should be counter-signed at the end of

Table 7.5 Typical daily monitoring of a waste facility

Category	Principal records	Inspection details
Weather	Site meteorological data should be recorded daily	Rainfall and evaporation data are essential for the site water balance. Note also that weather conditions during any inspection should be recorded as part of the overall monitoring
Hydraulic fill	The total tonnage & volume of mine waste & water discharged into the facility should be recorded daily	The data are important for the efficient operation of the facility, for the site water balance and for advance waste planning
Embankments	Regular inspections of all confining embankments should be undertaken rigorously	It is important to note and record the general appearance of all sections of the confining structures, of any signs of seepage, settlement, surface movement, cracking, erosion or other disturbance caused by whatever means, including animal damage. The records should be clear and unambiguous and, if necessary, be accompanied by sketches showing the location of the occurrence so that remedial actions can be taken and recorded when completed. The facility supervisor and, as appropriate, the MWF Manager or the IIE should be notified immediately of any occurrences where significant remedial actions are required so that an appraisal can be undertaken and the necessary measures agreed. Where remedial works are necessary, a note should be included in the "Remarks" section of the record sheet until they have been carried out. If an event has not been addressed, a note that the necessary work is still outstanding should be included in the "Remarks" section
Embankment seepage	The measurement of seepage flow is of major importance as it is recognised to be one of the primary indicators of the condition of an embankment	Seepage measurement is generally obtained either from a flowmeter or a v-notch weir located at the toe of the embankment(s). The condition of all seepage waters should be noted on a daily basis and any changes in appearance recorded, particularly any evidence of discolouration, precipitation or the

(continued)

Table 7.5 (continued)

Category	Principal records	Inspection details
		transportation of sludge, tailings, slimes or other solids
Flowmeters	The operation of any flowmeters needs to be checked regularly to ensure that inlet pipes are clear of obstructions and that silt and precipitates are not building up and preventing effective pump operations	Regular maintenance of return pumps and float switches is required to make sure that they are in full working order. The security of pump chambers and the condition of any inspection hatches should be monitored to prevent both vandalism and potentially damaging items from entering the chamber
Pipelines	The condition of all pipelines on or near embankment surfaces should be checked for joint failure, leakage or deterioration	The presence of any pipelines on the face of the embankment(s) increases the risk of severe erosion and instability if they should burst. These pipelines, and any exposed joints, should be checked to ensure that there are no leakages which might endanger the stability of the face or cause erosion
V-notch weirs	To ensure accuracy in measurement over a v-notch the crest of the weir should be sharp and there should be an air gap between the flow and the plate	The v-notch gauge board should be located at the correct distance upstream and silt should not be allowed to build up behind the plate. The approach channel should be cleaned out frequently, taking care not to dislodge the measuring staff. Where flow measurement via the v–notch is not practicable, seepage should be recorded by measuring the time taken to fill a one-litre beaker. This process should be repeated to ensure that the flow is correctly measured
Spillways, decant structures and waterways	The condition of the spillway and both inlet and outlet channels should be recorded to ensure that they are open, unobstructed and capable of carrying the design flow without endangering the confining embankment	The condition of the spillway and surround both upstream and downstream should be inspected and any abnormalities reported on the record sheet. The area downstream should also be inspected for any seepages related to the spillway structure. Such seepages should be noted on the inspection sheets and the MWF Manager advised at an early stage in order to avoid the risk of the structure deteriorating

(continued)

Table 7.5 (continued)

Category	Principal records	Inspection details
		All waterways should be monitored to ensure that they remain in good condition. The upstream and downstream channels should be inspected to make sure that there are no obstructions to flow, particularly vegetation or contractor's debris which could block either the inlet or outlet
Reservoir/pond level monitoring	A gauge board or other water level monitoring device should be installed in each reservoir, lagoon or pond. The board or similar instrument should be securely installed, set to minimum embankment crest level and marked with minimum safe freeboard based on peak inflow and local hydrology. Detailed operating rules and an emergency action plan should be prepared and provided together with appropriate training of all operators in the meaning of the gauge board and the emergency protocols	The gauge board should be securely installed in a location where it is permanently visible and can be regularly cleaned, and should be marked with coloured bands as follows: ● green, indicating safe (normal) operating water level ● orange, indicating warning (action) water level ● red, indicating emergency water level, i.e. exceedance of maximum permissible water level, defined as the minimum embankment crest level minus the defined freeboard
Reservoir level	Continuous reservoir level records are necessary as part of the overall embankment monitoring. Levels should be recorded in mOD using a gauge board or similar device installed within the facility, and be checked against the critical values identified in the flood studies	The reservoir level should not be allowed to exceed the maximum operating level, except where permitted during flood periods. If reservoir levels do exceed the critical value after a flood event, every effort must be made to reduce these as quickly as possible to below maximum operating level. The MWF Manager and/or IIE should be advised if the reservoir has not returned to, or below, maximum level within one week
Operating freeboard	The operating freeboard is the difference in elevation between the current and the maximum reservoir level, as defined in the operating procedures	Freeboard should be checked regularly, particularly during periods of heavy rainfall, and should be noted on the record sheet if it falls below the minimum value and the MWF Manager and/or IIE advised immediately
Active deposition	The active deposition and disposal pipelines should be monitored to ensure that both disposal methods and	For sub-aqueous deposits maintenance of the minimum cover depth should be checked and disposal points changed to prevent

(continued)

Table 7.5 (continued)

Category	Principal records	Inspection details
	hydraulic fill placement are compliant with agreed working procedures	the development of exposed deposits or extensive islands which may oxidise and lead to deterioration in water quality For sub-aerial deposition each disposal point should be checked to ensure that none is blocked, that excessive erosion is not occurring, reducing the efficiency of beach development, and that re-entrant or dead storage areas do not develop
	The minimum freeboard and maximum deposition levels should be maintained within each facility to ensure that the confining embankments cannot be overtopped or the waste exceed the planned level	Water levels should be measured daily on the gauge board installed for this purpose. Deposition into the facility should cease immediately if the freeboard is equal to, or less than, the permitted operating minimum. Where appropriate, the reservoir level should be drawn down to meet the operating criteria and to maintain levels within the recommended parameters
	The operating pipelines and valves should be checked to ensure that there are no leakages, pipeline movements or potential blockages caused by sedimentation	The operation of all pumps and valves should be checked regularly to ensure that they are fully functional, that access is not obstructed and that there is no indication of untoward interference
Haul roads and edge protection	Regular inspection of all embankment crests should be made while they are being used for site access or for transporting materials. The condition of all haul roads should be recorded on the inspection sheets	Note should be made of the general condition of all embankment crests and elevated berms and of any signs of instability or safety hazards for operating personnel. In particular, the condition of edge protection on all elevated access roads within the operating area should be noted. Failure to comply with operating rules or working procedures, and any change in the status of the berms or stockpiles which might pose a significant stability risk and require a geotechnical assessment, should be noted on the sheets

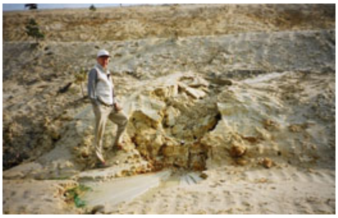
Category	Examples of specific inspection elements	
Face stability		
Crest movement		
Tension cracks		
Erosion gullying		
Face seepages		

Fig. 7.9 Examples of inspection elements

Category	Examples of specific inspection elements	
Toe seepages		
Seepage quality and quantity management		
Acidic seepages		
Geochemical effects on embankment rockfill		
Animal damage		

Fig. 7.9 (continued)

Category	Examples of specific inspection elements	
Damage caused by pipelines and valves		
Safety of old mine workings		
Reservoir level monitoring		
Site safety and security		

Fig. 7.9 (continued)

each month by the Departmental or Mine Manager. Typical monthly monitoring requirements are shown below:

(i) disposal pipelines—a monthly walkover survey of all disposal and water return pipelines should be undertaken in order to assess their condition, together with that of the valves, alarm systems and associated equipment;

(ii) diversion channels—diversion channels which carry catchment runoff around embankments during periods of heavy rainfall should be checked monthly and after heavy rainfall to confirm that they are free from debris and that no erosion damage has occurred which might limit their hydraulic capacity in the event of further rain;

(iii) instrumentation—the operation of all instruments installed within the embankments should be checked and a summary of the data submitted for review. Any faults on the system or apparent deterioration should be noted and the details recorded on the inspection report sheets so that remedial works can be instigated and operation of the instruments verified before the subsequent monthly inspection.

Table 7.6 Typical weekly monitoring of a waste facility

Category	Principal records	Inspection details
Return water pumps	All return pumps should be checked to confirm that the inlets are clear of obstructions and the return system fully functional. The condition of the float switches should also be checked to confirm that they are fully functional and operating to the required reservoir or pond level	The return pump flow meter recording running hours should be checked to confirm that they are being recorded as required
Surface water drains	The general condition of all surface water runoff and diversion channels should be checked	All secondary waterways should be reviewed weekly to confirm that they are clean and free from debris and have suitable hydraulic capacity
Seepage control sumps	All seepage control sumps and installations should be checked to ensure that the inlets are clear of obstructions and the return system fully functional. The condition of all float switches should be checked to confirm that they are fully functional and operating at the required water level	The internal condition of the seepage sumps should be checked to confirm that they are free from significant levels of precipitates or sediments which might affect their efficient operation. The inspection hatch should be tested to confirm that it is kept closed, and the return pump running hours checked to confirm that they are being recorded as required
Pumps and pipelines	The condition of all other pumps, pipelines, non-safety valves and flow control systems should be checked weekly to ensure that they are fully functional, that they can operate in accordance with the recommended rules and that there are no leakages	The pump running hours should be recorded as necessary
Safety and security	The inspection should confirm that all site boundaries are secure against third-party and animal ingress and that all safety equipment such as lifebuoys and warning signs are visible	The record sheets should record whether all fencing is secure, all safety equipment is in place and that there are no breaches of safety practices

These inspection reports should include the results of the physical inspection, together with a summary of deposition and instrumentation data and details of any health and safety or other issues. In addition, the report should include the results of any geotechnical appraisals or other investigations undertaken in the preceding month.

7.2.2.9 Internal Management Inspections

The operator may consider that a formal three-monthly inspection of the facility should also be undertaken by senior personnel to ensure that the regular monitoring and inspection routines are being undertaken appropriately and that nothing untoward passes unnoticed. These inspection reports should include an overview of the physical inspection, together with a summary of any stability, hydraulic, deposition, instrumentation, health and safety or other issues. The internally-managed inspections should be accompanied by a review and sign-off of the daily, weekly and monthly inspection records. The internal inspections should cover all parts of the facility and, again, the methods to be adopted and the records kept should be fully described in the Manual. The management inspection routines should facilitate the preparation of an annual report which, together with a summary of the data records, should subsequently be provided to the IIE/Competent Authority. Internal inspections and reviews should be carried out by personnel with documented competence in extractive waste, dam safety or environmental emissions as appropriate.

7.2.2.10 Annual Records

Annual testing of all emergency protocols should be undertaken, together with the operation of all safety valves to ensure that they would function in an extreme event and discharge excess water safely. The operation of any failsafe closure systems should also be checked, and the sensors confirmed to be fully functional. Details of the tests and of any concerns regarding the emergency protocols, the condition of the valves and their ease of opening should be recorded on inspection sheets. In addition, regular surveys of all embankments and waste facilities should be undertaken so that the instrumentation records and freeboard monitoring are kept up-to-date. The guidance below describes typical regular surveys which should be carried out annually:

(i) facility surveys—the plans showing the topographic details of all facilities should be kept up-to-date. Any significant changes in the layout or levels will mean that the facilities will need to be re-surveyed in compliance with statutory, regulatory or permitting requirements. In particular, it is essential that the crests of all embankments be maintained at the specified elevation and the minimum level be recorded;

(ii) embankment surface monitoring—the survey beacons installed on the crest and berms of the various embankment sections should be surveyed annually. If any disturbance of the beacons is noted they should be re-surveyed to establish the precise co-ordinates and levels. Surveys should then be carried out every four months until a suitable database has been reestablished. After this, surveys should be undertaken annually but the frequency should be kept under review in agreement with the IIE. The accuracy of these surveys should be recorded and any significant movements reported to the MWF Manager or IIE;

(iii) reservoir level gauge boards—the accuracy of all reservoir water level recording devices such as gauge boards and measuring staffs should be confirmed during the regular embankment surveys at a minimum of yearly intervals.

(iv) instrumentation (piezometer collar) levels—the elevation of all instrumentation such as standpipe piezometers and settlement gauges should be re-surveyed on a regular basis, and at least yearly, to ensure that the levels calculated for each installation within the dam are accurate. Other sensitive instrument installations may need to be surveyed annually in parallel;

(v) maintenance of surface monitoring points—the surface monitoring beacons and instrument boxes installed on the embankments and downstream should be maintained during the regular observations. In order to avoid deterioration, suitably secure caps should be retained on each survey or piezometer installation. Any missing caps or locks should be replaced immediately to prevent deterioration, and any damage reported on the inspection report sheet;

(vi) annual reporting—a summary of the previous year's inspection and monitoring records and instrumentation data should be prepared in advance of the inspection and reporting on the facilities by the IIE. This summary should include not only an analysis of the 12-month data record but analysis of these data against the design criteria, together with a register of compliance with the previous year's recommendations made by the IIE in his inspection report.

7.2.2.11 Maintenance and Remedial Measures

It is important that an inspection of a MWF and associated structures be undertaken in accordance with the inspection and monitoring procedures and criteria described in the Manual. Such inspections should be undertaken and recorded at the specified intervals, with additional visits following heavy rainfall or other exceptional circumstances, or should there be any untoward occurrence or concerns regarding the accuracy of the daily inspection records. In order for such inspections to be effective, the embankment faces and crests, as well as the toe area and the ground surrounding all critical structures, must be kept clear of undergrowth. The vegetation should be regularly strimmed or mown in order to effect inspection of the slopes and foundation areas for any untoward slope movements, seepages, animal damage or similar occurrences (Fig. 7.10). In particular, all saplings, deep-rooted shrubs and other invasive vegetation should be removed from embankment faces in order to:

- prevent deterioration and erosion;
- promote, where appropriate, the development of good grass growth;
- improve access for inspections;
- reduce maintenance costs.

Fig. 7.10 Crest of embankment obscured by vegetation

Fig. 7.11 Storage of materials against embankment toe

Further, the embankment toe area and surround should not be used for stockpiling materials or for parking site plant or machinery as this inhibits access for inspection and may obscure important detail (Fig. 7.11). Finally, the toe area should be kept in a drained condition so that untoward seepages are not obscured by inundation (Fig. 7.12).

Fig. 7.12 Toe inundation preventing detailed inspection

Fig. 7.13 Poor maintenance leading to uncontrolled discharges

Potential erosion-inducing features on embankment surfaces, such as oversized cobbles or boulders on sloping faces, should be removed. Untoward activity on the face, such as uncontrolled discharges of tailings or process water (Fig. 7.13), should be prevented as they may otherwise lead to erosion, gully development and potential slumping of the face.

Repairs to embankments or associated structures, other than the infilling of minor erosion gullies, should not be undertaken without the advice of the MWF Manager, the Designer and/or the IIE. It is important to determine the type and source of any cracks, settlement, seepage and erosion before repairs are undertaken as uncontrolled filling and reshaping can conceal problems. If, after consultation with the responsible person, it is decided that immediate action is required to prevent further damage, remedial works should be undertaken based on the construction specification, written instructions for the works or, as appropriate, on design drawings.

7.2.3 Independent Inspection Regime

Experience in a number of jurisdictions has shown the value of engaging suitably qualified independent professionals to undertake inspections and to report on them to the relevant bodies. The IIE ensures technical and Corporate assurance as well as providing confirmation of regulatory compliance to the Competent Authority. This independent expert is variously titled Inspecting Engineer, Competent Person or Independent Expert in the various domains, but in these guidelines the term “IIE” has been considered to be that most appropriate to cover the role described in the European guidelines (EC 2012) developed to address inspection issues defined in the EWD. This sub-section explores the role of the IIE and provides guidelines for minimum qualifications, outlines of the inspecting and reporting process, and presents the interaction between the recommendations and their subsequent enforcement.

7.2.3.1 Competence

It is important that a facility be inspected by an IIE with the relevant qualifications and experience and that this engineer is able to recognise good practice and to identify poor procedures and potentially serious defects so that these may be corrected and failures prevented. It is recognised that the range of skills and technical expertise required for an inspection of an extractive waste facility is broad, and thus it is unlikely that a practitioner with less than ten years’ experience will have the necessary knowledge to undertake the role. The minimum qualifications reflect the skills likely to be necessary to appropriately inspect and report on MWFs and to assess their potential environmental impacts. In particular, it is important that the IIE have a strong grounding in hydrology and flood management skills, together with geotechnics, mineralogy, waste characterisation and environmental impact assessment. The minimum qualification requirements are based on experience of inspection and reporting on large and high-risk extractive waste facilities worldwide. It is noted that these qualifications mirror those adopted by multi-national mining companies for their regular corporate risk assessments of mine waste facilities and mine sites in general.

The generally recognised qualifications which make for competence in an independent inspection of a Category A MWF, as implicit in the EWD, deliberately require practical industrial experience since competence on the grounds of academic ability alone is considered to be inadequate. The general qualifications are listed below:

- suitable engineering degree;
- professional qualification—requiring a minimum period of practical experience in industry, and being subject to a peer review process;
- design and construction experience of all facets of dam engineering;
- proven expertise (minimum of 10 years) of inspections of mine waste facilities;
- minimum of 15 years' experience of engineering aspects of mining projects, and specific knowledge of the geotechnical characteristics and behaviour of a range of extractive wastes from coarse rock to ultra-fine hydraulic fill;
- documented experience in relevant environmental aspects of mining projects, including waste characterisation, mineralogy, ARD, cyanide management, chemical management and environmental impact assessments, as appropriate.

Importantly, it is recognised that there may be a limited number of engineers who have the recommended qualifications specified and it is incumbent on the Competent Authority to ensure that the appointment, whether made by the operator or the authority itself, is appropriate for the facility in question and that the required practical skills and experience are available. Where the necessary expertise is not vested in a single person, groups of experts will need to be appointed to ensure that all necessary technical proficiency will be available during the inspection process.

7.2.3.2 Scope

The IIE for a facility fulfils an expert role during design and permitting, operation and post closure, (Cambridge 2017) as shown in Fig. 7.15. A review of the design process at permitting will enable an independent consideration of the engineering and environmental mitigating procedures proposed, and identify shortfalls in the design or long-term expectations for the facility or the planned waste management system. The IIE may advise the operator or permitting authority that modifications in the design or operational parameters are necessary in order to meet environmental requirements or to comply with good practice. It would then be for the Competent Authority to ensure that such recommendations be incorporated into the permit conditions.

During operation, the purpose of the regular inspection by the IIE is to ensure that the facility is safe and stable, both geotechnically and geochemically, and that not only is it fully compliant with the permit but is also being operated in accordance with good practice (Cambridge et al. 2006). The IIE may therefore identify areas where the operation is non-compliant and, in addition, where there are concerns that an untoward event might occur unless modifications to the facility were implemented. The IIE should make such recommendations in the inspection report and ensure that there is a timetable for corrective action.

It is also the role of the IIE to regularly review key design parameters such as hydrology, seismology or slope stability, particularly in the light of knowledge gained during the construction of the facility and the ongoing deposition of the extractive waste. In particular, hydrological re-assessments and the design of the

Fig. 7.14 The importance of inspection in reducing risk of instability

various waterways for the extreme event should be reviewed regularly, not just for water-retaining facilities and spillway or decant designs but also for stream diversions and pollution control structures. The inspection report should include the conclusions of such analyses and any recommendations arising, together with a timetable for corrective works where appropriate (Fig. 7.14).

The frequency of such inspections may reduce post closure, but the intent and scope would not be affected. In some instances, inspections may be required in perpetuity due to the long-term risks posed. However, in the majority of cases it would be the role of the IIE to ensure that the structures were compliant with the closure plan and that no untoward events were identified. Finally, it would be the role of this engineer to prepare the sign-off report stating that the facility were safe and stable and that it no longer posed an unacceptable risk to life or to the environment (Fig. 7.15).

7.2.3.3 Frequency of Independent Inspections

The frequency of inspections of operating facilities undertaken by the IIE on behalf of the operator would initially be defined by the permit (as referenced in the Waste Management Plan) and, in particular, by the risk categorisation. It is likely that in some jurisdictions a similar frequency of inspection regimes would apply to Non Category A facilities in cases where the risks posed are considered to require a higher level of observation and control. Non Category A facilities where a significant volume of water is stored above ground level may come into this category.

It may, however, be necessary to undertake updated risk assessments of mine waste facilities to ensure that any new, or previously unknown or unidentified, hazard is then addressed by existing procedures. The IIE should therefore review the risks posed at each inspection and recommend changes to their frequency where the risks or the structural condition of the facility indicate the need.

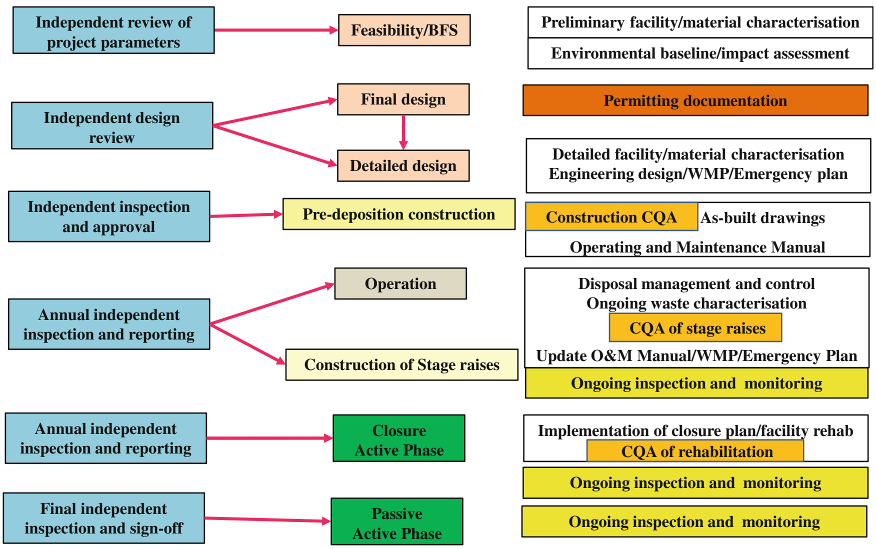


Fig. 7.15 The role of the IIE from permitting to closure (Cambridge 2017)

7.2.3.4 Inspection Procedures

The site inspection visit may require significant preparation and planning from the IIE, who will be expected to review all site data and to personally inspect all relevant facets of the facility. The Waste Management Plan and the Manual would normally be used to provide background to these inspections, and the performance of the facility would be assessed against these parameters to enable compliance with design and permitting objectives to be confirmed. To this end the operator should prepare in advance a synopsis of all relevant inspection and monitoring data and instrumentation records, and provide this to the IIE before the inspection. Where necessary, additional data or sampling may be sought during the inspection for confirmatory purposes.

On completion of the inspection the operator should arrange a round-up meeting in which the preliminary results and recommendations of the inspection process are discussed with the relevant site personnel. This meeting provides the opportunity to review any safety or stability issues which require urgent attention, and also for additional data requests to be made. This meeting should be fully minuted for inclusion in the final inspection report. The programme for inspection and reporting by the IIE is shown in Table 7.7.

Table 7.7 Programme for inspection and reporting by IIE

Inspection phase	Activity
Pre-inspection planning	Preparation and issue of pre-inspection data request to operator
	Scope inspection visit following review of the data provided
Site inspection	Site inspection by IIE
	Presentation of initial findings at minuted final site meeting
Inspection reporting	Issue of draft inspection report to operator for comment
	Finalisation of inspection report and issue of signed/certified report to operator
	Issue of Executive Summary report to operator for comment
	Issue of signed/certified executive summary to Competent Authority
Remedial programme	Issue of notice and programme for any necessary safety, corrective or compliance measures to operator
	Supervision of safety, correction or compliance measures by IIE
	Issue of Certificate of satisfactory completion of safety, corrective and compliance measures to operator by IIE
Enforcement programme	Issue of enforcement notice by Competent Authority following non-compliance with safety, corrective and compliance measures by operator

7.2.3.5 Reporting

The preparation of the inspection report will involve significant data review and analysis, and may from time-to-time require stability assessments and hydrological reviews. The report should include in summary the appraisal of all the information obtained and should identify any shortfalls, whether in the inspection regime, operations or sampling. Typical contents of the IIE's inspection report are shown in Table 7.8. It is not anticipated that stability or hydrological reassessments will be required where inspections are undertaken annually, but the IIE should ensure that such reviews take place, at minimum, at five-yearly intervals, or ten-yearly where the risk is deemed to be low. Clear and concise conclusions and recommendations should be prepared for inclusion in the report, which should be issued to the operator in draft for comment to ensure that there are no inconsistencies or misinterpretation of data. However, it is considered unlikely that such a review of the draft would lead to modification of the conclusions or recommendations. The final report should be issued promptly, but no later than six months from the date of the site visit, and should include an Executive Summary for issue to the Competent Authority and for publication. It is NOT considered appropriate for the full report to be made publically available other than in exceptional cases, e.g. a public enquiry or in a similar legal context.

If the inspection by the IIE has been contracted by the Competent Authority as a regular inspection or to validate the monitoring and inspection report provided by the operator, the report should be submitted directly to that Authority.

Table 7.8 Typical contents of the IIE's inspection report

Section no.	Section headings
1.	Name and location of mine waste facility:
2.	Name and address of IIE:
3.	Qualifications of IIE: Date of appointment as IIE Date of expiry of statutory appointment
4.	Name and address of Operator who appointed the IIE:
5.	Name and address of Enforcement Authorities:
6.	Name and address of Responsible Contacts: Owner/Operator Mine/Quarry Manager Deputy Mine/Quarry Manager Mill Superintendent Facility Supervisor
7.	Date of Inspection:
8.	Background:
8.1.	The Terms of Reference, i.e. legislation/regulation/compliance/post incident reporting
8.2.	Scope of Inspection
8.3.	Documentation
9.	General description:
9.1	Description of the facility
9.2	Catchment
9.3	Geology
9.4	Details of modifications, remedial works and history, recent reports and investigations
9.5	Embankment details, main confining embankment, decant system, tailings disposal system, emergency spillway, etc.
9.6	Access details
10.	Description of inspection and conditions found:
10.1	General
10.2	Confining embankment(s), main embankment, saddle dams, disposal paddocks/lagoons
10.3	Spillway arrangements, decant system, emergency spillway
10.4 10.5	Reservoir area Return water system
10.6	Tailings deposition
10.7	Old workings
10.8	Inspection and monitoring routines
10.9	Instrumentation, surface/hydrographic survey, piezometers, seepage, freeboard
11.	Review of flood and discharge capacity:
11.1	Hazard categorisation
11.2	Flood study

(continued)

Table 7.8 (continued)

Section no.	Section headings
11.3	Alterations to overflow sill or to the level of water that may be stored
11.4	Means of lowering the water and of controlling the inflow
12.	Seismic risk:
13.	Supervision provided by the Operator:
14.	Correctness of particulars in the statutory record:
15.	Findings and recommendations of the IIE:
15.1	Conclusions
15.2	Recommendations in the interests of safety and timetable for completion
15.3	Recommendations not in the interests of safety
16	Date of next inspection:
17.	Figures/Plans:
18.	Photographs:
Appendices	

7.2.3.6 Recommendations

The most important outcome of the inspections by the IIE is the findings summarised in the Conclusions and Recommendations and, in particular, any measures which are identified as to be taken by the operator "in the interests of safety". Recommendations for modifications to any aspect of the management, operation or inspection and monitoring of the facility should be identified in the report conclusions as being either in the interests of improving operational efficiency or "in the interests of safety". It is therefore anticipated that the IIE would provide the following as part of these recommendations:

Recommendations in the interests of improving operational/environmental performance

These recommendations would relate to non-urgent aspects of the operation or management of the facility. A general guidance timetable for the implementation of these measures should be included, and should be defined to suit the operator's programme and resources, but must be in accordance with good practice. However, recommendations should in general be satisfactorily completed prior to the next inspection by the IIE. Where such measures were of any significance, the Competent Authority would need to be advised of their extent, the reasons for their execution and the proposed timetable. It is anticipated that the Competent Authority would track the measures to ensure that they were completed within the specified time-frame.

Recommendations in the interests of safety

These recommendations would concern issues relating to safety, stability or environmental performance which require to be addressed with a degree of urgency. It is essential that such issues be discussed directly with the operator and that the IIE provide a strict timetable for completion of such works, preferably during the inspection. The key stages of the works at which a further inspection of the specific elements of the facility is to be carried out should be indicated. The Competent Authority should be advised of the extent of such works, the reasons for their execution and the recommended timetable. It is anticipated that the Competent Authority would then track the works assiduously to ensure that they were completed within the specified time-frame. On completion of the works the IIE would undertake a follow-up inspection in order to prepare Certification that the measures had been satisfactorily carried out and that the facility were fully compliant at that date. The Authority should then receive a copy of this Certification.

Specific issues related to extractive waste phases

These issues would be recommendations concerning aspects of specific phases of the operation and deposition cycle which raise particular issues of concern and importance.

The recommendations included in the inspection report should be reviewed annually by the IIE and a record in the form of a compliance register made of the satisfactory completion of each where applicable. This record should then be made available for review at the subsequent inspection and appended to the inspection report. Where the recommendation has not been addressed the register should provide a clear and concise summary of the reason and of any interim mitigation measures taken (Table 7.9).

Table 7.9 Outlines of inspection and reporting procedures during the life of a MWF

Stage of facility	Outline details
Pre-deposition stage	The design details of the facility, together with the Waste Management Plan and the initial version of the Manual, would be prepared and submitted during the permitting stage. The independent review and certification of the design should be undertaken on behalf of the owner or Regulatory Authority by a suitably competent IIE. The document prepared by the IIE and submitted to the Competent Authority for approval would therefore need to include the design Certification, together with a programme for the inspection and Certification of the pre-deposition works
Operational stage	The annual inspection of the operating facility would include a review of the operator's annual report on the monitoring of the MWF, of the CQA data for any staged raise undertaken during the previous twelve months and a reassessment of the flood standard and freeboard criteria for the facility. The report would include an Executive Summary for issue to the Competent Authority
Closure	The operator should ensure that the facility has achieved the pre-closure design stage in the period immediately preceding cessation of deposition of the hydraulic fill and the initiation of the closure plan. Once deposition has ceased and the closure plan been initiated, the need for inspection should be re-defined in accordance with the permit and the approved closure plan. The inspection regime at each level would be site-specific and based on the extent of the facility and the residual risk. At the highest risk level (which includes all Category A facilities) it is normal practice for the Competent Authority to receive a final closure report prepared by the IIE to be completed at the cessation of operations. This report would use as its basis both the ongoing operating inspection reports prepared by the operator and

(continued)

Table 7.9 (continued)

Stage of facility	Outline details
	the closure plan itself, and would determine whether the Competent Authority would need to undertake an inspection at this stage. The facility becomes less dynamic as the closure plan is instigated and it is likely that the frequency of inspection and monitoring would be reduced as the associated risks and level of the hazard potential decrease. However, some quality control monitoring would be required where the closure works were of a significant extent or involved complex engineering works. These works would then also be subject to approval by the Competent Authority based on a report submitted by the IIE. A joint inspection involving the Competent Authority, the IIE and the operator would almost certainly be required at the end of the closure period so that the necessary reporting and Certification could be provided and the level of monitoring and intervention during the post-closure period agreed
Post closure	A period of monitoring would be required on completion of the closure works in order to confirm the competence of the engineering and compliance with the closure objectives and would continue, albeit at a lesser frequency. Independent inspection and reporting by the IIE would also continue to be required, initially annually but reducing to between five-yearly and ten-yearly dependent upon the risk the facility posed and the results of the closure monitoring. The facility would continue to receive inspection and monitoring by the owner's team and, from time-to-time, by the IIE until the site were considered to be safe, geotechnically and geochemically stable and no longer to represent a significant risk to human life or to the environment. The owner would, for the duration of this period, continue to report the results from the monitoring and inspections to the Competent Authority. At this stage it would be anticipated that the final series of inspections and Certification would be prepared before the facility were finally handed over to any future long-term owner

The EWD covers mine waste facilities at the pre-deposition stage, at operation, at closure and post closure, together with abandoned facilities. Table 7.9 provides the outlines of the generic approach to the inspection and reporting by the IIE at each stage of a mine waste facility with guideline frequencies included in Table 7.10.

Table 7.10 Example of inspection frequency for all project phases

Inspector	Phase				
	Operational	Active closure	Passive closure	Passive closure	Sign off
	LOM	Years 1–5	Years 6–10	Years 11–24	Year 25
IIE	Annual	Annual	Biennial	Five-yearly	Final inspection
MWF supervisor	Daily	Daily reducing to weekdays only	Fortnightly	Monthly	Monthly
MWF Manager	Monthly/ three-monthly	Three-monthly	Annual	Biennial	Final

7.3 Instrumentation

7.3.1 Performance Monitoring

For each MWF the design will require the regular measurement of key parameters (ICOLD 1996). The design should therefore include the installation of instrumentation to record the operational parameters, either continuously or at specified intervals. Typical instrumentation and monitoring details for a large MWF and for a quarry silt lagoon are shown in Table 7.11. Note that the installation of ALL instrumentation should be suitably recorded and the subsequent CQA data record filed in the quality file.

The performance monitoring of many of the specified parameters may be combined with the daily inspection routines but, due to the nature of the parameters, others may be recorded weekly, monthly or in some instances such as hydrographic surveys, annually. The function and key operating parameters are detailed in Table 7.11 and the principal monitoring data sets are summarised below:

- surface and sub-surface settlement and movement;
- seepage volume and quality;
- piezometric levels;
- reservoir level;
- return water discharge flow and quality;
- seismic disturbance;
- production tonnage and hydraulic transport flow;
- spigot and cyclone performance;
- hydraulic fill characteristics and in situ density;
- effluent recycle;
- construction CQA;
- water-borne emissions quality;
- airborne emissions quality;
- river flows and quality;
- groundwater levels and quality;
- climatic data.

Such a monitoring programme is intended to indicate changes and to provide early warnings which could signify potential operating, safety or environmental problems and, in addition, provide the basis for assessment of overall performance and long-term condition. The scope, intervals and type of measurements should be adapted to the classification of the facility and to the specific situation at each. Monitoring and review should be carried out by personnel with documented competence, and regular peer review of all instrumentation performance and records is essential.

Specific monitoring programmes should be established for each extractive waste facility, updated as required to suit data records, as a result of recommendations received from the IIE following the regular inspections or following the issue of an enforcement notice prepared by the Competent Authority. Data such as piezometric levels or seepage volumes should be recorded, verified and plotted on a continuous basis such that trends can be established. It is generally helpful to include reservoir levels and rainfall on such data plots for comparative purposes. Regular survey of the datum for key instruments such as standpipe piezometers and other surface instrumentation is required, together with checks on the accuracy of the equipment. The datum of all instrumentation, particularly piezometer collars, must be recorded on every record sheet, and new survey data obtained before the next date of each reading if any suspected movement of the installation takes place. The instruments installed within the embankments and downstream should be maintained during the regular observations. In order to avoid deterioration all instrumentation locations should be kept in good condition and secure from untoward interference. Any noticeable interference or damage to the installations should be reported in order to avoid a disruption of the data record. Items such as secure end caps on surface mounted piezometers or survey monitoring beacons should be regularly checked and all instrument boxes kept firmly locked. Any missing caps or locks should be replaced immediately and any deterioration or damage be recorded on the monthly inspection report sheet.

Automatic monitoring will, in many cases, generate computer records for some instrumentation data or for topographic surveys, and paper records may not always be necessary. However, it remains important that the computer records be generated in a format which ensures that a satisfactory analysis of the data can be performed and it be shown that there are no untoward signs. Routines for reporting, quality control and data evaluation need to be established such that management overview is simplified. In particular the rate of data collection from automatic recorders must be reviewed and an appropriate frequency agreed such that the results are not obscured by excess numbers which might otherwise disguise the important trends. Recording piezometric levels from a vibrating wire instrument at 15-min intervals will in most cases not improve the record, which could equally have been obtained from daily data without loss of accuracy or sensitivity. Further, a plethora of data may serve to highlight instrument/automated data collection issues and thus prevent the important results from being analysed. The Manual should establish strict protocols for both installation and monitoring as well as establishing trigger values, with both action and emergency levels indicated. The action and emergency levels should be accompanied by reporting and emergency procedures. Evaluation should be carried out continuously by qualified personnel and should be overviewed and signed-off regularly by management with all data retained in the CQA files, which should be suitably future-proofed.

Monitoring data should be compiled on a regular basis and reported internally to the MWF Manager, and an annual summary report prepared for issue to the IIE and to the Competent Authority as appropriate.

The monitoring programme should be set up in order to maintain a record of the condition of the facilities and to provide data for ongoing stability, flood and storage risk assessments, linked with the inspection procedures detailed above. Brief details of the monitoring devices installed and of the operation and maintenance of each are given in Table 7.11.

Table 7.11 Typical instrumentation details for a MWF

Parameter	Instrumentation	Function
Surface movement	Surface beacons Extensometers Reflector-less laser mapping Synthetic Aperture Radar (SAR) Global Positioning System (GPS) Surface tiltmeter	Instruments should be installed on the crest and berms of all embankments in order to monitor any movement of the dam surfaces. The instruments should comprise robust units located to avoid disturbance by vehicle movements. Three-dimensional surveys using these instruments should be undertaken annually or as considered appropriate following data review. The surveys need to be related to a control point which has been accurately tied into the mine grid and is located off the main embankment. The movement accuracy needs to be defined and should be at least ±5 mm in three dimensions in order to ensure the correct interpretation of data from regular monitoring. The continued monitoring of the beacons will enable any movement of the embankment to be noted and appropriate remedial action taken at an early stage
Sub-surface movement	Slope inclinometers Settlement gauges Time domain reflectometry Micro-seismicity Ground penetrating radar	Slope inclinometers and settlement gauges may be installed within the embankments, deposited hydraulic fill or foundations to monitor the internal deformation of the facility. Such measurements enable both total and incremental movement to be assessed and are an important stability parameter in sites with an elevated seismic risk. The installation of such devices is important in areas of historic mining where such workings may extend beneath the facility
Pore pressures	Standpipe piezometers Hydraulic piezometers Pneumatic piezometers Vibrating-wire piezometers	Piezometers should be installed within the embankments, foundations and the deposited hydraulic fill in order to monitor pore pressures within the soil mass. The instruments should be installed to an appropriate specification and the associated data be filed in the CQA register. Care is needed to ensure that the appropriate piezometer be installed in the MWF and its foundations as some types desaturate very quickly and stop working if the pore water pressure drops below atmospheric pressure for any length of time. Piezometers are read either from a remote data device or in situ in the case of standpipes, or where installation locations prevent a suitable datalink. The pore pressures should be measured using the equipment supplied by the manufacturer, and the data recorded at regular intervals as determined by the designer or following recommendations by the IIE. Note that standpipe piezometers often form the primary groundwater piezometric monitoring system for the facility, enabling sampling as well as pore pressure monitoring. These piezometers should either be recorded manually using a probe, which is lowered down the standpipe tubing, or via a pressure gauge screwed into the surface fitting. The data

(continued)

Table 7.11 (continued)

Parameter	Instrumentation	Function
		should be recorded against an accurately defined datum level (top of standpipe) which requires regular surveying to confirm elevation
Seepage measurement	V-notch weirs Rectangular plate weirs Open pipes (stopwatch and measuring cylinder) In-line flowmeters Pump operating recorders	Seepage discharge channels are generally located at the toe of the confining embankment and the flow measurements constitute a primary record in terms of dam safety and stability. Readings should be taken accurately, generally daily and, in the case of weirs, on the appropriately-located gauging staff. To ensure accuracy in measurement, silt should not be allowed to build up behind the weir and the channel should be cleaned out frequently, taking care not to dislodge the measuring staff. Any measuring staff should be cleaned regularly to facilitate reading, and be checked for accuracy. A replacement staff should be available for use if excessive corrosion or staining prevents accurate readings from being taken
Reservoir level	Gauge board Ultrasound devices	Water level monitoring devices should be installed in all critical reservoirs at suitable locations. Gauge boards need to be located such that they can be read easily, are protected from damage and can be cleaned on a regular basis to ensure that the water level can be accurately recorded. Potential inaccuracies in level recording by ultrasound devices in water bodies where precipitation of gypsum or other salts is likely should be confirmed prior to installation
Flowmeters	In-line flowmeters Pump operating recorders	Pipeline flows may be continuously monitored by flowmeters which record instantaneous discharges or operating hours. Calibration of the flowmeters is essential in order to ensure that accurate flows are recorded. Note that regular inspection and maintenance is required to ensure that silt or precipitates do not lead to reduced flow and an underestimate of discharge
Seismographic recorders	Embankment seismographs	Seismographic recorders may need to be installed on the principal embankment with a separate base station on stable ground off the facility. The data is generally collected remotely and is often tied into the national seismic event-recording network. These instruments are delicate and expensive to replace, and thus regular inspection is required to ensure that they are protected from damage during any works in their vicinity. It is noted that both seismographs must be fully functional in a seismic event if the data are to be useful for subsequent stability-verification checks
Weather station	Temperature Rain gauge Evaporation pan	The weather station should be located as close to the MWF as practicable and readings of rainfall, temperature, humidity and evaporation taken, as appropriate, on a daily basis and be included on the site inspection records

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Chapter 8
Specialist Application of Hydraulic Filling Techniques

Mike Cambridge, Gavin Ferguson and Jonathan Roberts

The objectives of this Chapter are to provide guidelines to the hydraulic filling techniques for materials derived from both the broader extractive waste sector and the non–extractive industries. The common element between these sectors is the production and engineering of fine particulate wastes and their storage in a safe, stable and environmentally acceptable location. This Chapter therefore applies to practitioners in the energy and other extractive industries where similar techniques may be applicable and for which no other European guidance exists. It is recognised that the guidelines provided relate to specific uses of hydraulic filling techniques and that there are other industries for which they may be applicable.

This Chapter includes a brief description of the following:

- Industrial minerals and aggregates industry wastes—background and context only
- Fly-ash
- Hydraulic backfill in underground workings

8.1 Industrial Minerals and Aggregates Industry Wastes

The non-metal extractive industries, including industrial minerals and aggregates, include a wide range of extraction and refining techniques which require similar processes to those described for metal mining. The residues from the processing of these extractive operations produce a comparable waste product which is regulated by the EWD and thus requires disposal in a controlled extractive waste facility. The range of the non-metal extractive industry operations in Europe covers a broad spectrum of production rates and waste-to-mineral ratios and thus the resulting

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MWFs extend from some of the largest in Europe to low-height, low-volume facilities common to quarried aggregate sites. The process residues may be produced by a simple crushing and gravity separation process, as for many aggregates, or involve a complex flow sheet covering a range of refining processes including gravitational separation, flotation circuits, acid leaching and magnetic separation. In general, these residues constitute a lower proportion of the processed geological material, being as low as 10% of the extraction on some sites compared with >95% for most metal mining operations. Further, due to their geological origin, many of the processes produce a finer residue containing a larger fine fraction and a higher proportion of true clay particles (clay minerals as opposed to clay-sized particles). The sites may therefore present some of the more difficult hydraulic fills to handle in terms of density and consolidation and the closure of many such facilities represents an engineering challenge. For this reason the wastes on many sites are discharged as a low-density slurry from the screening/washing/process plant into a series of lagoons rather than into a single large MWF, as is common on most mine sites. Hydraulic disposal into a series of lagoons can be advantageous for projects with a low throughput, high water content and an elevated clay fraction. A system of successive settlement, sedimentation and gravity decanting of the supernatant water, rather than more sophisticated disposal processes, provides a low-cost minimal management solution which has been proved to be cost-effective.

Most industrial minerals and aggregates industries use similar hydraulic transport and placement systems to those described in these guidelines, though for the most part the hydraulic fill is produced as a low density slurry and transported in pipelines under gravity to the disposal area rather than being pumped as a thickened waste. As for metal mining, a facility for these hydraulic fills is intended to act as a simpler thickener, with sedimentation taking place progressively throughout the waste circuit. The intention is to achieve a clean water lagoon at the end of this process for either discharge into the environment or for recycle. Therefore in its simplest form the hydraulic placement of the waste is by gravity discharge from a single open pipe at the head of a lagoon towards a fixed decant. The overflow is then discharged into a succession of similar lagoons downstream in order to achieve satisfactory clarification of the effluent. In theory, this system requires a series of lagoons with increasing settlement areas in order to reflect the reduced settling velocity required to effect sedimentation of successively finer particles. The final effluent may, subject to quality, be discharged into the environment downstream or, as appropriate, re-used in the washing and processing circuit.

Some industrial minerals projects may require larger and more complex MWFs of a size and structure comparable with those for the metals industry. The residues arising from processing of such industrial minerals therefore require similar techniques of waste and facility characterisation to those described in Chaps. 4, 5, 6 and 7. Such MWFs are also subject to the provisions of the EWD and therefore similar standards for the design, operation, inspection and monitoring and closure are applicable. Further, the additional requirements for waste management plans, emergency planning, financial agreements and regulatory inspection will apply to all industrial minerals and aggregates industry Category A waste facilities.

8.2 Power Station Fly Ash

Coal-fired power stations produce ash residues which require either disposal into a suitably engineered facility or are recycled for use in the construction industry. Two particulate residues are generated by combustion, namely:

- fly ash, also known as pulverised fuel ash (PFA) in the United Kingdom, which is driven out of the boiler with the flue gases and usually captured by electrostatic precipitators or other particle filtration equipment before these gases reach the chimneys of the power plant. This waste product is comprised of fine spherical particles, the diameter of which vary with the source of the coal burned at the power station but are typically between 2 and 10 μm;
- furnace bottom ash (FBA) comprises the ash which falls to the bottom of the boiler and is a coarser product. FBA has a larger particle size, typically between 35 and 150 μm, and is usually removed from the bottom of the boiler with the fly-ash.

Although these ash products are sometimes combined during removal from the bottom of the power plant boiler they are usually disposed of separately due to the significant difference in particle size. This section primarily addresses the disposal of PFA as it constitutes the primary element of the hydraulic fill emanating from a power station.

8.2.1 Transport and Storage of Fly Ash

Historically, PFA was released into the atmosphere with the flue gases, but increasing air pollution control standards now require that it be captured prior to release by fitting suitable control equipment. A significant proportion of PFA is recycled as a construction fill material or used as a pozzolan to produce cement and plaster and as a replacement, or partial replacement, for Portland cement in concrete production. The fly ash for disposal is generally either stored at the power station site at which it is produced, often using dry disposal techniques, or in more remote waste facilities is transported hydraulically to a depository. The two waste storage systems can be summarised as follows:

(i) Dry disposal at or near to the power station involves transport by lorry or conveyor to the repository and disposal in engineered embankments, the ash being spread and compacted in thin layers with or without the addition of water to aid compaction. The deposited ash is formed into a mound with gentle slopes and the surface treated to prevent erosion. This is generally the cheapest method but is reliant on a suitable land area being available for the MWF. Dry disposal provides improved storage efficiency with between 30 and 40% higher volumes being stored on a similar footprint due principally to the increased height of the mound. The dry disposal method also offers the advantage of minimising the risks associated with poor quality seepages and contamination of groundwater.

(ii) Hydraulic disposal into a remote site involves pumping the PFA in slurry form via distribution pipelines for ultimate discharge into lagoons where it is allowed to settle in a similar manner to fine extractive wastes. This method of disposal mirrors the technology in use for the hydraulic transport and placement of extractive waste except that dewatering of the slurry at the facility is sometimes undertaken to enable subsequent dry disposal, albeit at a higher unit cost.

8.2.2 Regulatory Context

The proportion of fly ash which is not recycled needs to be disposed of in appropriate waste facilities. In Europe design, construction and management of active fly ash lagoons and the associated impoundment structures are regulated through the Extractive Waste Directive rather than by national reservoir legislation (Cambridge 2008). In the UK this regulation is undertaken through the Environmental Permitting (England and Wales) Regulations 2016, the updated EWD transposition legislation, which is enforced by the UK Environment Agency. Whilst fly ash lagoons are generally specifically excluded from national reservoirs legislation, it is accepted as good practice that they should be designed, constructed and operated in accordance with comparable standards to a large raised reservoir and be managed in a similar fashion to a mine waste facility.

8.2.3 Material Characterisation

8.2.3.1 Investigation and Sampling

The characterisation of all geotechnical and geochemical properties of fly ash is necessary to understand its behaviour throughout the life-cycle of a project. As described in Chap. 4, the success of a characterisation programme relies on being able to test the full range of materials to be encountered, namely:

(i) foundation materials beneath the MWF, including both superficial deposits and the solid geology;
(ii) all construction materials for incorporation into the confining embankments and associated structures;
(iii) representative samples of all extractive waste materials to be deposited, confined or stored.

Of particular significance for fly ash is the need to obtain suitable samples for testing which accurately reflect the physical and chemical properties. The sampling campaign therefore needs to be properly planned and the investigation and protocols include specification for the preservation, transportation and storage of materials so that no alteration or degradation, either physical or chemical, occurs before they are tested in the laboratory and that no significant change in material parameters is experienced.

During operation, geotechnical sampling will normally be performed in order to confirm the parameters used for initial design purposes as well as for those associated with future embankment raises. The fly ash should be sampled for characterisation both as a slurry from source, i.e. at the outlet from the power plant and as a settled solid fraction from the deposit. Standard ground investigation boreholes are appropriate for confirming the physical characteristics of the embankment construction materials and both structural and low permeability (core) zones. Standard Penetration Tests (SPTs) may be used to determine the relative density of the fly ash where it is unsaturated. However, where the hydraulic fill is saturated, conventional cable percussive boreholes and SPTs do not provide representative indications of in situ strength due to the dynamic effects, which cause liquefaction of the fly ash at depth. In these conditions the piezocone (CPTu) provides a more reliable indicator of in situ strength.

The difficulty of obtaining representative undisturbed samples of fly ash from conventional boreholes is recognised and the most effective method of assessing the in situ properties is from block samples taken from trial pits. These may provide suitable material for shear box testing as it is noted to be difficult to replicate in situ strength from remoulded samples of fly ash. However, a cautious approach is necessary when using in situ tests designed for natural soils to infer material properties for fly ash.

8.2.3.2 Chemical Properties

Fly ash at source is strongly alkaline, exhibits a pH value of between 9 and 11 and is composed of substantial amounts of silicon dioxide (SiO_2), both amorphous and crystalline, aluminium oxide (Al_2O_3) and calcium oxide (CaO), the main mineral constituents of coal-bearing rock strata. The additional minor elements which, depending upon the geological origin of the strata, may be present include trace concentrations of up to 100 ppm of the following:

- arsenic;
- beryllium;
- boron;
- cadmium;
- chromium;
- hexavalent chromium;
- cobalt;

- lead;
- manganese;
- mercury;
- molybdenum;
- selenium;
- strontium;
- thallium;
- vanadium.

There may also be very small concentrations of dioxins and PAH compounds. The proportions of each mineral in the PFA vary considerably depending upon the source and makeup of the coal. In addition, some trace elements are naturally radioactive, and these include uranium (U), thorium (Th) and their numerous decay products, including radium (Ra) and radon (Rn). However, the majority of the radioactive elements in coal are released from the original matrix during combustion and are distributed between the gas phase and solid combustion products (PFA), with most fly ash not being significantly enriched with radioactive elements in comparison with common soils or rocks (USGS 1997).

As indicated, a significant proportion of PFA is recycled and the physical, chemical, and mechanical properties are delineated in appropriate ASTM and other standards. For example the two classes of fly ash to be used in concrete (ASTM C618) are classified as follows:

- Class F fly ash is defined as pozzolanic, with little or no cementing value and is usually derived from the burning of anthracite or bituminous coal;
- Class C fly ash is defined as having self-cementing as well as pozzolanic properties and is usually derived from the burning of lignite or sub-bituminous coal.

8.2.3.3 Physical Properties

Ash-lagoon-specific geotechnical properties are defined as follows:

In Situ Density

The dry density of the hydraulically placed fly ash, and of that which forms the confining embankments, is an important parameter. Values of dry density can vary over a wide range and are a function, in particular, of the grain size. Low values of dry density can be attributed to the spongy, porous nature of the ash particles, the presence of cenospheres and the unburned carbon content. Different coal sources can have a marked effect on the in situ properties and thus a review of source materials is essential. Regular testing should be undertaken, with additional analyses required when the source changes.

Strength Parameters

Fly ash as an embankment fill material exhibits a significant gain in strength with age due to the self-hardening properties, related partly to soil-suction and partly to pozzolanic effects. However, this gain is also accompanied by an increasingly brittle response, with some ash tested reaching peak stress at less than 0.5% strain. There is also a substantial strength loss with rising water content since the gain from soil-suction will be negated.

Fly ash also exhibits significant effective cohesion, primarily as a result of self-hardening characteristics, and the evaluation of this parameter is critical in the stability assessment for economic design. However, the amount of cohesion which can be relied upon for embankment design needs to be interpreted with caution as, due to its brittle behaviour, the post-peak strength of the fly ash can be very much less than the peak strength at higher strains.

Brittleness

Brittleness can be defined as an inability to resist the development of cracks and is characterised by Griffiths-like fractures which, once initiated, will propagate rapidly and may lead to sudden failure. One of the essential factors of brittle behaviour is that the material will fail at levels of applied stress which may be significantly lower than the general yield strength of the material. This brittleness increases with the cementation of the PFA, often with age. The effects of cementation are observed during investigations at lagoon sites, particularly in trial pits and other excavations which exhibit stable vertical faces over a considerable time. The effect of the brittle behaviour may be demonstrated effectively in shear box tests by continuing the test beyond peak strength to the full travel of the shear box. However, for re-compacted samples which exhibit limited cementitious properties, testing in small shear boxes results in some reduction in post-peak strength and the behaviour is not obviously brittle.

Liquefaction Potential

Though some properties of fly ash can be generalised, site-specific sampling and testing are generally required for the assessment of static and seismic liquefaction potential. The response of hydraulically deposited fly ash to loading is a function of both the configuration of the site-specific containment facility and the characteristics of the material. The design of the engineered works associated with the development of such facilities needs to take account of the fly ash-specific response to static and dynamic loading, both in terms of magnitude and rate.

It is noted that some work (Amaya et al. 2013) suggests that fly ash does not exhibit a ‘brittle’ response, i.e. that there is no substantial difference in the peak and post-peak undrained shear strengths during triaxial testing, and that fly ash specimens do not generally exhibit the strong contractive response to loading necessary for static liquefaction. The physical characteristics of fly ash therefore underline the necessity of assessing stability issues at each fly ash disposal facility in order to take account of the different sources and properties which may be present. However, fly ash may exhibit diagenetic cementation and, as a result, there may be a critical load which could lead to sudden collapse. If ignored during design and construction, this could lead to localised or widespread instability. Likewise, uncontrolled construction or development activities may lead to rapid build-up of pore water pressure in the fly ash, which can in turn also lead to instability.

Determination of Free Lime Content

The free lime content is an important parameter in determining the capacity of a particular sample of fly ash to exhibit cementitious properties. A pozzolanic reaction is one in which siliceous material reacts in the presence of moisture and calcium to form compounds exhibiting cementitious properties. The engineering performance of fly ash is improved with time by virtue of the pozzalanic reaction. To determine the impact and extent of potential cementation and self-hardening of the fly ash, tests to determine the free lime content should be undertaken regularly (BSEN 451-1 2017). These should be supplemented by additional analyses when the source changes since the free lime content may vary widely between coal deposits.

8.2.4 Disposal Principles

The disposal of fly ash in power station ash lagoons mirrors the technology in use for the hydraulic transport and placement of extractive waste (Figs. 8.1 and 8.2). As for a MWF, therefore, the design of both confining system and depository requires specialist expertise which needs to take into account the site setting, topography, climate, hydrology and seismology as well as project-specific data such as production rates, storage volume, permit requirements and environmental considerations. The design of the facility also needs to take into account any potential changes which may occur over the lifetime of the disposal facility.

Hydraulic disposal generally takes place behind confining embankments from a single open-end point, resulting in the development of peripheral beaches which slope towards the final settling pond in the location of the decant. Excess water is decanted from the pond via an outlet pipe located within the lagoon. When the

Fig. 8.1 Hydraulic disposal of fly-ash

Fig. 8.2 Beach development in a fly-ash depository

deposit reaches the maximum permitted level, a number of options for extending the facility are available:

(i) construction of a new lagoon, using conventional construction materials;
(ii) excavation for dry disposal of the previously-deposited ash following a period of drainage;
(iii) raising the existing embankment using conventional construction materials, as for the initial starter dam;
(iv) raising the existing embankment using ash excavated from the lagoon after a period of sub-aerial exposure, desiccation and drying.

In common with most MWFs, utilisation of the hydraulic waste (fly ash) in the confining embankment cross-section is generally considered the most economic and has been utilised extensively.

8.2.5 Embankment Design and Construction

Specific elements relating to hydraulic filling of ash lagoons are fundamental to robust and economic design and may be similar to technologies applied to the minerals industry for MWFs, but with a different emphasis. Ash lagoon-specific design considerations are described in summary below.

The initial deposition of fly ash slurry generally takes place into a lagoon confined by an initial starter embankment constructed from conventionally placed and compacted local soils. These starter dams eventually form the internal core of the largely fly ash embankment and may vary in height from about 10–15 m. The location of the power station often provides a source of suitable fill materials, such as cohesive colliery spoil, for use in the embankment. Where available, such a fill material has advantages for embankment construction as its greater density and strength enhances stability. In addition, the lower permeability of these fill materials, if used for the embankment core, reduces seepage rates and maintains a low phreatic surface, again enhancing stability. However, the use of colliery spoil is dependent on suitable characterisation, particularly of sulfide levels, which may prove environmentally deleterious and if elevated may, in extreme cases, lead to combustion. Control of seepage through the embankment is important and, for a section including a low permeability zone, a properly designed and constructed drainage system will need to be installed.

The most cost-effective long-term containment system comprises confining embankments constructed above the starter dam using a significant portion of fly ash excavated from the depository, placed and compacted using conventional civil engineering plant. However, the fly ash may be difficult to compact due to its particle size and shape and sensitivity to water content, with higher-than-optimum values making construction challenging, particularly during rainfall periods. The selection of suitable embankment fill from within the depository is therefore

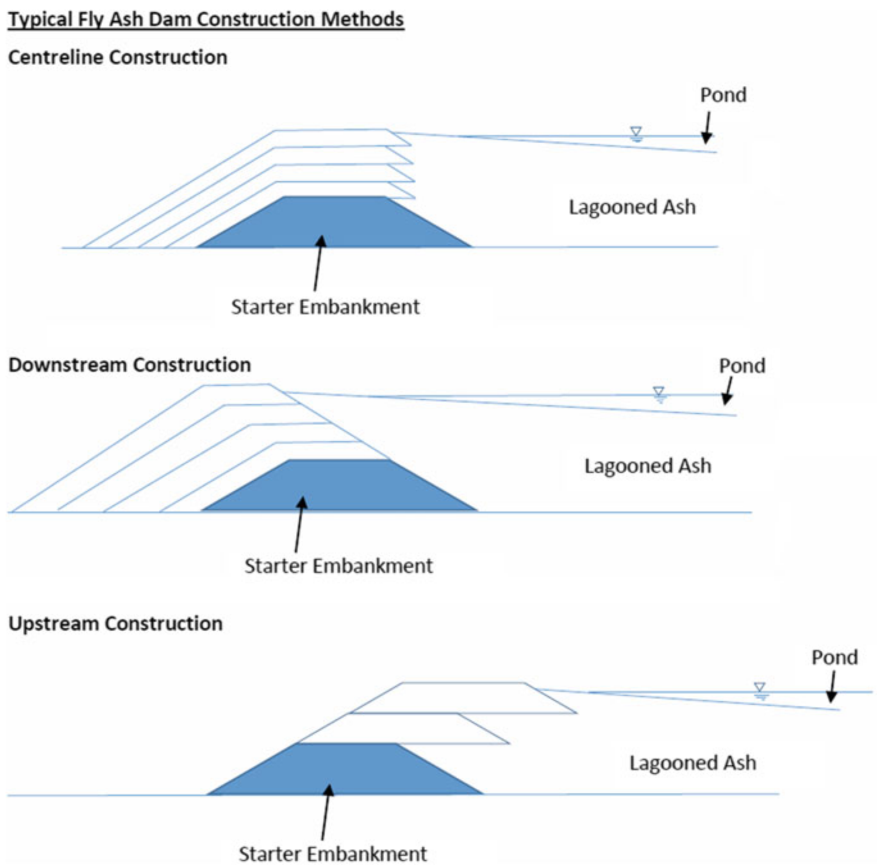

Fig. 8.3 Typical fly ash dam construction methods

important and is highly dependent on the deposition system and drainage achieved in the beached fly ash, with unsuitable material leading to construction issues and also increasing the risk of instability and erosion. The confining embankment cross-sections shown in Figs. 8.3 and 8.4 include, in addition to the structural zones, an internal drainage system in order to control the phreatic surface and improve stability. The internal drainage system may include granular underdrains to collect and discharge lateral seepage, together with zones to collect basal seepages and discharge these downstream in a controlled manner. The cross-section will also include horizontal benches on the embankment at approximately 15 m vertical intervals to control runoff and erosion. Cover materials to the embankment should include a soil cover on the inclined faces for external erosion protection, together with topsoil in order to promote vegetation growth. Durable weather-resistant rock

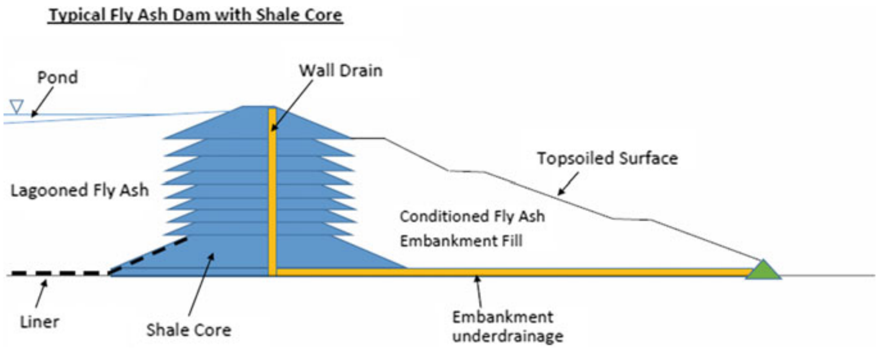

Fig. 8.4 Typical fly ash dam with shale core

is usually incorporated in the associated swales, ditches and seepage control channels to ensure stability and to maintain long-term hydraulic capacity.

'Fir tree' (centre line) construction, as shown in Fig. 8.4, is common practice and involves the upstream shoulder of the external embankment being founded on previous deposits of hydraulically placed fly ash. This construction technique requires additional design checks to ensure that there is adequate stability under all conditions including both climatic and operational. An adequate factor of safety against liquefaction is essential for such cross-sections.

The close proximity of coal-fired power stations and their associated ash lagoons to areas of underground coal mining activity may give rise to the occurrence of mining-induced settlement (subsidence). The potential for large settlements and irregular deformations requires detailed consideration during design. Seismic disturbance caused by any rapid or sudden ground movements causing subsidence may induce liquefaction of hydraulically placed fly ash. Lagoon systems may therefore need to be designed so that active disposal in a particular lagoon may be suspended during periods when subsidence may be induced by mining of particular blocks, and may be defined by an upper limit of tensile strain resulting from foundation settlements.

Finally, due to the particular economic pressure on the operation of fly ash disposal lagoons, some features may be adopted more widely than in other forms of MWF. Additional design features and considerations include the wider use of geotextiles and geomembranes in confining embankments.

8.2.6 Disposal Management

Hydraulic placement of fly ash is the most common form of disposal, with slurry transported from the power station by means of pipeline to remote ash lagoons and deposited behind confining embankments. The characteristics of the hydraulic fill require good underdrainage in order to allow effective dewatering, to maximise in situ densities and to improve long-term stability. As for many mine wastes, the chemical characteristics of the fly ash often lead to the development of a surface crust which inhibits desiccation and drainage. This results in the underlying material remaining largely saturated and specific drainage provisions are required in order to inhibit this tendency. Some fly ash operations utilise a paddock system by separating the depository into smaller settlement areas by the construction of internal dividing embankments. These paddocks are used cyclically, with active disposal areas and "fallow" paddocks in which drainage and desiccation takes place and facilitates subsequent excavation for dry disposal. Suitable underdrainage provisions are therefore essential to allow the sequence of operations to be undertaken efficiently and within a predictable and reasonably short timescale. Effectiveness of underdrainage should be monitored by use of piezometers and any errant seepages recorded as part of water balance calculations.

8.2.7 Water Management

8.2.7.1 Flood Design

The hydrology of the ash lagoon must be assessed using the most appropriate national rainfall and runoff models and the approach to this assessment should be similar in character to that adopted for water supply reservoirs as described in Sect. 5.5 (HMSO 1975). Both summer and winter storm events should be considered, together with peak slurry and other potential inflows in order to determine the critical condition. The fly ash lagoon confining embankment must be robust under the appropriate flood standard. Therefore, as the lagoon will be likely to operate as a "zero controlled-release" facility, sufficient freeboard should be available at all times to store the design event (generally the PMF or equivalent).

8.2.7.2 Decant Design

The inlet level of the fly ash slurry open-end point and the outlet of the decanting structure (outfall) must be selected to ensure that a "beach" develops across the lagoon with deposition managed to minimise the depth of ponding at the outfall position. The area of the pond will determine the clarity of the supernatant water as described in Sect. 4.3. The decant should always be positioned in a location which facilitates peripheral beach development and prevents the pond from developing against the confining embankment. This approach ensures drained conditions in the beach, reduces piezometric levels within the outer embankment and reduces seepage volumes. As a result overall stability is enhanced and the risk to the downstream environment, in the event of a breach, is reduced by minimising the volume of fly ash which will be mobilised and flow.

8.2.8 Environmental Issues

The key environmental issues related to the hydraulic disposal of fly ash include:

- airborne pollution;
- contamination of surface water from surface run-off;
- contamination of groundwater from infiltration of seepage and drainage water.

Supernatant water from the ash lagoon is generally recycled and the facility operated as a "zero controlled" discharge facility. Where recycle is not practicable, however, any industrial water from the facility will require treatment in order to correct high pH values and, as appropriate, to remove potential contaminants.

The choice of hydraulic disposal is usually based on the costs of transportation and handling. However, enhanced environmental regimes now in place have led to more stringent design and construction measures to protect the environment.

8.2.9 Understanding Storage System Failure Mechanisms

The construction, operation and closure of power station ash lagoons contribute to the financial overheads of power generation, and it is therefore essential that ash be deposited cost-effectively and with due regard to the safety of persons, property and the environment surrounding the disposal site. Robust but economic design of the hydraulic placement system, including internal and external embankments, is essential and must be followed by appropriate construction techniques, site supervision and CQA with assured ongoing operation, management, inspection and monitoring. The failure of ash lagoon systems is often due to poor operation and maintenance coupled with inadequate or inappropriate non-compliant construction methods, as exemplified below:

- over-steep slopes and poor geometry of the embankments;
- lack of adequate compaction of the fly ash due to wetter than optimum material being incorporated into the embankments;

- use of inappropriate compaction plant;
- poor drainage due to deficiencies in construction or poor CQA of filter media leading to reduced effectiveness;
- reduced structural and operational function caused by embankment or foundation settlements;
- ponding of water against external embankments.

8.2.10 Inspection and Monitoring

The design should be accompanied by an Operating and Maintenance Manual which specifies all design parameters, operating criteria, inspection and monitoring requirements and instrumentation systems as well as emergency protocols. A robust system of inspection and monitoring is essential in preventing untoward occurrences, and should be supported by a suitable instrumentation system including reservoir level gauge boards, seepage monitoring devices, settlement gauges and piezometers. In particular:

(i) standpipe and other types of piezometer are required in order to monitor the phreatic surface within the embankments and foundations. These instruments should be read regularly and the data plotted against both rainfall and pond level. The data should be regularly compared with the critical and trigger levels presented in the Manual prepared with the initial design;
(ii) all seepages should be monitored for quantity and quality and the flow data recorded regularly, with any untoward occurrences noted and investigated in order to prevent deterioration in embankment or foundation stability. As appropriate, seepage data should be input to the site water balance and the effectiveness of the drainage system regularly assessed;
(iii) the installation and monitoring of inclinometers within lagoon embankments may provide supplementary assurance of stability as they can provide early indication of any movement and assist in the detection of potential failure mechanisms, enabling early mitigation measures to be effected.

Regular inspection of lagoons and embankments will reveal conditions which may be symptomatic of potential failure, such as untoward seepage through the embankment face, potentially leading to piping, together with tension cracks and surface movements, including slips, slumps and bulges in the crest, face and toe. The inspections should include the condition of the disposal and decant structures and ensure that there are no occurrences which could lead to health, safety and environmental concerns. Additional inspection and monitoring protocols are necessary with respect to the risks associated with the installation of any pipelines laid directly through the internal bunds and the confining embankments. The records of all instrumentation and monitoring should be presented annually to the IIE for review during the regular compliance inspections.

8.3 Hydraulic Placement of Backfill in Underground Workings

This section covers the hydraulic placement of mine tailings in underground stopes and aims to demonstrate how the recommended engineering design process should be used to develop a competent backfill for use in underground workings.

8.3.1 Placement of Backfill Underground

Backfill is typically made from waste rock or dewatered tailings residues and is often mixed with cement to achieve moderate strengths. It can be delivered to stopes in several ways, namely by truck or, and relevant to this Section of the Guidelines, by pipeline either pumped under pressure or under gravity. The hydraulic fill generally comprises a dense slurry or "paste" which can be delivered underground into the mine through boreholes and pipelines. Hydraulic backfill in underground mine workings is used to fill stope voids, maintaining stability of the adjacent working areas and reducing the risk of local or regional ground failure. If cement-based binders are added the backfill may achieve higher strengths, enabling increased ore recovery and the extraction of adjacent stope pillars where the backfill is self-supporting. There are additional environmental benefits from the use of backfill, particularly of "paste" tailings which, having been dewatered to a toothpaste-like consistency, permit a higher percentage of tailings to be deposited underground, utilising up to 50% of the total fine extractive waste (tailings) produced by the process plant. This has additional benefits of reducing the surface footprint of the MWF and may permit potentially acid-generating waste to be placed with the backfill, thus reducing closure costs and liabilities. A higher proportion of hydraulic fill placed underground therefore reduces the environmental footprint of the mine and leads to lower costs and risk from final mine closure and site rehabilitation.

The design, operation and management of the backfill system involve a number of technical disciplines within the mine, namely:

- the mineral processing department, responsible for the production and delivery of backfill, and for the quality, cost and process monitoring;
- the mine geotechnical department, responsible for the specification for backfill, including strength, cement content and fill design as well carrying out quality control and analysis of fill performance;
- the mine planning department, responsible for developing the backfill schedule and for determining location and placement volumes.

However, it is considered good practice to appoint a single manager for the entire backfill process.

The strategic objectives for placing backfill underground include:

Table 8.1 Design support register for placement of tailings underground (blasthole stopes) (Ferguson 2015)

Stage	Function	Property	Design element
Structure/facility	Storage	Type of depository	Stope
		Infinite lifetime	Rock mass stability & construction quality
		Capacity	Stope volume
		Construction technique	Fill-fences and plugs
		Controlled placement	Deposition tactics
	Rock mass support	Consolidation and strength	Backfill mixture

- minimising the storage of tailings on surface;
- maintaining stable conditions of the surrounding rock mass by limiting the movement of the footwall and hanging wall rock mass;
- maximising ore recovery by confining or supporting secondary and tertiary stope pillars;
- utilising a high-quality distribution system which suffers a minimum of disruptions during the deposition of backfill.

These strategic objectives should be linked directly to the function and properties of the hydraulic fill and its application in the specific design elements (Table 8.1).

8.3.2 Characterisation of the Backfill

The backfill can be characterised using standard sampling and testing systems and the following key properties should be determined, as indicated in Chap. 4:

- grain size;
- chemistry;
- water content;
- percolation rate;
- particle specific gravity;
- strength;
- rheology and abrasiveness.

The defining characteristics of any backfill are the strength and the ability to flow, though these parameters are dependent on the basic geotechnical characteristics of the hydraulic fill. In order to engineer the backfill the geotechnical characteristics and the constituent parts, i.e. tailings, sand or waste rock, must be fully understood (Belem et al. 2002; McKibben et al. 1991; Steward and Spearing 1992; Thomas 1973; Thomas et al. 1979; Yu 1992).

8.3.3 Stope Environment

The stope environment in which the hydraulic backfill is to be deposited is determined by the mine plan and, particularly, by the configuration of the mineralisation, the storage capacity being governed by the residual stope volume following each phase of ore extraction. The quantity of hydraulic backfill for each stope panel needs to be established from an accurate measurement of the residual void. However, for the hydraulic backfilling to fill the void effectively, the stope must remain stable both prior to and during the deposition of the hydraulic fill. Stabilisation may be achieved by the installation of rock and cable bolts, and by carefully engineering the stoping sequence to minimise the magnitude of induced stresses.

8.3.4 Implementation Problems

8.3.4.1 Pipe Plugging

The deposition of solids in backfill pipelines occurs when the flow velocity falls below a limiting value known as the critical velocity (V_c) and results, in the extreme form, in a plugged pipe. The onset of plugging can occur in pipe sections furthest from the vertical underground feedline, usually where there is an extensive horizontal run, a variation in direction or slope or when a change in the consistency of a slurry occurs.

It is important, where practicable, to monitor and manage the composition of the tailings in order to achieve, where possible, homogeneous flow in the pipes. In addition, the velocity of tailings within pipes should be maintained above V_c in order to achieve this.

8.3.4.2 Pipe Wear

Several reports have shown that the wear rate of pipes is proportional to the velocity of the slurry being transported (McKibben and Shook 1991). The primary factor affecting pipe wear is velocity (Steward and Spearing 1992) which needs to be controlled in order to reduce pipe wear. Uneven wear can be anticipated near elbows or surge points, in vertical pipes and after free-fall.

8.3.4.3 Backfill Liquefaction

A major concern with backfill is liquefaction. Liquefaction resistance is increased once the backfill is consolidated, with improvements being achieved through the addition of cement or binder, thus reducing any potential to liquefy and enabling higher pressures to be generated. The necessary consolidation can be achieved by establishing good procedures for hydraulic placement and maintaining quality control of the backfill rather than by constructing elaborate fences or using excessive cement/tailings ratios. The presence of a large fine fraction in the backfill (more than 15% <20 μm) can, for example, reduce fill permeability, limiting drainage and consolidation and increasing the risk of ponding and thus of liquefaction.

8.3.4.4 Fill-Fence Failure

Analyses of fill-fence failures indicate either that such fences were acting as bulkheads supporting an unconsolidated backfill or that the failures were triggered by unsupervised placement procedures and it is therefore evident that high hydraulic pressure is a major factor in fill-fence failures. Since hydraulic pressure contributes 70% of the load applied to the fill-fence it is consequently important to ensure adequate drainage during hydraulic placement of the backfill.

8.3.4.5 Low Tailings Strength

Inadequate backfill strengths are indicated by high dilution during blasting or by frequent fill failures during mucking operations. Characterising backfill performance in terms of strength, and comparing this to the design strength, allows the backfill practitioner to determine a suitable factor of safety. This provides a starting point for improving backfill performance and making it more cost-effective. The largest influence by far on backfill strength is the addition of binder or cement, though the proportion of water to binder, commonly referred to as the water-to-cement ratio, plays a significant role. Uncontrolled water/cement or water/binder ratios have a negative effect on strengths and need to be closely monitored and controlled.

8.3.5 Failure Mechanisms

The following are the principal failure mechanisms for a hydraulic backfill operation:

- pipeline failure—heterogeneous flow, high velocities and highly abrasive fill materials increase the rate of pipe wear which can lead to pipeline failure and may be minimised by achieving homogenous flow at reduced fill velocities;
- fill-fence failure—fill-fences fail under tension brought about by the hydraulic pressures generated from poor drainage of backfill during fill placement, together with poor quality monitoring of backfill pore pressures;
- backfill failure (low-strength)—low strength, even in a consolidated fill, may lead to shear failure from self-weight alone where it is exposed next to an open stope;
- backfill failure (blast-induced)—failure induced by blasting operations leads to the failure of low-strength fills from exposure to the low velocity compression waves which cause the fill to vibrate and potentially to liquefy.

8.3.6 Design Elements

8.3.6.1 Distribution System—Fill Pipelines

The principal problems to consider in the design of the backfill distribution system are plugging of pipes and excessive wear leading to backfill spillage in the mine workings. Plugging of pipes may be managed by monitoring the composition and velocity of backfill within pipelines. Design practice to reduce excessive slurry velocity and thereby achieve homogenous flow to minimise pipe wear and the likelihood of plugging, includes:

- adjusting fill particle sizing;
- increasing fill pulp density;
- using non-vertical pipe inclinations and reducing pipe diameters;
- adding additional horizontal piping to absorb energy;
- minimising the number of pipe direction changes;
- making direction changes gradual, using long transition pieces;
- designating high-wear pieces for sacrificial wear, and designing these sections such that they can be quickly and regularly changed;
- letting fill flow against fill, i.e. allowing the dead-end portion of a "T" piece, utilised at the transition between a vertical and horizontal pipeline, to fill up with

backfill, thus permitting the vertical flow of slurry to be deflected across to the horizontal pipe;
- using wear-resistant materials or coatings in the pipe.

8.3.6.2 Fill-Fence

The design of fill-fences has progressed over the past century from timber-based to steel-cable-based construction. In general, the design of fill-fences should meet the following criteria:

- fence design should be as simple as possible in order to facilitate rapid construction;
- fences should be free-draining in order to avoid pressure build-up.

With good drainage, the hydraulic pressure exerted on the fill-fence will reduce and should eventually dissipate. However, a conservative approach to plug design should be adopted, requiring that the plug withstand the full hydrostatic head of fill acting on it. This approach is considered to be conservative since the potential for fill to liquefy above the draw points is negligible given that the fill is consolidating at all times. Moreover, the arching effect between the fill and stope walls is not taken into account in these design calculations.

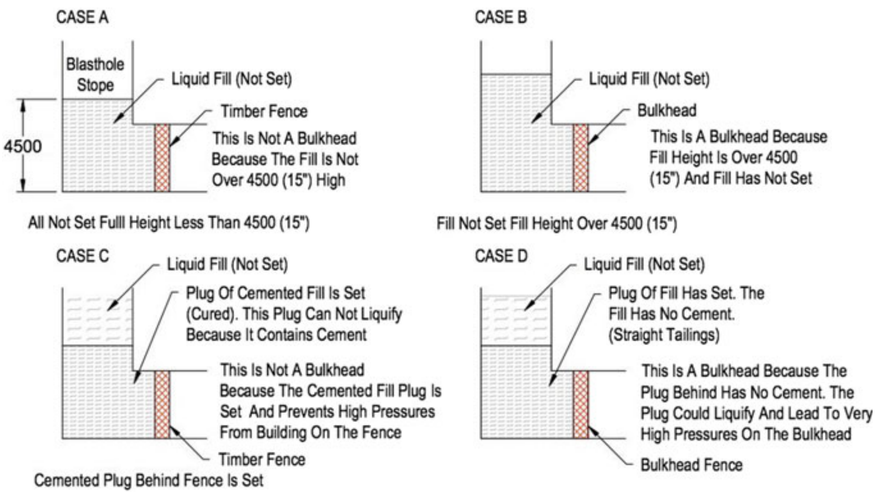

Fig. 8.5 Definition of bulkheads (Bharti and West 1993)

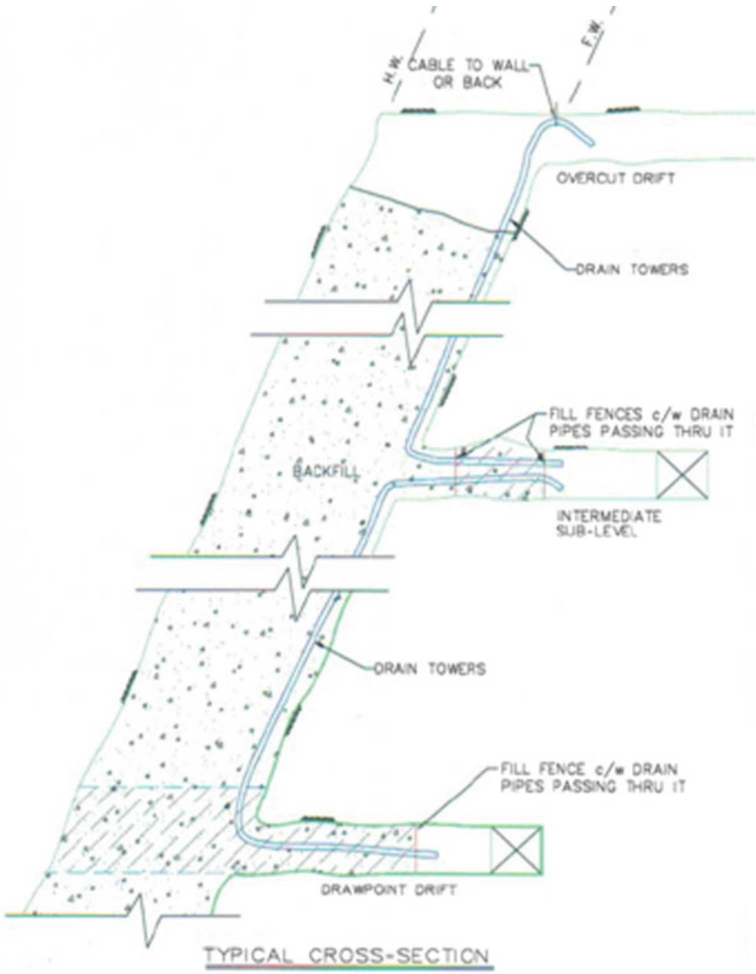

Fig. 8.6 Fill stope drainage arrangements (Bharti and West 1993)

The plug design is calculated for various values of cohesion and friction to reflect different cement-to-sand ratios in order to determine the minimum acceptable length of the plug required to withstand the full hydrostatic head of the backfill above (Fig. 8.5). An alternative approach to plug design is to erect two fill-fences and to pour a plug between them.

Drain towers of 100 mm-diameter should be installed through each fill-fence and visually monitored to determine their effectiveness. The primary objective of drain towers is to drain the fill plug rapidly. Damage to the drainage system must be avoided wherever possible and, consequently, the introduction of hydraulic fill into the stope should only occur after the fill plug is in place and has cured (Fig. 8.6).

The long-term effectiveness of drain towers is a function of the fines fraction present in the fill as this proportion determines permeability and thus governs the rate of free drainage. To compensate for any reduction in drainage rate, the simple expedient of increasing the number of drain towers installed, generally by a factor of at least two, should be used.

8.3.7 Risk Management

The risks associated with the placement and use of backfill are well known, as shown in Table 8.2.

The severity assessment of the risks given above indicates that their occurrence must be fully mitigated in the design, implementation and monitoring approach as previously outlined. The severity of risk of severe injury or of death of mine workers arising from the failure of a fence requires that a high level of supervision be imposed during hydraulic placement operations. A high level of supervision will lower the risk severity of fill-fence failure to Level 5 (see Table 8.3).

Table 8.2 Severity of known risks in underground backfill placement systems

Known risk	Likelihood	Consequence	Severity
Pipe plugging	Probable	Low-to-moderate	Level 5
Pipe wear	Probable	Moderate	Level 5
Liquefaction	Unlikely	High	Level 5
Fill-fence failure	Probable	High	Level 6
Low strength	Probable	Low-to-moderate	Level 5

Table 8.3 Risk severity matrix

Risk Severity Matrix				
Likelihood	**Consequence**			
	Very Low	**Low**	**Moderate**	**High**
Very Unlikely	Level 1	Level 2	Level 3	Level 4
Unlikely	Level 2	Level 3	Level 4	Level 5
Probable	Level 3	Level 4	Level 5	Level 6
Highly Likely	Level 4	Level 5	Level 6	Level 7

8.3.8 Implementation Tactics

8.3.8.1 Tailings Chemistry

If natural sands are utilised as fill material they should be screened to remove any organic matter, large-sized aggregate or agglomerations of wet or hardened material. Organic material will cause adverse reactions with any binders and over-sized aggregate can plug distribution systems.

The presence of approximately 5% of sulfide minerals can cause cemented backfill to lose strength over time. The presence of zinc can delay the set time of binders from a few days to several weeks. Removing or diluting the mineral or element causing adverse problems in backfills is one approach. An alternative solution may lie in the choice of binder to restrict the impact of the mineral element which is causing problems.

8.3.8.2 Fill Water Percolation

Although a rate of 100 mm/h (Ref. http://minewiki.engineering.queensu.ca/mediawiki/index.php/Backfill_properties) is accepted as the benchmark for percolation rates, the means of measuring this makes it difficult to achieve consistent results. A more pragmatic approach involves improving fill practices, as indicated below:

- the addition of a minimal amount of cement, approximately 2%, to all stopes to be backfilled (excluding rock fill);
- the adjustment of the size distribution of backfill, either removing fines and/or adding coarse material;
- the use of weeping tiles in the stope to assist fill drainage and allow adequate drainage at barricades;
- the prevention of ponding by monitoring pours and being prepared for operations to be terminated quickly if necessary, i.e. to stop hydraulic filling in order to allow drainage;
- the maximisation of the pulp density of the slurry (i.e. reducing the water content) such that adequate slurry velocity in the distribution system is still achieved;
- the prevention of flush water from entering the filled stope.

In a true paste backfill there is no excess, or very little, water bleeding from the paste. As the hydration reaction in the binder requires only a small proportion of water, percolation rate is not an important factor in cemented paste backfill.

8.3.8.3 Pipe Wear

Methods of reducing excessive slurry velocity include:

- adjusting fill particle sizing;
- increasing fill pulp density;

- using non-vertical pipe inclinations;
- reducing pipe diameters;
- using additional horizontal piping to absorb energy.

Methods of minimising pipe wear include:

- minimising the number of pipe direction changes;
- making directional changes gradual using long transition pieces;
- designating high-wear pieces for sacrificial wear, and designing these sections such that they can be quickly and regularly replaced;
- letting fill wear against fill, i.e. the dead-end portion of a "T" piece utilised at the transition between a vertical and horizontal pipeline will fill with backfill, allowing the vertical flow of slurry to deflect across it to the horizontal pipe;
- using wear-resistant materials or coatings in the pipe.

8.3.8.4 Fill-Fence

Methods to reduce the likelihood of fill-fence failure include:

- sufficient monitoring and/or experience should be gained to ensure that fill-fences never carry a pressure in excess of 15 psi, though it is noted that monitoring results indicate that most fill-fences do not experience pressures of more than 1–2 psi;
- the plug behind the fence should be poured at a controlled rate to ensure that it cures adequately and does not exert unacceptable pressure on the fill-fence. It is therefore important to establish strict guidelines and procedures for pouring the plug behind the fence;
- the best check on the performance of a fence is to monitor it both as the plug is being poured and when the bulk pours are being completed. Simple procedures for monitoring pressure on the fence and checking drainage should, therefore, be established and the results recorded to identify any unusual trends so that pouring may be terminated quickly if necessary.

8.3.8.5 Pouring the Plug

Pouring the plug should be carried out in a controlled manner:

- the drawpoints should be emptied of any obstructions before constructing the fence;
- the 1:20 ratio fill using Normal Portland Cement should be poured over two shifts and allowed to drain on the third shift;
- during pouring, a visual inspection of the fences should be carried out by the foreman to check for drainage and a written record be kept;

- poor drainage from the fences or any blockages require investigation and may lead to a temporary halt in pouring operations;
- the total quantities of backfill poured should be recorded to ensure that adequate fill has been used;
- a visual inspection of the fill-fence should be carried out, if practicable, with a strong external source of light;
- after the plug has been poured it should be allowed to cure for at least 48 hours before the bulk pour is started;
- no waste rock should be added into the blast hole stope when pouring the plug.

8.3.9 Monitoring Programme

On-site monitoring is essential for successful backfill placement in blasthole stopes. The following procedures should be adopted:

- the first two to three fences installed should be monitored using a simple pressure gauge and, in general, the pressure should never exceed more than 2–3 psi (12–20 kPa) and the placement of the hydraulic fill be halted should the pressure exceed 5 psi;
- visual inspection of the drainage from each of the fences and from the drain towers should be conducted and an approximate estimate of the quantities of water coming from the fence and the drain towers be determined;
- a water balance should be determined to assess the quantity of water, if any, trapped in the blasthole stope;
- a backfill pour logbook should be established and maintained in a suitable location for inspection by all concerned.

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Chapter 9
Conclusions

Mike Cambridge

Next time I travel to a conference I do not wish to fly in a biodegradable aircraft.

—Hoskins, UNEP, 2000

The extractive industries are ubiquitous and have underpinned social growth and development over the last 4000 years. They remain both a vital part of modern industrial society and the focus of environmental concerns, particularly with respect to the management of the ensuing extractive wastes. It was reported in 2000 that the volume of waste generated annually by metal mining alone was roughly equivalent to the eruptive discharge from Mount St Helens, Washington, USA in 1980. Therefore whilst the extractive industries remain viable, MWFs will continue to be the main environmental focus of the international mining industry. These facilities are often large and complex structures whose design, construction, operation and closure need to be closely monitored. Since poorly designed or badly managed waste facilities lead to higher closure costs, to ongoing impacts to the environment and to an increased risk of failure, extractive industries face the challenge of effectively and efficiently managing these structures throughout their life-cycle. This management must apply from initial site selection and design, through construction and operation, to eventual decommissioning and closure. Further, at cessation of operation MWFs constitute the most visible legacy of a mining project and, after closure and rehabilitation, are required to remain safe and stable and to produce no detrimental effects on the environment, effectively in perpetuity. It is evident that a poorly designed or badly managed mine waste facility will lead to increased risk to public health and safety and to the potential for ongoing negative impacts to the environment.

The engineering design of a waste management facility is complex and must be undertaken by competent consulting engineers with relevant experience in order to meet the requirements of cost-efficiency, safety and stability, as well as compliance with planning, environmental regulations and closure strategy. In order to attain the fundamental principles of good design, operation and management of a MWF the practitioner must:

M. Cambridge (ed.), *The Hydraulic Transport and Storage of Extractive Waste*,
Professional Practice in Earth Sciences,
https://doi.org/10.1007/978-3-319-69248-7_9

- research the geology of the site (both sequence and history);
- scope the characterisation investigation and test programme with flexibility;
- define function and parameters (design, operating and closure);
- assess hazard potential, risk and consequence, both short- and long-term;
- absorb lessons of historic failures;
- undertake a comprehensive "what if?" analysis for all project stages;
- never underestimate the potential of any water (impounded or interstitial);
- prepare operating rules and criteria, together with action and emergency protocols;
- prepare a comprehensive inspection, monitoring and independent auditing plan;
- design for closure and site rehabilitation from project inception.

Appendices

Appendix A: Standards and Guidelines of Relevance

Mike Cambridge and Jason Saint

Appendix A1: European Standards and Guidelines of Relevance

The following lists of standards and guidelines were provided by national experts throughout the course of the preparation of these guidelines. It is recognised that other relevant European documents relating to embankment dams and to mine waste facilities may be available.

Czech Republic

ČSN 75 24 10 Malé vodm na'drze, Small water reservoirs, Issued April 2011
ČSN 75 23 10 Sypané hraze, Embankment dams, Issued September 2006
Details: www.unmz.cz

France

Recommandations du programme ERINOH sur l'érosion interne – 2013 (ERINOH guidelines on internal erosion – A project from the National Agency of Research)
Recommandations pour la justification de la stabilité des barrages et des digues en remblai – CFBR-2010 (Guidelines for the justification of dam and dykes embankments stability)
Recommandations pour le dimensionnement des évacuateurs de crues de barrages – CFBR-2013 (Guidelines for spillway design of dams)
Risque sismique et sécurité des ouvrages hydrauliques – Novembre 2010 - Guide du Ministère de l'Ecologie, du Développement Durable et de l'Energie. (Guide on seismic risk and safety for hydraulic works).

Germany

Advisory Leaflet, ATV-DVWK-M 503E, Basic Information on Investigation and Remediation of Tailings Impoundments, December 2001

M. Cambridge (ed.), *The Hydraulic Transport and Storage of Extractive Waste*,
Professional Practice in Earth Sciences,
https://doi.org/10.1007/978-3-319-69248-7

Deutsche Norm DIN 19700 Stauanlagen, Teil 10: Gemeinsame Festlegungen, Deutsches Institut fur Normung e.V., Beuth Verlag GmbH Berlin, Januar 1986
Deutsche Norm DIN 19700 Stauanlagen, Teil 11: Talsperren, Deutsches Institut fur Normung e.V., Beuth Verlag GmbH Berlin, Januar 1986
Deutsche Norm DIN 19702 Standsicherheit von Massivbauwerken im Wasserbau, Deutsches Institut fur Normung e.V., Beuth Verlag GmbH Berlin, Oktober 1992.

Portugal

Decree-Law N.º 344/2007 – Regulamento de Segurança de Barragens [Dam Safety Regulation]
Regulatory Ordinance N.º 846/93 – Normas de Projecto de Barragens [Dam Design Rules] – Under review
Regulatory Ordinance N.º 847/93 – Normas de Observação e Inspecção de Barragens [Dam Monitoring and Inspection Rules] – Under review.

Spain

010 Guía Técnica de Seguridad de Presas Nº 1, Seguridad de presas.
021 Guía Técnica de Seguridad de Presas Nº 2, Criterios para proyectos de presas y sus obras anejas (Volumen 1 I)
021a Adenda de la Guía Técnica Nº 2 (Volumen 1), Actualización de todos los aspectos referents al Hormigón Compactado
022 Guía Técnica de Seguridad de Presas Nº 2, Criterios para proyectos de presas y sus obras anejas (Volumen II 11), Presas de Materiales Sueltos
030 Guía Técnica de Seguridad de Presas Nº 3, Estudios geológicos-geotécnicos y de prospección de materiales
040 Guía Técnica de Seguridad de Presas Nº 4, Avenida de Proyecto
050 Guía Técnica de Seguridad de Presas Nº 5, Aliviaderos y desagües
060 Guía Técnica de Seguridad de Presas Nº 6, Construcción de presas y control de calidad
070 Guía Técnica de Seguridad de Presas Nº 7, Auscultación de las presas y sus cimientos
081 Guía Técnica de Seguridad de Presas Nº 8, Explotacion de Presas y Embalses. Tomo 1 Análisis de riesgos aplicado a la gestión de seguridad de presas y embalses
081e Technical Guide on Operation of Dams and Reservoirs Nº. 8, Operation of Dams and Reservoirs. Volume 1 – Risk analysis applied to management of dam safety
090 Guía Técnica de Seguridad de Presas Nº 9, Medio ambiente de presas y embalses

Sweden

Energiföretagen Sverige AB (2016). RIDAS Kraftföretagens riktlinjer för dammsäkerhet, kapitel 1-3

Svensk Energi AB (2012). RIDAS Kraftföretagens riktlinjer för dammsäkerhet
Svensk Energi AB / SveMin (2012). GruvRIDAS Gruvindustrins riktlinjer för dammsäkerhet.

United Kingdom

Charles J. A., Abbiss C. P., Gosschalk E. M., and Hinks J. L., – An engineering guide to seismic risk to dams in the United Kingdom, BRE, 1991
Dams and Reservoir Conduits: Inspection, monitoring, Investigation, Maintenance and Repair, CIRIA, 2015
Deane, M.. Hill, T. & Warren, A – A Guide to the Reservoirs Act 1975, ICE Publishing, 2014
Department for Environment, Food and Rural Affairs, Explanatory Memorandum to The Reservoirs Act 1975 (Capacity, Registration, Prescribed Forms, etc.) (England), Regulations 2013, no. 1677, Regulation 2
Department for Environment, Food and Rural Affairs, The Reservoirs Act 1975 (Capacity, Registration, Prescribed Forms, etc.) (England), Regulations 2013, no. 1677, Regulation 2
Environment Agency – EPR 6.14 How to Comply with your Environmental Permit, Additional Guidance for: Mining Waste Operations. 2011
Flood and Water Management Act 2010 (c.29), Schedule 4 – Reservoirs, 28 Feb 2011
Health and Safety England and Wales and Environmental Protection England and Wales – The Major Accident Off-Site Emergency Plan (Management of Waste from Extractive Industries) (England and Wales) Regulations 2009, Statutory Instruments No. 1927
HMSO, Mines and Quarries (Tips) Regulations, 1971
HMSO – Statutory Instrument 1999 No. 2024, The Quarries Regulations 1999, ISBN 0 11 082955 7
ICE – Floods and Reservoir Safety, 4th edition, ICE Publishing, 2015
Johnston T. A., Millmore J. P., Charles J. A., and Tedd P., – An engineering guide to the safety of embankment dams in the United Kingdom, BRE, 1999

Appendix A2: International and Non-European Standards and Guidelines of Relevance

International Commission on Large Dams (ICOLD)

Nr.	Document title
1	Bulletin No. 45, Manual on tailings dams and dumps; 1982
2	Bulletin No. 56, Quality Control for Fill Dams; 1986
3	Bulletin No. 74A, Guide to Tailings Dam Safety; 1989
4	Bulletin No. 95, Embankment Dams Granular Filters and Drains-Review and Recommendations; 1994

(continued)

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Nr.	Document title
5	Bulletin 97, Tailings Dams-Design of Drainage-Review and Recommendations; 1994
6	Bulletin 98, Tailings Dams and Seismicity-Review and Recommendations; 1995
7	Bulletin No. 101A, Guide to Tailings Dams-Transport and Placement; 1995
8	Bulletin No. 103, Tailings Dams and Environment-Review and Recommendations; 1996
9	Bulletin No. 104, Monitoring of Tailings Dams-Review and Recommendations; 1996
10	Bulletin 106, A Guide to Tailings Dams and Impoundments-Design, Construction, Use and Rehabilitation; 1992
11	Bulletin 121: Tailings Dams Risk of Dangerous Occurrences Lessons learnt from Practical Experiences; 2001
12	Bulletin 139: Improving Tailings Dam Safety – Critical Aspects of Management, Design, Operation and Closure; 2011
13	Preprint Bulletin 153: Sustainable Design and Post-Closure Performance of Tailings Dams; 2012
14	In preparation: Tailings Technology update; 2017

Australian references

Nr.	Document title
1	AS 1289 Series: Methods of Testing Soil for Engineering Purposes; 2000
2	AS 1726: Geotechnical site investigations; 1993
3	AS 2033: Installation of Polyethylene Pipe Systems; 2008
4	AS 2439.1: Perforated plastics drainage and effluent pipe and fittings. Part 1: Perforated drainage pipe and associated fittings; 2007
5	AS 2566.1: Buried flexible Pipelines. Part 1: Structural Design; Amendment 1; 2017
6	AS 3704: Geotextiles – Glossary of Terms; 2005
7	AS 3705: Geotextiles – Identification marking and general data; 2012
8	AS 3706.7: Geotextiles – Methods of Test; 2014
9	ANCOLD Guidelines for dam instrumentation and monitoring systems; 1983
10	ANCOLD Guidelines for Design of Dams for Earthquake; 1998
11	ANCOLD Guidelines on Tailings Dam Planning, Design, Construction, Operation and Closure; 2012
12	ANCOLD Guidelines on Acceptable flood capacity for dams; 2000
13	ANCOLD Guidelines on Consequence Categories for Dams; 2014
14	ANCOLD Guidelines on Dam Safety Management; 2003
15	ANCOLD Guidelines on Risk Assessment; 2003
16	ANCOLD Guidelines on Dam Safety Management; 2003
17	Australian Rainfall and Runoff, Geosciences Australia; 2016
18	Leading Practice Sustainable Development Program for the Mining Industry – Tailings Management; 2016
	Additional State Based Guidelines are also in use

Canadian references

Nr.	**Document title** (http://www.mining.ca/site/index.php/en/news-a-media/publications.html*)*
1	Mining Association of Canada: *Operation, Maintenance and Surveillance Manual for tailings and water management facilities; 2011*
2	Mining Association of Canada: Second Edition. *A Guide to the Management of Tailings Facilities; 2011*
3	Mining Association of Canada: *Audit and Assessment of Tailings Facility Management; 2011*
4	Canadian Dam Association – *Dam Safety Guidelines; 2007*
5	Canadian Dam Association – *Technical Bulletin, Application of Dam Safety Guidelines to Mining Dams; 2014*
6	Canadian Dam Association – *Technical Bulletin, Dam Safety Reviews; 2016*
7	Association of Professional Engineers and Geoscientists of British Columbia – *Professional Practice Guidelines – Site Characterization for Dam Foundations in BC; 2016*
8	Government of British Columbia – *Health, Safety and Reclamation Code for Mines in British Columbia; 2016*
9	Government of Quebec – *Directive 019 Sur L'Industrie Miniere 2012*
10	Government of Alberta – *Dam and Canal Safety Guidelines, 1999 – under revision*

Chilean environmental practice

Nr.	**Document title**
1	Guide to Good Environmental Practice for Small Scale Mining. Construction and Operation of tailings dams. Intellectual Property Registration No 134326 ISBN 956-8038-03-5 Guía de Buenas Prácticas Ambientales para La Pequeña Minería. Construcción y Operación de Tranques de Relaves. Registro de Propiedad Intelectual No 134.326 ISBN 956-8038-03-5
2	Supreme Decree No. 248 – Regulations for the Approval of Projects. Design, Construction, Operation and Closure of Tailings Impoundments. Ministry of Mining; Published in the Official Journal, 11 April 2007 Decreto Supremo Nº 248 - Reglamento para La Aprobación De Proyectos. De Diseño, Construcción, Operación y Cierre de Los Depósitos de Relaves. Ministerio de Minería; Publicado En El Diario Oficial El 11 De Abril De 2007
3	National Service of Geology and Mining – Mining Safety Department. External Document – Technical Guide Operation and Control of Tailings Deposits DSM/07/31 December 2007 Servicio Nacional de Geología y Minería - Departamento de Seguridad Mineria. Documento Externo - Ramírez M. N A Guía Técnica de Operación y Control de Depósitos de Relaves; DSM/07/31 de Diciembre 2007
4	Regulations for the Design, Construction and Operation of Certain Water Works – with reference to Article 294 of the Water Code; Draft format – 2007 Reglamento Para El Proyecto, Construcción y Operación de Ciertas Obras Hidráulicas a Que se Refiere El Artículo 294; Del Código de Aguas - 2007

Appendix B: Geotechnical Parameters and Testing

Appendix B1: Basic Mass and Volume Relationships in Particulate Media

Rafael Monroy and Ciaran Molloy

The parameters most commonly used to describe packing and density in a particulate material are included in this Appendix. The terminology employed corresponds to that used in the following two European standards:

- EN ISO 14688-1 Geotechnical investigation and testing—Identification and classification of soils—Part 1: Identification and description.
- EN ISO 14688-2 Geotechnical investigation and testing—Identification and classification of soils—Part 2: Principles for a classification.

A more extensive discussion on packing and density can be found in textbooks on soil mechanics and tailings dam engineering, such as Soil Mechanics Concepts & Applications (Powrie 2004), Planning, Design, and Analysis of Tailings Dams (Vick 1990), and Geotechnical Engineering for Mine Waste Storage Facilities (Blight 2010).

When the hydraulic fill is in the form of a slurry, the material can be described by measuring the mass of solid content M_s per unit mass of slurry M. This gives the **solids content** or **concentration** (also sometimes referred as **pulp density** (P) in the literature (Vick 1990)).

$$P = \frac{M_s}{M}$$

In the settled form, a number of parameters can be used to define internal geometry and evaluate strains. For a given sample of hydraulic fill, it is possible to consider on the one hand the mass of gas (0), liquid M_w, solids M_s, and total mass M and, on the other, the volume of gas V_g, liquid V_w, solid V_s, total volume V and the combined volume of voids $V_v = V_g + V_w$.

The **void ratio** (e) is the ratio of the volume of void space to the volume of solids:

$$e = \frac{V_v}{V_s}$$

The **porosity** (n) is the ratio of volume of voids to total volume (usually expressed as a percentage):

$$n = \frac{V_v}{V}$$

Porosity and void ratio are related by the following expression:

$$n = \frac{e}{1 + e}$$

The **degree of saturation** (S_r) defines the proportion of void space occupied by fluid (often expressed as a percentage):

$$S_r = \frac{V_w}{V_v}$$

The gravimetric **water content** (w) is given by the ratio of mass of fluid to mass of solid:

$$w = \frac{M_w}{M_s}$$

By knowing the density of the soil mineral, ρ_s, and taking ρ_w as the density of water, it is possible to determine the **specific gravity** (G_s) of the soil mineral:

$$G_s = \frac{\rho_s}{\rho_w}$$

Knowledge of specific gravity allows volumetric and gravimetric ratios to be related using the following expression:

$$wG_s = S_r\mathrm{e}$$

The **bulk density** (ρ) of the material can be obtained by dividing the total mass by the total volume of a sample:

$$\rho = \frac{M}{V} = \frac{M_s + M_w}{V_s + V_v}$$

The **saturated density** (ρ_{sat}) corresponds to the situation where the degree of saturation S_r is 1; whereas the **dry density** (ρ_d) indicates that the voids are completely dry.

The state of packing of hydraulic fill can also be described in relation to the maximum and minimum values of water content or void ratio. It is usual to separate the material on the basis of gradation into coarse and a fine fraction, referred to sometimes as sand and slimes in the literature (Vick 1990). If the fine material displays plasticity, the state of packing can be related to the **liquidity index** (I_L) or **consistency index** (I_C):

$$I_L = I_C = \frac{w - w_P}{w_L - w_P}$$

where w_L and w_P correspond to the water content at the liquid and plastic limit respectively. The state of packing in slimes not displaying plasticity, as well as in coarse fill, can be described in terms of **relative density** (D_r) or **density index** (I_D):

$$D_r = I_D = \frac{e_{max} - e}{e_{max} - e_{min}}$$

where e_{max} and e_{min} correspond to the voids ratio at the minimum and maximum density respectively obtained in the laboratory.

Appendix B2: Non-Standard Geotechnical Tests

The characterisation of the physical and mechanical properties of hydraulic fill requires the use of some tests not covered in the current European standard for geotechnical laboratory testing EN ISO 17892. Some of these tests are presented in this Appendix and include the following:

- Solids content;
- Particle settling velocity;
- Undrained settling;
- Drained settling;
- Air-drying;
- Slurry consolidation.

The above list is not exhaustive, and specialist advice should be sought when specifying and performing any of these tests, as well as any other test not covered in standards. The description that follows has been adapted from a document originally prepared by WLPU consultants (unpublished).

Solids content test

Description

This test is used to determine the solids content (also known as concentration or pulp density) of a sample of hydraulic fill. The test measures the mass of solid material in a sample of slurry. Tests can be prepared at different solids contents to allow for process discharge changes. The same test can also be used to determine the water content of the slurry.

Apparatus

- Oven set at 105±0.5 °C
- Balance

Procedure

A sample of slurry is placed in a container and weighed. The slurry is then placed in an oven set at a temperature of 105 °C for 24 h, after which it is weighed again. This process is repeated at regular intervals until the mass of the slurry equilibrates.

The following quantities are measured during the test:

- Mass of container, C (g)
- Mass of wet slurry and container before drying, W_{sc} (g)
- Mass of slurry and container after drying, D_{sc} (g)

Results

The solids content, P, can be calculated as a percentage from the following expression:

$$P(\%) = \left(\frac{D_{sc} - C}{W_{sc} - C}\right) \cdot 100$$

The gravimetric water content, w, can also be obtained from the same data:

$$W(\%) = \left(\frac{W_{sc} - D_{sc}}{D_{sc} - C}\right) \cdot 100$$

The solids content and water content are obtained from evaporation of the pore fluid. If the fluid filling the pores has a density significantly different from that of water, the above two equations will give erroneous results. For a pore fluid with a specific gravity, G_f, greater than 1 the following expressions should be used to determine P and w:

$$P(\%) = \left[\frac{(D_{sc} - C) - (W_{sc} - D_{sc}) \cdot (G_f - 1)}{W_{sc} - C}\right] \cdot 100$$

$$W(\%) = \left[\frac{W_{sc} - D_{sc}}{(D_{sc} - C) - (W_{sc} - D_{sc}) \cdot (G_f - 1)}\right] \cdot 100$$

Particle settling velocity test

Description

This test is used to determine the settling velocity of the coarse fraction of hydraulic fill. This allows definition of the minimum required operating pond area. During the test the time taken for particles of a given size fraction to fall a certain distance in a column of water is measured.

Apparatus

- Stopwatch
- 1 litre measuring cylinder
- Ruler
- Thermometer
- Balance

Procedure

- The cylinder is filled to the 1000 ml mark with deionised water.
- Both the internal diameter of the cylinder and the temperature of the water are recorded.
- The sample is divided into fractions depending on particle size:
  - Material retained in the 0.15 mm sieve.
  - Material passing the 0.15 mm sieve and retained in the 0.1 mm sieve.
  - Material passing the 0.1 mm sieve and retained in the 0.063 mm sieve.
- For each fraction, approximately 5.0 g are placed inside a small container and this is held over the measuring cylinder. The material is then tipped and the stop watch started.
- The time taken for all the particles that can be identified with the naked eye to reached the bottom of the cylinder is recorded.
- The process is repeated 5 times for each fraction, using fresh deionised water for each test.

Results

- The average of five measurements is taken as the time for a given fraction to reach the bottom of the cylinder.
- Both the temperature of the water and the height of the water column should be reported.
- The particle setting velocity, obtained by dividing the height of the water column by the time taken for all the samples to reach the bottom of the cylinder, should be given in m/s.
- On some projects it may be necessary to undertake the test using both deionised and process water.

Undrained settling test

Description

The test is conducted on a sample of slurry at a given solids content by filling a one-litre measuring cylinder and monitoring the height of the mudline. The information derived from this test can be used to determine the rate at which the supernatant fluid separates from the slurry (known as the bleeding rate) and the minimum density of the settled material when deposited under water (sub-aqueous deposition).

Apparatus

- Balance
- 1 litre measuring cylinder
- Stopwatch
- Oven set at 105±0.5 °C

Procedure

- The mass of the 1 l measuring cylinder is recorded.
- A sample of slurry is placed inside the measuring cylinder and the mass and volume recorded.
- The top of the cylinder is covered to prevent evaporation and loss of material during shaking.
- The sample is vigorously shaken to ensure a homogeneous mix at the start of the test.
- The cylinder is placed on an even surface and the stopwatch started.
- The volume of the settled solids is recorded at intervals of time. The following recording times are recommended for plotting volumes against the square root of time: 0.25min, 0.5min, 1min, 2.25min, 4min, 9min, 16min, 25min, 36min, 49min, 64min, 1.5hr, 2hr, 4hr, 8hr, 24hr.
- Readings are taken until the volume of settled solids is constant.
- At the end of the test the supernatant water is carefully decanted and the slurry is removed from the cylinder and placed in a container of known mass. The slurry is dried in an oven set at 105±0.5 °C and the mass of solids determined.
- Some of the dry material is used to determine the particle specific gravity as indicated in EN ISO 17892-3.

The following quantities are measured before the start of the test:

- Mass of measuring cylinder, C (g)
- Mass of measuring cylinder and slurry, W_{sc} (g)
- Initial volume of slurry in the cylinder, V_{T0} (ml)
- Initial time at start of test, T_0

The following quantities are measured during the settling period:

- Time when reading is taken, T_n
- Volume of settled solids, V_{Tn} (ml)

The following quantities are measured at the end of the test:

- Time of final reading, T_f
- Volume of final settled solids, V_{Tf} (ml)
- Mass of dry solids after drying, D_s (g)

Results

The mass, W_f, and initial volume, $V_{f.T0}$, of fluid in the slurry is obtained from the following expressions:

$$W_f(g) = W_{sc} - C - D_s$$
$$V_{f.T0}(ml) = \frac{W_f}{G_f \cdot \rho_w}$$

where ρ_w is the density of water (in g/ml) and G_f is the specific gravity of the pore fluid. The value of G_f can be determined with a hydrometer. The final dry density of the slurry, $\rho_{dry.Tf}$, is given by

$$\rho_{dry.Tf}\left(\frac{g}{ml}\right) = \frac{D_S}{V_{Tf}}$$

An indication of the density of the solid particles, ρ_s, can be obtained from the expression

$$\rho_S\left(\frac{g}{ml}\right) = \frac{D_S}{V_{T0} - V_{f.T0}}$$

The value of ρ_s obtained from the above expression can be compared with results from specific gravity tests.

The final volume of supernatant fluid expressed as a percentage of the initial volume of fluid in the sample, $V_{sup.Tf}$, is given by

$$V_{sup.Tf}(\%) = \left(\frac{V_{T0} - V_{Tf}}{V_{f.T0}}\right) \cdot 100$$

The dry density of the slurry, $\rho_{dry.Tn}$, and the volume of supernatant fluid, $V_{sup.Tn}$, at any time T_n during the test can be obtained from the following expressions:

$$\rho_{dry.Tn}\left(\frac{g}{ml}\right) = \frac{D_S}{V_{Tn}}$$
$$V_{sup.Tn}(\%) = \left(\frac{V_{T0} - V_{Tn}}{V_{f.T0}}\right) \cdot 100$$

Values of $\rho_{dry.Tn}$ and $V_{sup.Tn}$ can be plotted against $(T_n - T_0)$.

Drained settling test

Description

A drained settling test is similar in principle to an undrained settling test, except that the sample is allowed to drain from the base. The main purpose of this test is to determine the increase in final density when underdrainage is provided. The test can also be used to obtain an indication of quality of the supernatant and underdrainage fluid emanating from the hydraulic fill.

Apparatus

- Balance
- 1 litre measuring cylinder
- Stopwatch
- Oven set at 105±0.5 °C
- Column with an open top and a drainage outlet at the base
- Two bottles with lids, one to collect supernatant fluid and the other under-drainage fluid during the test.

Procedure

- A sand filter or an equivalent high-permeability material is placed at the base of the column and this is covered with a filter paper, such as Whatman 42. The filter paper should fit tightly inside the column.
- The column is filled with deionised water to a level above the filter paper, the tap is opened, and water allowed to drain. When all the water has drained, the tap is closed.
- The mass of the two empty bottles with lids is recorded.
- The mass of the measuring cylinder is recorded.
- Dry material and deionised or process water, as appropriate, are mixed in the right proportions to create a slurry with the correct solids content. The 1 l measuring cylinder is filled with this mix.
- The mass of the cylinder and slurry is recorded and the top of the cylinder sealed to prevent evaporation losses.
- The sample is vigorously shaken to ensure a homogeneous mix at the start of the test.
- The slurry is poured inside the column and the initial height of the slurry recorded. The initial time is recorded and the stopwatch started. A perforated disk, with a diameter smaller than the internal diameter of the column, held at the end of a stick, can be used to protect the surface of the filter paper whilst the slurry is being poured.
- The height of the settled solids is recorded at intervals of time.
- At suitable intervals, supernatant and underdrainage fluid is removed, placed inside the bottles, and the mass recorded. This is continued until no more fluid can be collected. During all stages of the test it is important to take precautions to minimise evaporation losses.
- Readings are taken until the height of settled solids is constant.
- At the end of the test the remaining supernatant water is carefully decanted and the slurry is removed from the cylinder and placed in a container of known mass. The slurry is dried in an oven set at 105±0.5 °C and the mass of solids determined.
- Some of the dry material is used to determine the particle specific gravity as indicated in EN ISO 17892-3.

The following quantities are measured before the start of the test:

- Mass of the slurry placed in the column, W_s (g)
- Initial volume of the slurry placed in the column, V_{T0} (ml)
- Initial time at start of test, T_0

The following quantities are measured during the settling period:

- Time when reading is taken, T_n
- Volume of supernatant fluid removed, V_s (ml)
- Volume of underdrainage fluid released, V_u (ml)
- Volume of settled solids, V_{Tn} (ml)

The following quantities are measured at the end of the test:

- Time of final reading, T_f
- Volume of final settled solids, V_{Tf} (ml)
- Mass of dry solids after drying, D_s (g)

Results

The initial slurry density, $\rho_{slurry.T0}$, and solids content, P_{T0}, are given by the following expressions:

$$\rho_{slurry.T0}\left(\frac{g}{ml}\right) = \frac{W_S}{V_{T0}}$$

$$P_{T0}(\%) = \frac{D_S - (W_S - D_S)(G_f - 1)}{W_S}$$

where G_f is the specific gravity of the pore fluid. The value of G_f can be determined with a hydrometer.

The initial volume of fluid in the slurry, $V_{f.T0}$, is obtained from

$$V_{f.T0}(ml) = \frac{W_S - D_S}{G_{f \cdot \rho_w}}$$

where ρ_w is the density of water (in g/ml).

An indication of the density of the solid particles, ρ_s, can be obtained from the expression

$$\rho_S\left(\frac{g}{ml}\right) = \frac{D_S}{V_{T0} - V_{f.T0}}$$

The value of q_s obtained from the above expression can be compared with results from specific gravity tests. The final volume of the underdrainage fluid as a percentage of the initial volume of fluid in the slurry, $V_{u.Tf}$, is given by

$$V_{u.Tf}(\%) = \frac{\sum_n V_u}{V_{f.T0}} \cdot 100$$

where $\sum V_u$ is the total volume of underdrainage collected during the test. The calculation of the final volume of supernatant fluid $V_{s.Tf}$ as a percentage of the initial volume of fluid in the slurry is done in a similar way by measuring the total volume of supernatant fluid ΣV_s.

After the sample has reached equilibrium the final dry density of the sample, $\rho_{dry.Tf}$, can be obtained from the following two expressions, which should yield the same result

$$\rho_{dry.Tf}\left(\frac{g}{ml}\right) = \frac{D_s}{V_{Tf}}$$

$$\rho_{dry.Tf}\left(\frac{g}{ml}\right) = \frac{D_s}{V_{T0} - \sum_n V_u - \sum_n V_s}$$

The volumes of underdrainage, $V_{u.Tn}$, and supernatant fluid, $V_{s.Tn}$, as percentages of the initial volume of fluid at any time T_n during a test can be obtained from

$$V_{u.Tn}(\%) = \frac{\sum_n V_u}{V_{f.T0}} \cdot 100$$

$$V_{s.Tn}(\%) = \frac{\sum_n V_s}{V_{f.T0}} \cdot 100$$

where $\sum V_u$, and $\sum V_s$ now correspond to the total volumes of underdrainage and supernatant fluid collected between the start of the test and time T_n.

The dry density of the slurry, $\rho_{dry.Tn}$, at any time T_n during a test is given by the expression

$$\rho_{dry.Tn}\left(\frac{g}{ml}\right) = \frac{D_s}{V_{T0} - \sum_n V_u - \sum_n V_s}$$

The variation in dry density, volume of underdrainage fluid and volume of supernatant fluid can be plotted against $(T_n - T_0)$.

After completion of the drained settling test the sample can be tested in a permeameter.

Air-drying test

Description

This test simulates the deposition of hydraulic fill using the sub-aerial technique. It allows determination of the minimum dry density and rate of drying as well as the relationship between water content, saturation and dry density.

Apparatus

- Balance
- Two beakers of 1 l capacity each
- Measuring cylinder
- Stopwatch
- Two ovens, one set at 55±0.5 °C and the other at 105±0.5 °C

Procedure

- The two beakers are weighed and their internal dimensions measured.
- The inside surface of the beakers that will contain the slurry is coated with a lubricating layer, such as silicone grease. The lubricating layer ensures that cracking takes place around the perimeter of the sample. In this way it becomes easier to measure the final volume of the dry sample.
- Dry material and deionised or process water, as appropriate, are mixed in the measuring cylinder in the right proportions to create a slurry with the correct solids content. The lubricated beaker is filled with this mix.
- An equal volume of deionised or process water, as appropriate, is poured in the second beaker.
- The two beakers are placed next to each other in direct sunlight or under a heat source and the initial time recorded.
- During the initial settling stage, the mass and volume of the slurry and of the water are measured at regular intervals until the volume of the slurry equilibrates.
- As the slurry settles, supernatant fluid may be removed with a pipette. If this is done, the mass of the sample before and after removal of supernatant fluid should be compared with the mass of extracted fluid. Removal of fluid should be done with care to ensure that the surface of the slurry is not disturbed.
- If the volume of water filling the second beaker is low, more water can be added and adjustments made in the calculations.
- Once the slurry has completely settled and all supernatant fluid been removed, air drying commences. As the sample dries it will shrink. The volume and mass of the sample is still recorded at regular intervals; however, it might prove difficult to estimate the volume accurately, especially if the sample cracks unevenly. The use of lubrication on the internal wall of the beaker will, in most cases, result in a single crack forming along the perimeter of the sample, in the contact between the slurry and the beaker.
- After the sample has reached equilibrium and there is no further change in mass or volume, both beakers are placed on top of the oven set at 55 °C until equilibrium is again reached. This process is repeated by placing the beaker first on top of the oven set at 105 °C and thereafter inside the oven set at 55 °C. Once there is no further loss in moisture, the sample is considered air-dry.
- The air-dry sample is removed from the beaker and placed in the oven set at 105 °C to determine the mass of the dry soil.
- Some of the dry material is used to determine the particle specific gravity as indicated in EN ISO 17892-3.

The following quantities are measured before the start of the test:

- Mass of the beaker to be filled with slurry, C_s (g)
- Mass of the beaker to be filled with water, C_w (g)
- Area of the beaker to be filled with water, A_w (mm^2)
- Initial mass of slurry and beaker, $W_{cs.T0}$ (g)
- Initial volume of the slurry placed in the beaker, $V_{s.T0}$ (ml)
- Initial mass of water and beaker, $W_{cw.T0}$ (g)
- Initial time at start of test, T_0

The following quantities are measured during the settling period:

- Time when reading is taken, T_n
- Mass of slurry and beaker, $W_{sc.Tn}$ (g)
- Volume of slurry, $V_{s.Tn}$ (ml)
- Mass of water and beaker, $W_{cw.Tn}$ (g)

The following quantities are measured during the air-drying period:

- Time when reading is taken, T_n
- Mass of slurry and beaker, $W_{sc.Tn}$ (g)
- Volume of slurry before allowance for cracks, $V_{s.Tn}$ (ml)
- Volume of cracks, $V_{c.Tn}$ (ml)
- Mass of water and beaker, $W_{cw.Tn}$ (g)

The following quantities are measured at the end of the test:

- Mass of dry solids after drying, D_s (g)

Results

The formulae used to obtain the variation in dry density and percent supernatant fluid with time in an undrained settling test can also be used during the sedimentation stage of an air-drying test.

$$\rho_{dry.Tn}\left(\frac{g}{ml}\right) = \frac{D_s}{V_{s.Tn}}$$

$$V_{sup.Tn}(\%) = \left(\frac{V_{s.T0} - V_{s.Tn}}{V_{f.T0}}\right).100$$

where

$$V_{f.T0}(ml) = \frac{W_{sc.T0} - C_s - D_s}{G_f \cdot \rho_w}$$

and where ρ_w is the density of water (in g/ml) and G_f is the specific gravity of the pore fluid.

Once the air-drying stage has commenced, the percentage reduction in the volume of the sample at time T_n, $V_{s.\%}$, can be calculated from

$$V_{S.\%}(\%) = \left[\frac{V_{s.T0} - (V_{s.Tn} - V_{c.Tn})}{V_{s.T0}}\right] \cdot 100$$

The dry density of the sample, $\rho_{d.Tn}$, is given by the expression

$$\rho_{d.Tn}\left(\frac{g}{ml}\right) = \frac{D_s}{(V_{s.Tn} - V_{c.Tn})}$$

By knowing the particle specific gravity of the material forming the slurry, G_s, it is possible to determine the degree of saturation of the sample, $S_{r.Tn}$, at time T_n:

$$S_{r.Tn}(\%) = \left[\frac{(W_{sc.Tn} - C_s) - D_s}{(V_{s.Tn} - V_{c.Tn}) \cdot \rho_w - \frac{D_s}{G_s}}\right] \cdot 100$$

where ρ_w is the density of water (in g/ml). In addition, the gravimetric water content, w_{Tn}, is given by

$$w_{Tn}(\%) = \left[\frac{(W_{sc.Tn} - C_s) - D_s}{D_s}\right] \cdot 100$$

and the void ratio, e_{Tn}, can be obtained from the expression

$$e_{Tn} = \left[\frac{G_s \cdot w_{Tn}}{S_r \cdot Tn}\right]$$

During the test, the water filled beaker is used to monitor evaporation losses. The water loss, $W_{l.Tn}$, at time T_n is obtained from the following expression:

$$w_{1.Tn}(g) = w_{cw.T0} - w_{cw.Tn}$$

As 1 g = 1 ml, evaporation from the beaker, E, in ml/mm^2 is given by

$$E\left(\frac{ml}{mm^2}\right) = \frac{W_{1.Tn}}{A_w}$$

The variation in volume, dry density, water content, degree of saturation, and void ratio can be plotted against ($T_n - T_0$) or against evaporation.

Slurry consolidation test

Description

This test can be used to obtain the consolidation characteristics of hydraulic fill at very low stresses, in the range 0–5 kPa. A sample is prepared at the required solids content and placed in a column with an open top and a drainage outlet, similar to the one used to perform a drained settling test. With the bottom drainage outlet closed, the sample is first allowed to settle and the surface fluid removed.

Thereafter, the drainage outlet is opened to allow pore water dissipation. The change in sample volume with time is recorded during the test. Results can be used to calculate average values of vertical stress, void ratio, coefficient of consolidation, coefficient of compressibility, and permeability.

Apparatus

- Balance
- 1 l measuring cylinder
- Stopwatch
- Oven set at 105±0.5 °C
- Column with an open top and a drainage outlet at the base

Procedure

The test is conducted in two phases: settlement and consolidation. The first phase is similar to the initial stages of a drained settling test.

Preparation

- A sand filter or an equivalent high-permeability material is placed at the base of the column and this is covered with a filter paper, such as Whatman 42. The filter paper should fit tightly inside the column.
- The column is filled with deionised water to a level above the filter paper, the tap is opened, and water allowed to drain. When all the water has drained, the tap is closed.
- Dry material and deionised or process water, as appropriate, are mixed in the right proportions to create a slurry with the correct solids content. The 1 l measuring cylinder is filled with this mix.
- The mass of the slurry is recorded and the top of the cylinder sealed to prevent evaporation losses.
- The sample is vigorously shaken to ensure a homogeneous mix at the start of the test.

Settlement

- The slurry is poured inside the column and the initial height of the slurry recorded. The initial time is recorded and the stopwatch started. A perforated disk, with a diameter smaller than the internal diameter of the column, held at the end of a stick, can be used to protect the surface of the filter paper whilst the slurry is being poured.
- The height of the settled solids is recorded at intervals of time.
- During the settlement stage it is important to take precautions to minimise evaporation losses by covering the top of the column.
- Readings are taken until the height of settled solids is constant.
- When the sample has reached the end of the settling stage, the height of solids and supernatant fluid are recorded.

Consolidation

- The drainage outlet at the base of the column is opened and the starting time of the consolidation stage recorded.
- The height of the slurry and the volume of fluid collected from the drainage outlet are recorded at intervals of time.
- During the consolidation stage the level in the column of supernatant fluid is kept constant by the addition of water.
- The consolidation stage ends when there is no further compression of the slurry.
- At the end of the test the slurry is removed from the column and placed in a container of known mass. The slurry is dried in an oven set at 105±0.5 °C and the mass of solids determined.
- Some of the dry material is used to determine the particle specific gravity as indicated in EN ISO 17892-3.

The following quantities are measured at the start of the test:

- Mass of the slurry placed in the column, $W_{s.T0}$ (g)
- Volume of the slurry placed in the column, $V_{s.T0}$ (ml)
- Area of the column, A_c (mm^2)
- Initial time at start of test, T_0.

The following quantities are measured at the start of the consolidation stage:

- Height of settled slurry in column, $H_{s.Tc}$ (mm)
- Height of supernatant fluid above the slurry surface, $H_{w.Tc}$ (mm)
- Time of start of the consolidation stage, T_c, corresponding to the time when the drainage outlet is opened.

The following quantities are measured during the consolidation stage:

- Height of settled slurry in column, $H_{s.Tn}$ (mm)
- Height of supernatant fluid above the slurry surface, $H_{w.Tn}$ (mm)
- Volume of fluid released through the drainage outlet since the previous reading, ΔV_{Tn} (ml)
- Time of reading, T_n

The following quantities are measured at the end of the consolidation stage:

- Height of settled slurry in column, $H_{s.Tf}$ (mm)
- Height of supernatant fluid above the slurry surface, $H_{w.Tf}$ (mm)
- Mass of dry solids after drying, D_s (g)

Results

The initial slurry density, $\rho_{slurry.T0}$, and solids content, P_{T0}, are given by the following expressions:

$$\rho_{slurry.T0}\left(\frac{g}{ml}\right) = \frac{W_{s.T0}}{V_{s.T0}}$$

$$P_{T0}(\%) = \frac{D_s - (W_{s.T0} - D_s)(G_f - 1)}{W_{s.T0}}$$

where G_f is the specific gravity of the pore fluid. The value of G_f can be determined with a hydrometer.

The initial volume of fluid in the slurry, $V_{f.T0}$, is obtained from

$$V_{f.T0}(ml) = \frac{W_{s.T0} - D_s}{G_f \cdot \rho_w}$$

where ρ_w is the density of water (in g/ml).

An indication of the density of the solid particles, ρ_s, can be obtained from the expression

$$\rho_s\left(\frac{g}{ml}\right) = \frac{D_s}{V_{s.T0} - V_{f.T0}}$$

The value of ρ_s obtained with the above expression can be compared with results from specific gravity tests.

The following quantities can be determined at the start of the consolidation stage, corresponding to time T_c:

Initial slurry volume, $V_{s.Tc}$

$$V_{s.Tc}(ml) = \frac{H_{s.Tc} \cdot A_c}{1000}$$

Initial slurry dry density, $\rho_{d.Tc}$

$$\rho_{d.Tc}\left(\frac{g}{ml}\right) = \frac{D_s}{V_{s.Tc}}$$

Initial slurry bulk density, ρ_{Tc}

$$\rho_{Tc}\left(\frac{g}{ml}\right) = \frac{D_s + \left(V_{s.Tc} - \frac{D_s}{\rho_s}\right) \cdot G_f \cdot \rho_w}{V_{s.Tc}}$$

Initial void ratio, e_{Tc}

$$e_{Tc} = \frac{\rho_s}{\rho_{d.Tc}} - 1$$

Initial average effective stress, $\sigma'_{v.Tc}$

$$\sigma'_{v.Tc}\left(\frac{kN}{m^2}\right) = \frac{H_{s.Tc} \cdot (\rho_{Tc} - G_f \cdot \rho_w) \cdot 9.81}{2.1000}$$

where ρ_w is in g/ml.

Similar quantities can be calculated for the end of the consolidation stage, corresponding to T_f, using the final height of slurry:

Final slurry volume, $V_{s.Tf}$

$$V_{s.Tf}(ml) = \frac{H_{s.Tf} \cdot A_C}{1000}$$

Final slurry dry density, $\rho_{d.Tf}$

$$\rho_{d.Tf}\left(\frac{g}{ml}\right) = \frac{D_s}{V_{s.Tf}}$$

Final slurry bulk density, ρ_{Tf}

$$\rho_{Tf}\left(\frac{g}{ml}\right) = \frac{D_s + \left(V_{s.Tf} - \frac{D_s}{\rho_s}\right) \cdot (G_f \cdot \rho_w)}{V_{s.Tf}}$$

Final void ratio, e_{Tf}

$$e_{Tf} = \frac{\rho_s}{\rho_{d.Tf}} - 1$$

Final average effective stress, $\sigma'_{v.Tf}$

$$\sigma'_{v.Tf}\left(\frac{kN}{m^2}\right) = \frac{H_{s.Tf} \cdot (\rho_{Tf} - G_f \cdot \rho_w) \cdot 9.81}{2.1000}$$

From the above it is possible to determine a number of parameters: coefficient of consolidation, coefficient of compressibility, compression index and permeability.

Coefficient of consolidation, c_v

The average height of the slurry, $H_{ave,}$ is given by

$$H_{ave}(mm) = \frac{H_{s.Tc} - H_{s.Tf}}{2}$$

and the coefficient of consolidation, c_v, can be calculated from the expression

$$c_v\left(\frac{m^2}{yr}\right) = \frac{T_v \cdot \left(\frac{H_{ave}}{2}\right)^2}{T_n - T_c} \cdot 31.54$$

Where $(T_n - T_c)$ is measured in seconds.

The time factor, T_v, varies during the test. It is a function of the average degree of consolidation, U, and can be obtained from tables or charts for two-way drainage. The degree of consolidation is given by

$$U = \frac{H_{s.Tc} - H_{s.Tn}}{H_{s.Tc} - H_{s.Tf}}$$

Values of T_v for 50, 70 and 90% consolidation are 0.196, 0.398 and 0.848 respectively.

Coefficient of compressibility, m_v

The coefficient of compressibility, m_v, can be obtained from the expression

$$m_v\left(\frac{m^2}{MN}\right) = \frac{1}{H_{s.Tc}}\left(\frac{H_{s.Tc} - H_{s.Tf}}{\sigma'_{v.Tf} - \sigma'_{v.Tc}}\right) \cdot 1000$$

Compression index, C_c

The compression index can be obtained from the following expression

$$C_c = \frac{e_{Tc} - e_{Tf}}{\log_{10}\left(\frac{\sigma'_{v.Tf}}{\sigma'_{v.Tc}}\right)}$$

Coefficient of permeability, k_v

The average coefficient of permeability in the vertical direction, k_v, can be calculated from the following expression:

$$k_v\left(\frac{m}{s}\right) = c_v \cdot m_v \cdot G_f \cdot \rho_w \cdot \frac{9.81}{3.514 \cdot 10^{10}}$$

where ρ_w is in g/ml.

As the height of the slurry, height of supernatant fluid and volume of fluid released by the underdrainage are monitored throughout a test, it is possible to obtain an estimate of dry density, $\rho_{d.Tn}$, and vertical permeability, $k_{v.Tn}$, at any time T_n using the following formulae:

$$\rho_{d.Tn}\left(\frac{g}{ml}\right) = \frac{D_s}{H_{s.Tn} \cdot A_c} \cdot 1000$$

$$k_{v.Tn}\left(\frac{m}{s}\right) = \left(\frac{\Delta v_{Tn}}{\Delta T_n}\right) \cdot \left(\frac{H_{s.Tn}}{H_{s.Tn} + H_{w.Tn}}\right) \cdot \frac{1}{A_c}$$

where $\Delta T_n = T_n - T_{n-1}$ is in seconds. The above expressions allow a graph of permeability versus dry density to be drawn.

Appendix C: Proforma MWF Inspection Sheets Mike Cambridge

Table C1 Contact details for all inspection and monitoring personnel

Contact details (***name, full postal address, direct phoneline and emergency numbers***)		
Owner/Operator:		
Name and situation of mine waste facility:	***Include location and grid reference***	
General Manager:		
Facility Manager:		
Designer:		
Inspecting Engineer:		
MWF Responsibilities	**MWF Supervisors**	**Contact details**
	Inspectors	

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Owner’s responsible person (HSE Director)
Dated this ______ day of __________________________

Table C2 Daily inspection report (Sheet 1 of 2) Week ending_____________

Weather	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Rainfall (mm)							
Embankment seepage							
All flow meters/measurement weirs fully functional							
Any tailings/solids discolouration in seepage							
Toe drain channels clear of obstructions							
Spillway and surround							
Reservoir level (mOD)							
Freeboard to emergency spillway crest (mm)							
Emergency spillway inlet clear of obstructions							
Emergency spillway outlet clear of obstructions							
Diversion channel							
Obstructions in inlets to diversion channel							
Diversion channel clear of obstructions							
Diversion channel outlet clear of obstructions							
Tailings deposition							
ID number of operating disposal pipelines/spigots							
Number of spigots/open ends in operation							
Disposal spigots/open ends clear and unobstructed							
Excessive erosion of tailings beach							
Leakage or movement of pipeline							
Tailings control valves fully operational							
Signs of instability in pipelines							
Decant							
Decant approach channel clear of obstructions							
Return pump fully operational							
Reservoir clarity compliant							
Tailings in return flow							
General							
Suitable edge protection on all haul roads							
Any deviations from approved disposal procedures							
Inspector's initials							

Remarks ____
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Facility supervisor_________________ **Date**_____________________

Table C2 Daily inspection report (Sheet 2 of 2) Week ending______________

Main MWF embankment	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Development of new seepages in embankment face							
Development of new seepages downstream							
New cavities/cracks/erosion/animal activity in faces							
Signs of instability/surface movement							
Suitable edge protection on crest							
Saddle dam No. 1							
Development of new seepages in embankment face							
Development of new seepages downstream							
New cavities/cracks/erosion/animal activity in faces							
Signs of instability/surface movement							
Suitable edge protection on crest							
Saddle dam No. 2							
Development of new seepages in embankment face							
Development of new seepages downstream							
New cavities/cracks/erosion/animal activity in faces							
Signs of instability/surface movement							
Suitable edge protection on crest							
Saddle dam No. 3							
Development of new seepages in embankment face							
Development of new seepages downstream							
New cavities/cracks/erosion/animal activity in faces							
Signs of instability/surface movement							
Suitable edge protection on crest							
Old workings							
Signs of surface movement							
Development of new voids/depressions							

(continued)

Table C2 (continued)

Main MWF embankment	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
General							
Any deviations from agreed working procedures							
All site boundaries secure and safety provisions in place							
Any other health and safety issues							
Inspector's initials							

Remarks ____
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Facility supervisor_________________ **Date**_____________________

Table C3 Daily water supply/pollution control dam inspection report Week ending ____________

Water supply embankment	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Development of new seepages in embankment face							
Development of new seepages downstream							
New cavities/cracks/erosion/animal activity in faces							
Signs of instability/surface movement							
Spillway and surround							
Reservoir level (mOD)							
Freeboard to emergency spillway crest (mm)							
Emergency spillway inlet clear of obstructions							
Emergency spillway outlet clear of obstructions							
Embankment seepage							
Measurement weir fully functional							
Any solids discolouration in seepage							
Toe drain channels clear of obstructions							

(continued)

Table C3 (continued)

Water supply embankment	**Mon**	**Tue**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**
Seepage m^3/hr							
Return water system							
Inlet and return pumps fully functional							
Valves fully operational							
Leakage or movement of pipelines							
Any signs of damage or disturbance							
Pollution control dams							
Reservoir level (mOD)							
Freeboard to emergency spillway crest (mm)							
Emergency spillway inlet/outlet clear of obstructions							
Any signs of instability, seepage or erosion							
Signs of instability/surface movement							
Control structures and all valves fully functional							
General							
Any deviations from agreed working procedures							
All site boundaries secure and safety provisions in place							
Any other health and safety issues							
Inspector's initials							

Remarks ____

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Facility supervisor________________ **Date**____________________

Table C4 Monthly inspection reports (Sheet 1 of 2) Month ending _______________

MWF embankment surfaces	Comments	Actions
Main dam		
Any reported or noted change in condition of embankment		
Any signs of instability, seepage or erosion		
Saddle dam 1		
Any reported or noted change in condition of embankment		
Any signs of instability, seepage or erosion		
Saddle dam 2		
Any reported or noted change in condition of embankment		
Any signs of instability, seepage or erosion		
Seepage return system		
Seepage control sumps/weirs fully functional		
Pump and float switches fully functional		
Excessive siltation/oxide precipitation or other obstructions		
Any leakage or other damage to return lines		
Any erosional damage to embankment faces		
Embankment toe drains		
Toe drains clear of obstructions		
Toe drains clear of vegetation		
Emergency spillway		
Any reported or noted change in condition of spillway structure		
Emergency spillway inlet and approach clear of obstructions		
Emergency spillway outlet and channel clear of obstructions		
Diversion channel		
Channel inlets clear of obstructions and vegetation		
Channels clear of debris and vegetation		
Channel outlets clear of obstructions and vegetation		
Any significant erosion damage		
Diversion dams		
Any reported or noted change in condition of embankment		
Any signs of instability, seepage or erosion		
Signs of instability/surface movement		
Disposal system		
All tailings pipelines secure and stable		
All valves secure and correctly positioned		
Any sign of valve damage		
Any sign of pipeline leakage or movement		
Pollution control dams		
Any reported or noted change in condition of embankments		
Any signs of instability seepage or erosion		
Signs of instability/surface movement		

(continued)

Table C4 (continued)

MWF embankment surfaces	Comments	Actions
Control structures and all valves fully functional*		
* Note when valves last tested		
General		
Any deviations from agreed working or safety procedures		
All site boundaries secure and safety devices in place		
Any other health and safety issues		

Remarks ____
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Facility supervisor________________ **Date**____________________

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Mine Manager
Dated this _____________ **day of** _________________

Table C4 Monthly inspection reports (Sheet 2 of 2) Month ending _________

Water supply reservoir embankment	Comments	Actions
Any reported or noted change in condition of embankment		
Any signs of instability, seepage, erosion or animal damage		
Spillway and surround		
Reservoir level (mOD)		
Freeboard to emergency spillway crest (mm)		
Any reported or noted change in condition of spillway structures		
Emergency spillway inlet and approach clear of obstructions		
Emergency spillway outlet and channel clear of obstructions		
Seepage return system		
Seepage control sumps/weirs fully functional		
Downstream seepage outlet channel clear and unobstructed		
Excessive siltation in seepage channel		
Any leakage or other damage to seepage return lines		
Any erosional damage to embankment faces		
Embankment toe drains		
Toe drains clear of obstructions		
Toe drains clear of vegetation		

(continued)

Table C4 (continued)

Water supply reservoir embankment	**Comments**	**Actions**
Inlet channel		
Channel inlets clear of obstructions and vegetation		
All valves secure and correctly positioned*		
Control structures and all valves fully functional*		
* Note when valves last tested		
Return water system		
Inlet and return pumps fully functional		
Valves fully operational*		
Leakage or movement of pipelines		
* Note when valves last tested		
General		
Any deviations from agreed working or safety procedures		
All site boundaries secure and safety devices in place		
Any other health and safety issues		

Remarks ____
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Dam supervisor______________________ **Date**______________

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Mine Manager

Dated this _____________ **day of** ___________________