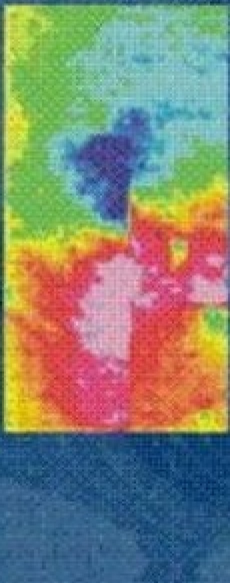
Geological Society Engineering Geology Special Publication 19

Geophysics in engineering investigations



dti

CIRIA

CIRIA C562 London 2002

Geophysics in engineering investigations

McDowell P W
Barker R D
Butcher A P
Culshaw M G
Jackson P D
McCann D M
Skipp B O
Matthews S L
Arthur J C R

CIRIA sharing knowledge ■ building best practice

6 Storey's Gate, Westminster, London SW1P 3AU
TELEPHONE 020 7222 8891 FAX 020 7222 1708
EMAIL enquiries@ciria.org.uk
WEBSITE www.ciria.org.uk

Contents

Geophysics in engineering investigations

McDowell P W *et al*

Construction Industry Research and Information Association

© CIRIA 2002 C562 ISBN 0 86017 562 6

Keywords		
ground engineering, ground investigation and characterisation, contaminated land		
Reader interest	**Classification**	
Geotechnical and civil engineers, geologists and engineering geologists, specialist geophysics contractors, consultants, clients	Availability Content Status User	Unrestricted Technical review Committee guided Engineering geologists and geotechnical engineers, those commissioning and using geophysical investigations

Published by CIRIA, 6 Storey's Gate, Westminster, London SW1P 3AU.

Note

Recent Government reorganisation has meant that DETR responsibilities have been moved variously to the Department of Trade and Industry (DTI), the Department for the Environment, Food and Rural Affairs (DEFRA), and the Department for Transport, Local Government and the Regions (DTLR). References made to the DETR in this publication should be read in this context.

For clarification, readers should contact the Department of Trade and Industry.

Acknowledgements

This report is the output of CIRIA's Research Project 562: Civil engineering applications of geophysical investigation techniques. It is the result of collaboration between CIRIA, a working party of the Engineering Group of the Geological Society, the British Geological Survey and the Building Research Establishment. The report constitutes the Environment Agency R & D Technical Report W265. The work was part funded under the Environment Agency's National R & D Programme under Project WSA-032.

Members of the working party were:

EurIng P W McDowell (chairman)	Consultant
Dr R D Barker	University of Birmingham
Mr A P Butcher	Building Research Establishment
Dr P D Jackson	British Geological Survey
Professor D M McCann	University of Edinburgh
Dr B O Skipp	Consultant

This report was written under contract to CIRIA by the members of the working party together with Mr W J Rankin of Mott MacDonald Limited and Mr J R Arthur of J Arthur and Associates (for chapters 3 and 11 and Appendix 1), Mr M G Culshaw of the British Geological Survey (chapter 4), and Mr S L Matthews of the Building Research Establishment (chapter 10). The report was edited by Dr A J Pitchford and Mr F M Jardine of CIRIA.

The project was carried out and the Report prepared under the guidance of the following steering group:

Professor M G Culshaw (chairman)	British Geological Survey Engineering Group of the Geological Society (representative)
Mr C D Eldred	Sir Alexander Gibb and Partners Ltd
Mr G Holland	British Waterways
Mr A T Pepper	Environment Agency
Mr W J Rankin	Mott MacDonald Limited
Mr P B Woodhead	Department of Environment, Transport and the Regions

CIRIA's Research Managers for the project were Mr F M Jardine and Dr A J Pitchford.

The project was funded by the construction directorate of the Department of the Environment, Transportation and the Regions, The British Geological Survey, The Building Research Establishment, The Environment Agency, British Waterways, The Research and Development Enabling Fund of the Institution of Civil Engineers and in-kind contributions from the working party and industry.

CIRIA and the authors gratefully acknowledge the support of these funding organisations and the technical help and advice provided by the members of the steering group. Contributions do not imply that individual funders necessarily endorse all views expressed in published outputs.

Summary

This report is the result of collaboration between CIRIA, the Engineering Group of the Geological Society, the British Geological Survey, and the Building Research Establishment. It presents a logical sequence through the process of using geophysical investigation methods in site characterisation. Following the introduction about the roles of geophysical methods, Chapter 2 provides the background to geophysics as an investigative tool. Chapter 3 sets out the procurement, management and reporting frameworks for a geophysical investigation and stresses the importance of the involvement of a recognised geophysics specialist adviser. Chapter 4 explains the need for a conceptual ground model in order that appropriate investigative methods are chosen. The underlying science and current practices of the main techniques are explored in Chapter 5. This is followed by an explanation of the processes of data acquisition, handling and presentation. There are separate sections for geological, geotechnical, geo-environmental and structural engineering applications, which consider the different targets determinable by geophysical methods. The report concludes with recommendations for practice.

List of figures

List of tables

List of boxes

Abbreviations

2-D	two dimensional
3-D	three dimensional
AC	alternating current
AGAP	Association for Quality in Applied Geophysics (of France)
ASTM	American Society for Testing and Materials
BGS	British Geological Survey
BRE	Building Research Establishment
BS	British Standard
BSI	British Standards Institution
CAT	cable avoidance tool
CCTV	closed circuit television
CDM	Construction (Design and Management) Regulations
CDP	common depth point
CIRIA	Construction Industry Research and Information Association
DGPS	differential global positioning system
DNAPL	dense non-aqueous phase liquid
EGA	Engineering Geophysics Adviser
EK	Electrokinesis
EKS	Electrokinetic sounding/surveying
EM	Electromagnetic
EN	Euro Norm
ER	electrical resistivity
FFT	fast Fourier transform (analysis)
FMS	formation scanning (tool)
FRF	frequency response function
GA	Geotechnical adviser
GIS	Geographical information system
GPR	ground-probing radar (ground penetrating radar)
GPS	global positioning system
HAC	high alumina cement
IP	induced polarisation
LNAPL	light non-aqueous phase liquid
MGLLS	mobile geomembrane leak location surveying
MT	magnetotelluric
NDT	non-destructive testing
NMR	nuclear magnetic resonance
PC	personal computer
PVC	polyvinyl chloride
QA	quality assurance
QA/QC	quality assurance/quality control

RMR	rock mass rating
RMS	root mean square
RQD	rock quality designation
SASW	spectral analysis of surface waves
SIRT	simultaneous iterated reconstruction techniques
SP	spontaneous potential/self potential
TDEM	time domain electromagnetic systems
TDR	time domain reflectometry
TEM	transient electromagnetic method
TIDEM	time domain electromagnetic system
TRL	Transport Research Laboratory
TRRL	Transport and Road Research Laboratory
UPV	ultrasonic pulse velocity
VES	vertical electrical sounding
VLF	very low frequency
VSP	vertical seismic profiling

COMMONLY USED UNITS AND CONVERSION FACTORS

(commonly used units are highlighted in bold)

Measured parameter or property	Cgs unit	SI unit	Conversion factor		
Electrical resistivity	ohm-cm (Ω cm)	**ohm-m (Ω m)**	1 Wcm	=	10^{-2} Ωm
Electrical conductivity	mho/cm	**Siemen/m (S/m)**	1 S/m	=	1 mho/m
				=	$ohm^{-1} m^{-1}$
		milliSiemen/m (mS/m)	1 mS/m	=	1 mmho/m
Seismic velocity	cm/s	**m/s**	1 cm s-1	=	10^{-2} ms^{-1}
		km/s	1 km/s	=	10^{3} ms^{-1}
		m/ms	1 m/ms	=	10^{3} ms^{-1}
Density	gm/cm^3 (g/cc)	**kg/m^3**	1 kgm-3	=	10^{-3} Mgm^{-3}
		$tonne/m^3$	1 tm-3	=	1 Mgm^{-3}
		Mg/m^3 / Mgm^{-3}	1kgm-3	=	10^{-3} gcm^{-3}
Gravitational field strength	Gal	gravity unit (gu)	1 Gal	=	1 cms^{-2}
			1 gu	=	10^{-6} ms^{-2}
	milliGal (mGal)		1 mGal	=	10 gu
	microGal (μGal)		1 mGal	=	10^{-2} gu
Magnetic field strength	Gamma (γ)	**nanoTesla (nT)**	1 nT	=	10^{-9} T
			1 nT	=	1 γ
				=	10^{-5} gauss
Thermal conductivity	—	**W/m°K**	—	—	—
Elastic moduli	—	**GigaPascal (GPa)**	1 GPa	=	10^{9} Pa
		GN/m^2		=	10^{9} Nm-2

Geological Society, London, Engineering Geology Special Publications

About this title

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. NP
doi:10.1144/GSL.ENG.1999.019.01.14

dti
Department of Trade and Industry

The Construction Directorate of the DTI supports the programme of innovation and research to improve the construction industry's performance and to promote more sustainable construction. Its main aims are to improve quality and value for money from construction, for both commercial and domestic customers, and to improve construction methods and procedures.

The full potential of geophysics in engineering investigations is still to be realised. The many available techniques can provide important information about the ground, its mass properties, its small-scale variations, and its anomalies of structure or content. The advantage of a geophysical survey is that it enables information to be obtained for large volumes of ground that cannot be investigated by direct methods due to cost. The applications of geophysics in the characterisation of contaminated land are still developing, but have great potential for example in the distribution and migration of pollutants in the ground and groundwater. Geophysics is still insufficiently or inappropriately used in engineering and the newer capabilities are not appreciated.

This report is published in co-operation with the Geological Society and presents a logical guide through the process of using geophysical investigation methods in site characterisation. It explores the roles of geophysical methods and provides the background to geophysics as an investigative tool. The procurement, management and reporting frameworks for a geophysical investigation are set out and the underlying science and current practices of the main techniques are explained, as well as the processes of data acquisition, handling and presentation. The different targets determinable by geophysical methods are considered in separate sections for geological, geotechnical, geo-environmental and structural engineering applications. The report concludes with recommendations for practice.

CIRIA

C562

ISBN 0 86017 562 6

Geological Society, London, Engineering Geology Special Publications

Geophysics in civil engineering

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 19-22
doi:10.1144/GSL.ENG.2002.019.01.01

1 Geophysics in civil engineering

The full potential of geophysics in engineering investigations is yet to be realised. With investigative capabilities ranging from the detail of well-logging to the long traverses of studies of geological structure, the many available techniques can provide important information about the ground, its mass properties, its small-scale variations, and its anomalies of structure or content. The advantage of a geophysical survey is that it enables information to be obtained for large volumes of ground that cannot be investigated by direct methods because of the costs involved. The applications of geophysics in the characterisation of contaminated land, eg the distribution and migration of pollutants in the ground and groundwater, are still developing, but with great potential. These are still insufficiently or inappropriately used in engineering and the newer capabilities are not appreciated. There is a need for up-to-date guidance about how to apply geophysical investigations.

The underlying aims of this report, therefore, are to prepare guidance for civil and geotechnical engineers, and their clients on:

- the integration of geophysical investigations into the design and construction process
- the use of geophysics for determining engineering parameters
- the capabilities of geophysics for investigating ground contamination and grouion.

1.1 ABOUT THIS REPORT

This report was prepared jointly by CIRIA and a working party of the Engineering Group of the Geological Society. In the mid-1990s, the Engineering Group of the Geological Society re-convened the working party to update its report, Engineering geophysics, which was published in the *Quarterly Journal of Engineering Geology* in 1988. At the same time CIRIA was actively engaged in fund-raising for a proposal *Civil engineering applications of geophysical investigation techniques*. The opportunity was taken to combine resources and methods of working in order to meet what were largely similar objectives.

The report was compiled by members of the working party, who were commissioned by CIRIA to be the lead authors of specific sections. Two members were usually assigned to each of the main sections. In addition to the Engineering Group working party members, CIRIA appointed Mott MacDonald to draft Chapter 3 on contractual arrangements, the British Geological Survey (BGS) to draft chapters 4, 6 and 9, and Building Research Establishment (BRE) to draft Chapter 10. Following CIRIA's usual practice, a steering group advised the working party and CIRIA staff on the technical sufficiency of the report. Thus the drafting has undergone several stages of review:

- by the sets of lead authors of the sections
- by the working party members as a whole
- by the Steering Group.

In addition, the drafts were reviewed by other experts and users at CIRIA's request and the draft was finally edited by CIRIA staff.

This report is the result of these processes. It embodies the experience and expertise of specialists with the guidance needed by construction and ground engineering professionals. One of the main purposes, recognised in CIRIA's proposal and a long-term aim of the geophysics specialists, was the need for guidance about setting up the right technical, administrative and contractual framework, to enable a geophysical investigation to be integrated effectively into a civil engineering site investigation.

An increasingly important employment of geophysical techniques is in the characterisation of contaminated land and in understanding changes to the environment of the ground. The need for good practice guidance on this rapidly widening subject, requires a separate section in this report.

1.2 WHAT IS GEOPHYSICS?

In the broadest sense, geophysics is the study of physical properties of the earth. As such, it makes use of the data available in geodesy, seismology, meteorology, and oceanography, as well as that relating to atmospheric electricity, terrestrial magnetism, and tidal phenomena. Applied geophysics has, by means of electrical, magnetic, gravitational, seismic, and other methods, achieved many discoveries of geological and economic importance below the earth's surface [*Chambers Dictionary of Science and Technology*, (ed) T C Collocott and A B Dobson, Revised Edition (W & R Chambers, Edinburgh, 1974)].

This report is about the geophysical techniques that are relevant to ground investigations, and the structural nature of the subsurface for engineering projects and environmental studies.

For two reasons, it is perhaps prudent not to put forward a definition of geophysical investigation:

1. The range of subjects for investigation continues to widen.
2. The techniques that are employed, and what can now be done with them, are developing rapidly.

1.3 BENEFITS AND LIMITATIONS OF GEOPHYSICAL INVESTIGATION TECHNIQUES

Geophysical investigation is an indirect approach to the investigation of ground or built structure. Geophysical techniques can be used, for example, to measure the variation of the physical properties of subsurface materials, eg compressional and shear wave velocities, electrical conductivity and resistivity. Interpretation of geophysical survey data usually requires some prior knowledge of the underlying geological structure. For optimum interpretation of geophysical survey data it is important that adequate direct control is available, which can be provided by boreholes or trial pits for example.

Geophysical surveys can offer considerable time and financial savings compared with borehole investigations. At an early stage of site investigation, it may be beneficial to undertake a reconnaissance geophysical survey to identify areas of the site which should be investigated by drilling, ie those where anomalous results are obtained. On sites where contamination is suspected, a geophysical survey may form part of a preliminary risk assessment, prior to drilling or sampling. During the on-site drilling programme geophysical surveys may be used to check the interpretation of the geological structure between the boreholes. Further geophysical surveys, both within and between the boreholes and on the ground surface, can be used to determine the geological, hydrogeological and geotechnical properties of the ground mass in which the engineering construction is taking place.

Using geophysical techniques to solve engineering problems has sometimes produced disappointing results, particularly when a method, which lacked the precision required in a particular site investigation has been used, or when a method has been specified that is inappropriate to the problem under consideration. In some cases these difficulties could have been avoided by taking expert advice before initiating the survey. In other cases the geological conditions at the site have been found to be more complex than anticipated at the planning stage of the geophysical survey and hence interpretation of the geophysical data by the geophysicist has not yielded the information expected by the engineer. It is often advisable to undertake a feasibility study at the field site to assess the suitability of the proposed geophysical techniques for the investigation of the geological problem.

Once the geophysical data have been obtained, it is possible to produce a model of the geological structure, which gives a realistic correlation with the data. The best overall model is obtained by using all the available geological information from boreholes and field mapping. Without this input of precise information, which includes knowledge of the fundamental physical properties of the geological materials at the site, the model cannot be constrained or evaluated in practical terms. There needs to be close collaboration between site geologists and engineers, and geophysicists in the interpretation of the geophysical data.

1.4 OBJECTIVES OF THE REPORT

This report has several main objectives.

1. To help engineers and engineering geophysicists avoid mistakes of the past.
2. To provide guidance on good practice for the selection, management and reporting of geophysical investigation techniques.
3. To demonstrate the need for an effective reliable team to design, carry out and interpret geophysical investigations.

1.5 REPORT STRUCTURE

The report is structured to present a logical sequence through the process of using geophysics in site characterisation (Figure 1.1). Following this introduction, Chapter 2 provides the background to geophysics as an investigative tool. The procurement, management and reporting frameworks for a geophysical investigation are set out in Chapter 3. This chapter stresses the importance of regular contact with a recognised geophysics specialist throughout the works. Chapter 4 explains the importance of producing a conceptual ground model to enable appropriate investigative methods to be selected. The basic science and general practices of common techniques and some newer techniques are explained in Chapter 5. This is followed by a description of the processes that are used to convert raw field data into a presentable format.

The different targets determinable by geophysical methods are considered in terms of: geological, geotechnical, geo-environmental and structural engineering applications (chapters 7 to 10 respectively). For each application there is a brief description of the nature of the target and what makes it amenable to particular geophysical investigation techniques, with an explanation of their practicalities and limitations. The report cites case examples and references.

The concluding remarks give guidance for practice, particularly on the way that the geophysical investigation should be planned, staffed and managed integrally with the whole scheme of investigation.

1.6 USE OF THE REPORT, ITS SCOPE AND COVERAGE

CIRIA's aim for this report is to promote good practice in the application of geophysics to construction, and this aim is shared by the Engineering Group's Working Party. The report, therefore, is about encouraging dialogue between user and specialist, about options, and about realistic expectations. If it leads to greater interaction between specifiers and those whose work is to be commissioned, between geotechnical engineers and geophysical specialists, and between those interpreting and those obtaining the data, it will be a worthwhile step in making better use of a potentially powerful set of investigative tools.

The report's coverage, however, is necessarily limited. It is not a text on geophysical methods, equipment or data processing, and it does not explain on how to "do" geophysics. Similarly, it is not a text on how to do site investigation. Instead, the intention of the report is to increase the understanding of both.

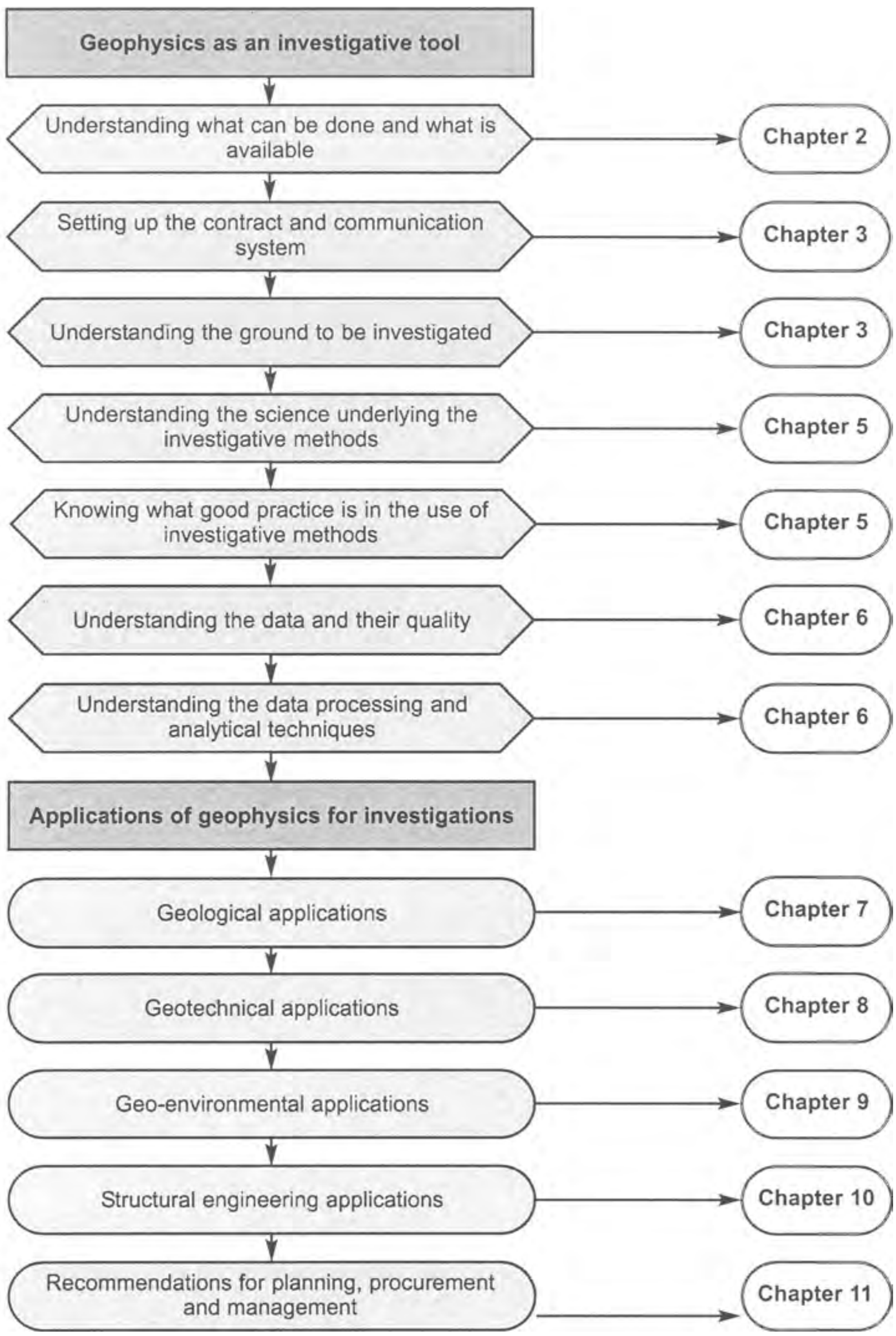


Figure 1.1 *Report structure*

Geological Society, London, Engineering Geology Special Publications

Geophysics as an investigative tool

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 23-35
doi:10.1144/GSL.ENG.2002.019.01.02

2 Geophysics as an investigative tool

2.1 HISTORICAL BACKGROUND AND DEVELOPMENT

Geophysical exploration was probably born in the early 1920s. This was after the successful development of electrical prospecting methods by the brothers Conrad and Marcel Schlumberger in France, and the seismic refraction method in the newly discovered oil fields of the mid-south USA. During the following decade experience was gained using these methods and new techniques were developed, such as seismic reflection, gravity, magnetic and electromagnetic surveying, borehole logging and the use of seismic methods at sea.

The exigencies of World War II led to the adaptation of many geophysical methods for use in detecting mines, submarines and enemy fire positions. This encouraged basic research, which led to tremendous advances in electronics, signal processing concepts, and computer methods. Consequently, during the following four decades, the geophysical exploration industry in the non-communist world grew rapidly to having an estimated annual turnover of £3 billion. The bulk of this effort was concerned with the petroleum and mining industries, but there was also a steady growth in the application of various geophysical techniques to civil engineering and groundwater studies. From early applications of the seismic refraction method to the determination of depth-to-bedrock in the 1930s, the practice of engineering geophysics has expanded to encompass a wider range of techniques, applied to more types of problems, than any other branch of geophysics.

To a large extent, the techniques and equipment of engineering geophysics evolved from the other sectors. The main differences relate to the relatively shallow depths of investigation required (rarely greater than 100 m) and the need for lightweight and rugged portable equipment. The objectives are also usually very different, as mineral exploration geophysics is concerned essentially with the detection and assessment of an economic resource, whereas engineering geophysics mainly involves ground investigations, the search for engineering materials and the investigation of engineering structures. Geophysics has been used on a wide variety of engineering projects, from high-rise buildings and major dams, to the disposal of nuclear and other toxic wastes. The recent increase in the investigation in to derelict or contaminated land and the associated environmental problems, such as groundwater pollution, has provided a further boost to the use of geophysical methods in ground investigation.

The increase in applications of geophysics has coincided with the development of digital methods for recording, processing and presenting geophysical data. This has resulted in a dramatic improvement in equipment and field techniques, which in turn has significantly increased the cost-effectiveness of geophysical surveys. Evaluation of the physical and engineering properties of rocks and engineering soils, both on site and in the laboratory, has also improved significantly and become more widely accepted.

Many geophysical techniques have been applied to structural engineering problems and now form a significant component of non-destructive testing (NDT).

2.2 BASIC PRINCIPLES OF GEOPHYSICAL SURVEYING

2.2.1 Geophysical measurements

Geophysics is essentially the application of the principles of physics to the study of the Earth, although some of the methods have been adapted to investigate engineering structures.

Geophysical methods can be divided broadly into two groups, passive and active. *Passive methods* involve the detection and accurate measurement of variations in naturally occurring fields, such as the Earth's gravitational and magnetic fields, in order to locate and delineate the features producing them. With *active methods*, some form of energy is directed into the ground, or engineering structure, and the returning signals or resultant fields are measured at suitable locations. Most of the seismic, electrical resistivity and electromagnetic methods fall into this second category.

Geophysical measurements are usually made from the ground surface, within boreholes and subsurface excavations, or some combination of these points of access for energy sources and receivers. Many geophysical methods can also be used in water-covered areas or from the air. A description of all of the main methods used in engineering geophysics is provided in Chapter 5 of this report.

For any particular geophysical method to be successful, there must be a significant variation in the physical property to which the method is sensitive. For the gravity and electromagnetic methods, the bulk density and electrical conductivity of the ground are, respectively, the relevant properties. In contrast, the seismic and radar methods depend upon more than one physical property. Chapter 5 of this report and geophysical texts, such as *An Introduction to Applied and Environmental Geophysics* (Reynolds, 1997), explain these relationships and provide typical values for relevant geophysical parameters, such as seismic velocity, electrical resistivity and magnetic susceptibility.

One example, which illustrates the importance of contrast in physical properties, is the case of a magnetic survey over a buried mineshaft. When the mineshaft is filled with material from the surrounding medium, no magnetic anomaly would be observed over the shaft because there is little or no contrast in magnetic properties. However, if the shaft is brick-lined or backfilled with ferrous debris, a significant anomaly would be observed in the magnetic traverse, because of the contrast between the values of magnetic susceptibility of the lining and/or infill and the surrounding medium.

Other important factors on which the success of a survey method depends are *depth of penetration, resolution* and *signal-to-noise ratio*. These factors are intimately related and are particularly relevant in the field of engineering geophysics. For example, the seismic reflection method is widely used in the investigation of the deep geological structures associated with oil and gas exploration. However, it does not find as much application in the shallower investigations associated with on-shore civil engineering projects. The main reason for this is that the majority of seismic sources, currently used for land-based surveys, have pulse widths, which are far too long to resolve the fine detail of the near-surface geological structure. Attempts to use higher frequency sources (giving shorter wavelengths) to improve the basic resolution of the method have been inhibited by lack of penetration of the seismic pulse, caused by greater attenuation of the seismic energy. Even when adequate penetration and resolution of the geological structure has been achieved, it may not be possible to observe the seismic signal if the environmental noise is excessive. Signal-to-noise ratio is an important parameter in all geophysical surveys, as it is a measure of the degree to which the required signal stands out from the environmental or ambient noise. In seismic reflection surveying, the signal strength received from a reflecting interface also depends upon there being a contrast in the physical properties of the two lithological units, above and below the interface. The reflection coefficient is directly related to the difference in the acoustic impedance of the two units and if this difference is small, the reflected signal is unlikely to be observed above the ambient noise.

Assuming that the appropriate equipment and field procedures are adopted, geophysical measurements are usually precise and reliable. It is in the interpretation and use of the geophysical data that ambiguities and inaccuracies most often arise.

2.2.2 Interpretation of geophysical data

Geophysical data are interpreted and presented in a variety of forms, depending upon the method used and the objective of the survey. Contoured maps of electrical conductivity data to locate buried metal objects, and seismic profiles to define bedrock, are just two of the many examples included within this report. These two examples illustrate, respectively, a qualitative and quantitative approach to interpretation.

For quantitative interpretation, the geophysicist often needs to develop a representational model of the ground conditions, perhaps as a mathematical surface. An abandoned tunnel, for example, would probably initially be represented by a horizontal cylinder. This would provide a basis for forward modelling (Chapter 6) to establish which geophysical method, if any, would be most applicable and for subsequent interpretation of geophysical anomalies. Figure 2.1 illustrates the amplitude and signature of the maximum gravity anomaly, produced by a gravity traverse across a 2 m diameter horizontal tunnel, in a rock mass of bulk density 2000 kg/m^3. An air-filled tunnel will give rise to a significant gravity anomaly of 42 μgal (0.42×10^{-6} m/s^2) at the surface when buried at a depth of 2 m to its centre, but only 8 μgal at a depth of 10 m, which may not be detectable even with very sensitive microgravimeters. If a near-surface cavity is filled with rubble that has a similar density to the surrounding rock mass, or with water, the resulting gravity anomaly at the surface in this case may also be insignificant. These statements presuppose that the environmental noise, such as ground vibration, does not result in fluctuations of 10 μgal or more while reading the gravity meter, and that there is no geological noise resulting from variation in the overburden thickness and surface relief. Larger voids would produce bigger anomalies and forward modelling, based upon appropriate information from the desk study and "site visit" stages, may well indicate that a microgravity survey would then be appropriate.

Geophysical anomalies can be interpreted using computer-modelling techniques, which are explained more fully in Chapter 6. For the modelling results to be unambiguous and accurate, as much information as possible regarding site conditions, topography and geology should be provided, and consideration given to the appropriate variables. A desk study will often help to define some of the variables, such as the type and depth of working, the natures of the host rock and void infill when investigating abandoned mine-workings. In this and many of the other applications discussed in this report, a combination of geophysical methods and direct investigations would normally prove to be advantageous.

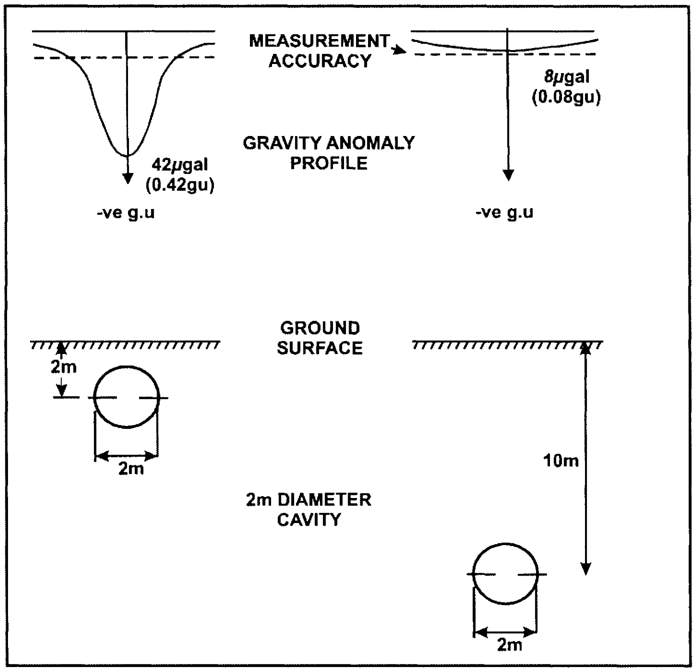


Figure 2.1 *The loss of resolution of a gravity anomaly with increased depth of burial of an air-filled cavity*

The geophysical interpretation is expressed in terms of geophysical parameters and this usually has to be transposed into geological terms. Without an input of precise information from boreholes or geological field mapping, the model often cannot be calibrated or evaluated in practical terms. A simple example of this is that of a modern seismic reflection record section, which is very similar in appearance to a geological cross-section, but which cannot provide real depth information until the time section has been converted to a depth section. This is done by using the appropriate seismic velocities in each of the resolved layers. This is illustrated in Figure 2.2, which shows a strong seismic signal reflected from the base of the Oxford Clay. The depth to this reflecting interface can only be calculated from the measured two-way travel time if the compressional wave velocities of the overlying strata are known.

Apart from the problems associated with lack of contrast between physical properties, there are other theoretical and practical limitations to geophysical surveying. For example, theoretical limitations, such as velocity inversion in a seismic refraction survey and equivalence and suppression in electrical resistivity depth sounding, can sometimes result in misleading interpretations and incorrect depth determinations (Reynolds, 1997). Unsatisfactory results would also probably be obtained if a magnetic survey was carried out close to a railway line, or electromagnetic surveys under power cables.

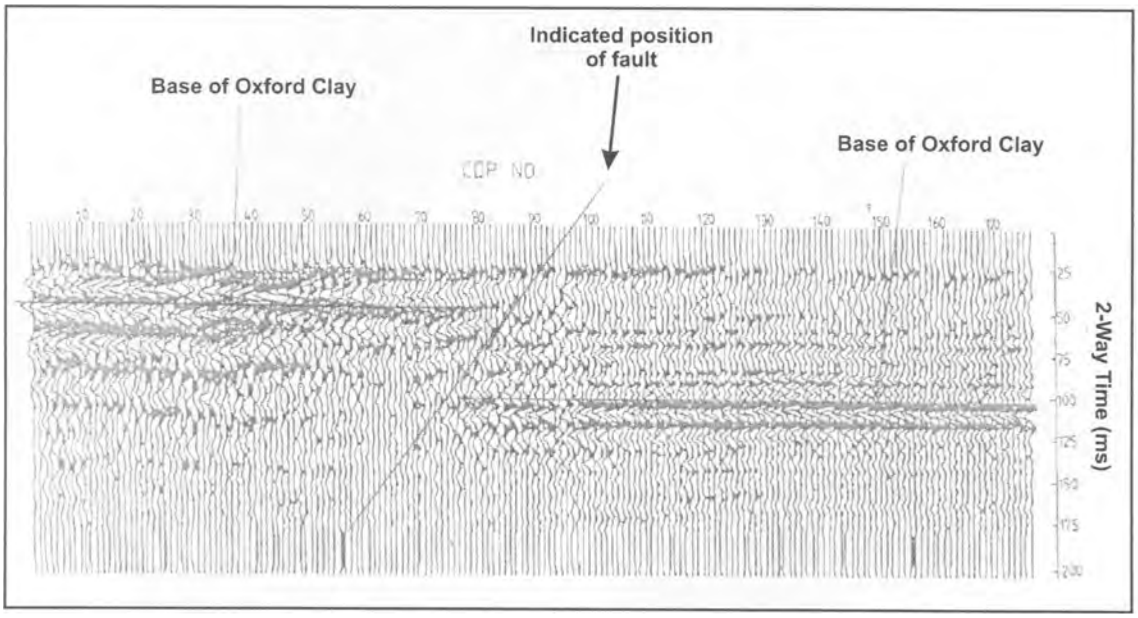


Figure 2.2 *A seismic reflection time-depth section with a fault indicated at CDP 80*

2.3 GEOPHYSICS IN GROUND INVESTIGATIONS

Geophysical methods are routinely used in the search for oil, water and metalliferous minerals, to identify prospects to be investigated directly by more expensive drilling and excavation. They are less often used to investigate the ground conditions for engineering projects. For shallow-depth ground investigations on land in particular, the use of direct methods has often been preferred to this combined approach, except when a desk study has indicated the possible presence of potential hazards, such as mine shafts or groundwater pollution plumes. This may have been due to a lack of appreciation of geological variation (McCann *et al*, 1997) or to the disappointing results of geophysical surveys through misapplication or misuse. The significant improvement in geophysical techniques in recent years has resulted in greater cost-effectiveness and increased confidence in their use.

Broadly speaking, geophysical surveys are used in one of two roles:

1. To allow a choice to be made rapidly and economically between a number of alternative sites for a proposed project, prior to a detailed design.
2. To complement a programme of drilling and trial pits as part of the detailed site ground investigation at the chosen site.

In comparison with boreholes and trial pits, geophysical surveys can offer considerable savings in both time and money. Site access is usually easier and the work causes less damage to the site surface. At an early stage in a ground investigation, it may be advantageous to undertake a reconnaissance geophysical survey. This will assist the subsequent direct investigation by identifying areas of the site where anomalous geophysical data are obtained that should be investigated by drilling. On sites where contamination is suspected, a geophysical survey may form part of a preliminary risk assessment prior to drilling or sampling. During the drilling programme on the site, geophysical surveys may be used to check the interpretation of the geological structure between the boreholes. At a later stage in the ground investigation, further geophysical surveys may be carried out both within and between the boreholes and on the ground surface to determine the geological, hydrogeological and geotechnical properties of the ground where the engineering construction is proposed.

Despite their advantages, geophysical methods are often overlooked or deliberately omitted from ground site investigations and the boreholes or trial pits set out on a grid basis, or at regular intervals along a linear route. This is unwise, as boreholes or trial pits located at regular intervals might not encounter the problem areas. A classic example is from the Love Canal area of Buffalo, USA described by Benson and Noel (1983). Six wells (boreholes) were drilled to investigate a concealed pollution plume, but did not make contact with it. A subsequent geophysical survey, utilising a rapid inexpensive inductive method of measuring variations in ground conductivity, clearly outlined the concealed pollution plume. Figure 2.3 shows a 3-D representation of the ground conductivity variation at the location of the boreholes and demonstrates why it is essential to target boreholes.

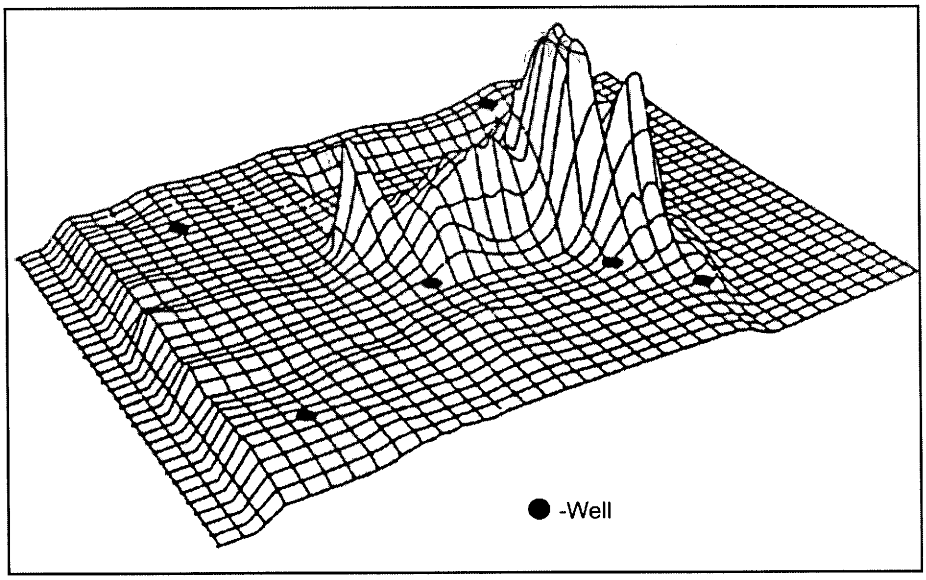


Figure 2.3 *Three-dimensional representation of conductivity data showing a concealed pollution plume. (Note that the six wells in the area failed to intersect the plume) (After Benson and Noel, 1983)*

A report from the Institution of Civil Engineers (1992) commented: "Much money can be wasted by covering sites with regular grids of boreholes and extensive programmes of routine tests rather than targeting the investigation towards areas where information is required and by using more appropriate investigation methods."

The use of geophysical methods does not, of course, preclude the use of exploratory holes; rather the boreholes and trial pits can be sited in anomalous areas previously defined by the geophysics. The subsequent comparison of the geophysical interpretation with the "ground truth" – the direct geological data – enables the geophysical survey results to be extrapolated into areas where little or no ground information is available and confidence can then be placed in the interpretation of the geophysical survey data.

There are four primary objectives of engineering geophysical surveys in ground investigations:

1. Geological investigation
2. Resource assessment
3. Hazard assessment
4. Determination of engineering properties of the ground.

Additional objectives could be, to investigate the forms and material properties of man-made structures in the ground.

Table 2.1 lists these applications, along with some of the more commonly used geophysical techniques (modified after BS 5930 *Code of Practice for Site Investigations*). This table is provided for initial guidance and should be used in conjunction with the relevant sections of this report.

In most of these applications, the geophysical techniques are intended to supplement direct methods. They are not a substitute for direct methods of site assessment such as drilling or trenching, etc. They may be thought of as a means of interpolating between, and extrapolating from, borehole data. By careful planning, the number of boreholes required for adequate definition of subsurface conditions can be greatly reduced if the proper geophysical methods are chosen to supplement the direct investigation programme. There are some situations in which the interpretation of geological conditions from borehole data alone could be very misleading, such as faulted ground or areas where buried channels are present, and the use of an appropriate geophysical method to aid the correlation between boreholes is vital.

Holes drilled on the engineering site also provide access to the environment of interest and a wide range of geophysical logging methods can be used to give information on the actual *in-situ* conditions, which prevail around each borehole. Provided the boreholes are close enough to each other, they can also be used for acoustic tomography, radar, and electrical resistivity surveys. Individual boreholes can additionally be used for surface-to-borehole measurements.

Table 2.1 *Geophysical methods in ground investigation and NDT (modified after BS5930)*

Problem		Examples	Main methods
Geological	Stratigraphical	1. Drift deposits over bedrock	Seismic refraction, resistivity, EM
		2. Interbedded arenaceous and argillaceous formations	Seismic reflection, resistivity
	Erosional	Buried channel	Seismic refraction, gravity, EM, resistivity, seismic reflection
	Weathering	Buried karstic surface	EM, resistivity, gravity, GPR
	Structural	Buried faults and fracture zones	EM, resistivity, seismic refraction, seismic reflection, magnetic, gravity
Resources	Water	1. Location of aquifer	Resistivity, EM, seismic refraction, seismic reflection
		2. Location of saline/potable interface	Resistivity, EM, MT
	Sand and gravel	1. Sand/gravel over clay	Resistivity, EM
		2. Offshore gravel banks	Marine seismic reflection, side-scan sonar.
	Rock	Igneous intrusions in sedimentary rocks	Magnetic, resistivity
	Clay	Clay pockets in sands and gravels	Resistivity, EM
Engineering	Ground deformation	1. Dynamic deformation moduli and Poisson's ratio 2. Soil stiffness	Seismic refraction, acoustic tomography, surface wave, down hole or cross-hole seismic
	Rock rippability	Choice of excavation method	Seismic refraction
	Corrosivity of soils	Pipeline surveys	Resistivity
Buried artefacts	Cables and pipes	1. In trenches on land	EM, magnetic, GPR, ER
		2. In structures	GPR
		3. Offshore	Continuous seismic reflection profiling
	Mine workings	1. Shafts and adits	Magnetic, EM, GPR
		2. Deep workings	Microgravity, acoustic tomography
	Archaeological remains	"Foundations, buried walls, crypts"	Magnetic, EM, resistivity, GPR

Borehole geophysical logging provides a series of profiles down the length of a borehole, each profile giving a different geophysical parameter measured with an appropriate sonde. The data are plotted against depth and a comparison of the data obtained from a number of sondes will generally yield useful information on the properties and characteristic of the subsurface. Experience of the use of these methods has increased considerably over the past decade and geophysical logging methods are used extensively on major site investigations to provide additional data from the site investigation boreholes. The subject of geophysical logging is very wide and many different types of logging tools have been developed for a variety of engineering and hydrogeological applications. For further information reference should be made to specialist textbooks, eg Keyes (1990), or standard guides, eg BSI (1989) and ASTM (1995).

It is essential that each logging tool is carefully calibrated against known standards and that the tool operates in the borehole at the correct operational speed. The application of borehole geophysical logging varies from site to site and it may be necessary to consult a geophysical advisor to achieve the optimum results. The logging is usually carried out by a specialist contractor.

The main applications of the principal borehole logging methods are given in Table 2.1

Table 2.2 *Geophysical logging methods and their applications*

Application or limitation	**Log type**															
	Formation micicro	**Televiewer**	**Spectral gamma**	**Diameter**	**Flowmeter**	**Fluid conductivity**	**Fluid temperature**	**Television**	**Calliper**	**Sonic**	**Neutron**	**Gamma-gamma**	**Natural gamma**	**Induction**	**Electrical resistivity**	**Spontaneous potential**
Lined hole			●		●	●	●	●	●	●	●	●	●			
Open hole	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Air-filled			●					●	●		●	●	●	●		
Water or mud filled	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Diameter									●							
Casing				●				●	●				●		●	
Fractures / joints	●	●		●	●	●	●	●	●	●		●			●	
Cement bond										●						
Bed boundaries	●	●	●	●				●	●	●	●	●	●	●	●	●
Bed thickness	●	●	●					●	●	●	●	●	●	●	●	●
Bed type			●							●	●	●	●	●	●	●
Porosity										●	●	●		●	●	
Density												●				
Permeable zones	●	●			●	●	●		●		●	●				
Borehole fluid quality						●										
Formation fluid quality														●	●	●
Fluid movement					●	●	●									
Direction of dip				●												
Shale / sand indication									●				●			●

Logging tools may be divided into four main categories:

1. Formation logs, which provide information on the geological formations immediately surrounding the borehole.
2. Fluid logs, which provide information on the fluid filling the borehole.
3. Physical properties logs, from which the geotechnical and hydrogeological parameters of the rock mass surrounding the borehole can be derived.
4. Borehole geometry logs, which normally provide information on the borehole construction parameters.

The first three categories are explained more fully in Chapter 5. Two of the geometry logging tools are described below.

Calliper log

The calliper log is a moving arm with mechanical sensors and transducers that respond to changes in the diameter of a borehole with depth. The log can be used for the identification of lithology and stratigraphical correlation, but its main use is in locating zones of fractured rock. It is used to correct other logs, which are sensitive to variations in borehole diameter. These profiles have been interpreted as indicating the direction of maximum horizontal stress in rocks.

Television

Borehole television logging involves the use of a low-light-sensitive closed circuit television camera system, specially adapted for use under water. Illumination is from a variety of external peripheral lighting heads attached to the camera and selected to suit the individual borehole conditions. The camera can be packaged as small as 50 mm diameter and can operate in boreholes to a minimum diameter of 100 mm allowing for adequate clearance. For general usage, a simple axial view of the borehole is adequate. However, for details of features on the borehole wall, mirror assemblies give a radial view, which can be scanned around the borehole by a motor-rotate unit fitted above the camera assembly. Focusing, light intensity, rotation and digital depth control on the image are from a surface control unit and it is recorded on VHS format videotape.

Borehole CCTV logging allows the condition (joints, leaks from corrosion perforation, damaged sections) and depth of casing in old boreholes to be determined, where records may be poor or lost, prior to reinstatement. In open-hole sections, the inclination, azimuth (from a compass attachment), frequency, and aperture of fractures can be determined together with any fluid ingress from above water level. The lithological nature and variation of the rocks in the borehole and the general borehole condition can be determined, ie zones of collapse, or lost pumps in water supply bores.

Geophysical techniques can also provide an indirect assessment of the engineering properties of the ground, or an assessment of rock mass quality. Seismic measurements of compressional and shear wave velocities are of particular importance in this respect, as they can be used to determine elastic moduli values and to assess the degree of fracturing. In this case the seismic and engineering parameters can be viewed as complementary and of equal importance to the overall assessment of rock mass performance.

In this report, the fundamental principles and practice of geophysical investigative methods are considered in some detail with a view to establishing a definitive role for them in the site investigation process. Part of this has to be the setting of agreed standards and guidelines, both for the execution of each surveying method in the field and for the interpretation and presentation of the geophysical data obtained, as an integral part of the investigation programme. The involvement of the geophysicist as an essential member of the site investigation team, has been the exception for too long for civil engineering projects in Britain.

2.4 SELECTION OF GEOPHYSICAL METHOD

The choice of the most suitable geophysical techniques for a given problem or geological situation is not necessarily obvious and a large measure of experience and insight is often required. The chosen methods should form an integral part of the overall geotechnical or structural investigation, and complement the other data-gathering activities.

Only by choosing an appropriate geophysical method (or combination of methods) for the survey, will provide value for money and obtain the desired geological or structural information of the right quality.

The practical limitations of the chosen geophysical method should be assessed in the light of performance criteria; and pre-survey modelling of the predicted geological structure, or anomaly should be undertaken to establish its likely response. Consideration has to be given to:

1. *The exact nature of the problem in the geotechnical sense.* For example, what is meant by "bedrock" in the context of the proposed structure and the anticipated ground conditions? Is the depth to bedrock really required or only information on conditions down to a certain depth, such as the depth of burial of a pipeline?
2. *Whether the problem may be solved by geophysical methods and which technique would be most appropriate in the first instance.* The main considerations at this stage will relate to signal penetration, resolution, signal-to-noise ratio and contrast in physical properties.
3. *The operating parameters for the chosen technique and the scope of work.* Thus, for a seismic refraction survey the geophone spacing should be agreed and be seen to be consistent with the resolution required. In a mineshaft location survey the measurement grid interval needs to be determined and agreed. Consideration should also be given to choice of equipment.
4. *Whether the site is suitable for a geophysical survey.* Aspects to be considered include the area, size, terrain, access, and vegetation of the site, and whether any existing man-made features might cause interference.
5. *The likely cost of the survey.* A large number of parameters have to be considered in order to estimate a production rate. These include the size and nature of the site, the depth of investigation and the density of observations required, among others. The following relative costs are therefore very generalised and should only be used for initial guidance.

Table 2.3 presents the relative costs and output of most commonly used land-based geophysical methods, based upon data provided in 1998 by eight UK-based geophysics contractors. These figures include the cost of data acquisition, processing, preliminary interpretation and reporting. They do not cover mobilisation and ancillary costs, such as the levelling of gravity stations. Other factors, which affect costs, are discussed in Chapter 3.

Table 2.3 *Relative costs and output of land-based surface geophysical methods (values based on 1998 costs)*

Method	Unit cost (£)	Cost per day (£)	Typical daily output
Magnetic (field/ gradient)	0.5 – 1 per station	500 – 1000	500 – 2000 stations
EM ground conductivity (0–6 m depth)	0.5 – 1 per station	600 – 1000	600 – 2000 stations
EM ground conductivity (6–60 m depth)	2 – 5 per station	600 – 1000	200 – 400 stations
Geo-electrical traversing	5 – 20 per station	600 – 1000	50 – 120 stations
Geo-electrical sounding	100 – 200 per array	600 – 1200	5 – 10 arrays
Geo-electrical imaging	400 – 600 per profile	800 – 1200	2 – 3 profiles
Geo-radar	140 – 1400 per km	800 – 1400	0.5 – 10 km
Gravity	8 – 20 per station	750 – 1200	50 – 100 stations
Seismic refraction	15 – 25 per station	1000 – 1500	5 – 10 spreads (50–100 stations)
Seismic reflection	30 per station	1000 – 1750	0.2 – 3 km
Seismic cross-hole (p and s waves)	33 per interval	2000	60 depth intervals
Surface wave	166–200 per spread	2000	10–12 spreads

Note: Typical outputs are very dependent on station interval, length of array, profile or seismic spread, and site access. The term "station" designates a measurement point for ER, EM, gravity and magnetic traversing, and geophones for seismic methods

Table 2.4 shows some typical costs (at 1998 prices) for some surveys in the UK.

Table 2.4 *Typical UK geophysical survey costs (1998)*

	Scale of survey		
Method	Small	Medium	Large
Seismic refraction	Bedrock survey for buildings £2000 – £5000	Tunnel route £10 000 – £20 000	Large dam with choice of sites £10 000 – £30 000
Marine seismic reflection	Jetty foundations £10 000 – £20 000	Site selection for long sea outfall £15 000 – £30 000	Off-shore platform >£35 000
Electrical resistivity	Pipeline corrosion study £2000 – £5000	Local ground water survey £5000 – £15 000	Regional deep aquifer study >£30 000
Magnetic/EM	Mine shaft location £1000 – £5000	Materials search £5000 – £10 000	Regional deep aquifer study >£30 000

Table 2.5 lists the various geophysical techniques, which have been found to be most useful in geotechnical projects. As such it can be used as an aid in choosing the most effective method to suit an engineering application. The matrix in this table is constructed in such a way as to provide a subjective numerical rating system for the effectiveness of each method for a particular application. The five numerical ratings of 0, 1, 2, 3, and 4, which are explained in the footnote to the table, can then be used as a guide in planning an effective and economical site investigation. A rating of four for the combination of a given method and application indicates that the method is well developed, practical for use, and likely to give good results, although it does not guarantee a successful outcome to the survey.

Table 2.5 *Usefulness of engineering geophysical methods*

	Applications																			
Geophysical methods	**Depth to bedrock**	**Stratigraphy**	**Lithology**	**Fractured zones**	**Fault displacement**	**Dynamic elastic modulus**	**Density**	**Rippability**	**Cavity detection**	**Buried artefacts**	**Groundwater exploration**	**Water quality**	**Porosity**	**Permeability**	**Temperature**	**Flow rate/direction**	**Buried channels**	**Clay pockets in limestone**	**Sand and gravel**	**Basic igneous dykes**
Seismic																				
Refraction	4	4	3	4	4	3	2	4	1	1	2	0	0	0	0	0	4	1	2	1
Reflection – land	2	2	2	1	2	0	0	0	2	1	2	0	0	0	0	0	1	0	0	1
Reflection – marine	4	4	2	2	4	0	0	1	0	2	0	0	2	0	0	0	4	0	0	0
Acoustic tomography	2	2	3	3	1	4	2	2	3	2	0	0	0	0	0	0	2	0	1	2
Electrical																				
Resistivity sounding	4	3	3	2	2	0	0	1	2	1	4	4	3	1	0	0	3	0	3	0
Induced polarisation	2	2	3	1	0	0	0	0	0	0	3	1	3	2	0	0	2	1	1	1
Electromagnetic and resistivity profiling	3	2	2	4	1	0	0	0	3	3	4	4	1	0	0	0	3	4	3	3
Electrical imaging	4	3	3	3	3	0	0	0	3	1	4	4	3	4	0	0	3	4	3	3
Other																				
Ground-probing radar	2	3	1	2	3	0	0	0	3	4	2	2	1	0	0	0	2	2	1	2
Gravity	2	0	0	0	2	0	2	0	2	1	1	0	0	0	0	0	2	1	1	2
Magnetic	1	0	0	0	2	0	0	0	2	3	0	0	0	0	0	0	1	3	0	4
Borehole logging																				
self-potential	2	4	4	1	1	0	0	0	1	1	4	2	0	0	0	0	0	0	0	0
Single-point resistance	2	4	4	0	0	0	0	0	0	0	4	2	1	0	0	0	0	0	0	0
long and short, normal and lateral resistivity	2	4	4	0	0	0	0	0	0	0	4	2	4	0	0	0	0	0	0	0
Natural gamma	2	4	4	0	0	0	0	0	0	0	2*	2	1*	3*	0	0	0	0	0	0
Gamma-gamma	3	4	4	0	0	0	3*	0	0	0	2*	0	3*	2*	0	0	0	0	0	0
Neutron	2*	4	4	0	0	0	3*	0	0	0	3*	0	3*	2	0	0	0	0	0	0
fluid conductivity	0	1	0	0	0	0	1	0	2	0	4	4	4	1	0	0	0	0	0	0
fluid temperature	0	0	0	1	0	0	0	0	1	0	2	3	0	0	4	2	0	0	0	0
Sonic (velocity)	3	4	2	3	0	3	2	1	2	0	1	0	1	0	0	0	0	0	0	0

Key

0 Not considered applicable
1 Limited use
2 Used (or could be used) but probably not best approach
3 Excellent potential but some limitations
4 Generally considered an excellent approach and techniques well developed
* Used in conjunction with other electric or nuclear logs

There is now the capability to produce 3-D models of the geological structure beneath a construction site and within a decade the production of this type of geological model, which incorporates all known information could well be the normal end-product of the site investigation process (Chapter 4).

2.5 STRUCTURAL INVESTIGATIONS

There is a wide range of non-destructive testing (NDT) methods, which are used in the civil engineering industry. These are summarised in Table 2.6, which is taken from the paper by Robery and Casson (1995). The geophysical tests (eg ultrasonic pulse velocity (UPV), radar, resistivity) have been highlighted. An excellent summary of the NDT methods used in the assessment of concrete structures is given in Bungey (1994).

Table 2.6 *NDT methods used in structural investigations (after Robery and Casson, 1995)*

Material	Application	Recommended methods of test	Comments
Testing Concrete	Strength	Cores, **UPV**, rebound hammer, near-to-surface tests	Cores are essential for calibration purposes
	Corrosion activity	Cover, half-cell, resistivity, Linear polarisation	Important to measure rate of corrosion, not just potential
	Honeycombing/ voidage	**UPV, radar**, confirmation by borehole/cores	Full interpretation requires semi-destructive calibration
	Cracking	**UPV**, crack width gauge, monitoring (Demec, VWG)	X-ray has also been used. Radar is usually unsuitable
	Cover	Covermeter, **radar,** calibration drillings	Radar gives a hard copy and is fast. Calibration is essential
	Fire damage	**UPV**, rebound hammer, cores	Petrographic examination plus cross dia. UPV
Screeds/ toppings	Soundness	BRE tester, Stanger nail test, chemical analysis	Detects strength beneath the surface crust
	Delamination	Tapping, assessed by displacement transducers and FFT analysis	"Determine delamination depth, with calibration"
	Wear resistance	Rebound hammer, wear tester, cores for strength	Can assess effect of surface strengthening treatments
Walls and roofs	Cavity insulation	**Thermography**, borescope	eg saturated insulation
	Wall ties	Metal detectors (ferrous and non), borescope, thermography, **radar**	Thermography can locate cold-bridges
	Cladding fixings	**Metal detectors, radar,** borescope, breakouts	Careful exposure of the fixings is required, followed by metallurgical examination
	Moisture penetration	**Resistance/capacitance** meters, dye penetrants, **thermography**	Need to find out where it gets in and where it is going
	Flat roof leaks	**Thermography, earth leakage, DEC scanner (+ radar)**	Using cooling by evaporation or electrical properties
Buried objects	Location of services / foundations / pipes	**Radar, CAT scanner,** trial pitting	Locate metallic and non-metallic services
	Archaeological remains	**Radar**, trial pitting	Detects disturbed ground and buried objects
	Checking for buried objects (waste dumps)	**Radar, magnetometer**	Metal objects can be located and size/depth determined
Machinery	Worn bearings	**Vibration meters, thermography, sound level meters**	Detect vibration and overheating
	Overheating (esp. electrical)	**Thermography**	Accurate to 0.2°C differences

Geophysical testing methods are shown in bold type

Geological Society, London, Engineering Geology Special Publications

Procurement, management and reporting

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 37-49
doi:10.1144/GSL.ENG.2002.019.01.03

3 Procurement, management and reporting

This chapter is about how to set up, procure and manage geophysical investigations, to have the best chance of providing information that is useful to an engineering project. There is a perception that geophysical techniques applied to engineering purposes have often been procured inappropriately and managed inadequately. This is particularly so for geotechnical investigations. A summary is given of this background to procurement practices in the UK and some other countries. This leads to a review of what the principal parties in the project want from a geophysical investigation and what this implies for the management framework in which to set the geophysical work.

The emphasis for this chapter is on effective management, clear focus, clarity of purpose and definition of deliverables. As in most engineering activities, the more care and thought that is put into the planning of the survey by appropriately qualified professionals, the better the chances of success and of providing a product that will satisfy all parties. To be successful in the selection of an appropriate technique, those involved need appropriate geological training and understanding as well as an adequate appreciation of the nature and impact of the engineering project.

Underlying the analysis and proposals of this section, is the intention to examine UK practice and to recommend ways for its improvement. These recommendations are based on the principle that the ground investigation and its component parts should be designed and undertaken in a conscious framework of risk management to achieve greater certainty of outcome. The conclusions that follow from the discussion in this chapter are presented in Chapter 11 as guidelines for good practice in geophysical investigation from its planning to reporting.

3.1 UK AND INTERNATIONAL PRACTICES

3.1.1 UK practice

In the UK about 20 relatively small geophysics contractors provide services and techniques for the investigation of engineering projects. These companies, as well as undertaking a survey, often provide consultancy or interpretation services if requested. About five large survey companies with operational bases around the UK service the petroleum industry (onshore and offshore). These occasionally undertake investigations for engineering projects. Some of these larger companies have advanced processing and in-house interpretation skills.

Relatively few UK consulting engineers have sufficient specialist geophysical work to justify employing full-time engineering geophysicists. Most of the top 30 UK consultancies, however, employ geotechnical engineers or engineering geologists with some knowledge of particular techniques applied to specific circumstances. Most geophysical work in the UK on small and medium-sized projects is let as an inclusive package, usually based on lowest price for acquisition, processing and interpretation, with the initial interpretation being carried out by the acquisition contractor's staff. The specifications for these works are not, generally, prepared by a geophysics specialist adviser. On the other hand, additional engineering geophysics expertise is sought at an early stage on most large projects. Many geophysical surveys, and generally all down-hole logging surveys, are carried out as a sub-contracted element within a larger package of investigative work, which the main contractor is likely to sub-let on the basis of price criteria. The client and engineer have little influence over the selection or terms of engagement of the specialist sub-contractor, which is often an unsatisfactory situation.

The geophysical survey is frequently paid for on the basis of linear measurement, although alternative systems are used. In many circumstances offshore it can be appropriate to pay on a day-rate basis, provided operating and readiness conditions are clearly defined and the corresponding risk sharing is properly identified and managed.

3.1.2 International practice

Information gained from contacts with professional engineering geophysicists in eight countries is given in Appendix 1. While there are international differences in procurement methods and attitudes to the value of geophysical investigations, there are several common problems:

- poor procurement systems leading to poor results and client scepticism
- cheapest price of unequal offers is often the basis of contract award
- few and relatively small contracting companies
- lack of national standards and codes.

3.2 OBJECTIVES OF THE PRINCIPAL PARTIES TO THE WORK

3.2.1 Client requirements

The Client is seeking value for money at all times, through all phases of a project from planning to operation. In recent years emphasis has been placed on value for money, rather than lowest price, in a deliberate attempt to reduce overall civil engineering project costs by up to one third. There are examples where these savings have been achieved in other sectors, such as in offshore petroleum production. A consistent theme that emerges from these successes is that it is necessary for all parties to join together as a team, to develop a real drive for innovation and to provide the incentive of savings being shared between all parties. Clients want to maintain programmes and budgets. They expect to be kept regularly informed of progress and costs.

The client, relying on the advice from the professional team, would reasonably expect the adoption of a particular technique to add value to other elements of the survey. One of the project manager's roles is to avoid surprises, ie adverse events of which the client has no forewarning, so therefore good communication from across the team is important. Unfortunately, the history of geophysical survey in civil engineering projects has many examples of failure and of techniques offered in inappropriate situations. This has led to the reluctance of many senior managers to recommend geophysical techniques for use.

> An example of overselling an inappropriate technique was the suggestion of profiling using ground-probing radar in a saline environment, with the equipment mounted on an experimental seabed crawler to investigate severe ground losses during tunnelling. Fortunately, those involved sought geophysics advice and the proposal was dropped.

However, there are many examples where geophysical techniques have been used in a very cost-effective manner, to provide essential information about ground hazards that could have severely jeopardised the project. The recognition of such hazards at an early stage allows the associated risks to be mitigated or accommodated during the design of the project.

One of the most effective geophysical surveys in recent years was carried out for the Channel Tunnel between England and France. The cost of surveying a 2 km wide corridor across the 35 km of the Channel in 1986 was £0.5 million, which was equivalent to the cost of drilling a single borehole in the Channel from a jack-up rig. The initial geophysical survey was able to delineate the base of the key tunnelling horizon, the Chalk Marl, to an accuracy of + 5 m with 95 per cent confidence in most areas, which was adequate for designing the detailed alignment of the tunnel. This accuracy was improved to + 2 m during a supplementary geophysical survey at the site of the UK Crossover.

An accepted approach for bringing adequate geotechnical expertise into the project team is for a geotechnical adviser (GA) to be appointed by the client at the early stage of any project, where a significant amount of geotechnical investigation is envisaged. The GA would have appropriate experience as defined by the Site Investigation Steering Group (1993). Clients should select their GA on the basis of relevant experience, track record, recommendation and interview. The status, qualifications and key experience of individuals should be checked using registers as part of the client's own risk management procedures. One of the responsibilities of the GA would be to advise the client at the desk study phase on the likely ground features and hazards, and whether geophysical techniques should be considered to investigate them.

At this point it may be appropriate for the client to involve a specialist engineering geophysics adviser (EGA). This appointment to the team should be on an equivalent basis to that of the GA, ie on relevant experience, track record, recommendation and interview and the status, qualifications and key experience of individuals should be checked as part of the client's own risk management procedures. The initial task for the EGA would be to nominate the techniques that would have a reasonable chance of identifying these features or hazards during the feasibility phase of the project.

The client should then receive expert advice on the most appropriate way of establishing the nature or location of the features, but in the context of realistic assessments of the limitations of the methods. Part of this would include the presentation of options, alternative strategies and associated costs for subsequent correlation or corroboration by direct intrusive investigation.

3.2.2 Engineers expectations as a user

The civil engineer expects geophysical investigations to aid understanding of the three-dimensional geological structure and to identify and locate particular hazards or obstructions in the ground. This information should be capable of being set in real space, ie in 3-D co-ordinates, ideally with accuracy compatible with the tolerances of the proposed works. (Note that at civil engineering project scales, this requirement can be much more demanding than that for determining geological structure in petroleum exploration where the survey tends to be on a much larger scale). Correspondingly, the engineer needs to understand the precision of the geophysics results, to be able to relate them to the geometry of the construction project. Additionally, both the engineer and the geophysicist need to establish correlations between observed or interpreted features, with results from direct intrusive investigations.

Therefore, all of those involved in the procurement, execution and interpretation of geophysical surveys should make sure that they understand the limitations of the techniques and the reasons for inaccuracies. This highlights the need for careful calibration and quantification of inaccuracies at the survey outset.

The engineer will want the advice from engineering geophysics specialists to be independent, balanced and based on direct experience. The conduct of the survey and subsequent reporting should be professional, logical, and scientifically accurate, with clear separation of fact, artefact and interpretation, and this should be combined with an unbiased assessment of error and uncertainty.

3.2.3 The engineering geophysics adviser

There are many aspects to the use of geophysics in engineering and environmental studies. In order to appraise the potential of different techniques, one needs to be aware of the advantages and the constraints applying to a given situation.

At the start of this CIRIA research project, a survey found that relatively few UK consulting engineers have much knowledge of geophysics. In most consultancies no call is made on an engineering geophysicist during the proposal stage of an investigation. It is hardly surprising therefore, that geophysics is often not used as a preliminary reconnaissance tool. When an external adviser was brought in for the geophysical investigations, the consulting engineers were generally satisfied with the adviser's understanding of their requirements. The greatest value was obtained, when such specialist advice had been taken at the planning stage of the investigation. This enabled the team to reject techniques known to be unsuitable at an early stage and shortlist those with potential value for improving the overall cost-effectiveness of the site investigation

Employing an engineering geophysics adviser (EGA) to work with the design team at the beginning of the investigation enables the team to learn from each other to the project's continuing benefit. This helps to prevent mistakes, rather than seeking advice when things go wrong. With the EGA on the design team from the start, the risk of adopting an unsuitable technique diminishes as each stage of the work progresses. This does not imply continual involvement, which would generally be unnecessary and certainly expensive, but access to an adviser on a when-required basis. This can be a cost-effective solution and the choice of such a person is critical.

Many geophysicists are employed in the petroleum and mineral prospecting industries. Often, they are highly specialised and have in-depth knowledge of only one technique. In the smaller scale spheres of engineering and environmental studies, it is wise to engage a geophysicist as the EGA (if one can be identified – these are relatively few) who has a broad understanding of all methodologies. The expertise of a specialist will be required later in the project, but at the early stages it is more important to have an appreciation of which techniques will be effective and what problems might be encountered. The EGA could consult with specialists to find out about new or unfamiliar techniques and how they are applied in different situations, ie land surface or downhole, marine or airborne.

It may be necessary to check the potential adviser's experience of contract and project management of the geophysical elements of work, as well as their technical capabilities. Where a contract team is being established for a given project this may be less important. For most studies however, it can be efficient to assign the management of the geophysical element of the project to an independent adviser working in conjunction with the geotechnical engineer. The specific responsibilities, communication and budgetary limit of liability have to then be clearly established.

3.2.4 The geophysics contractor

Data acquisition contractors specialised in servicing the engineering and environmental industry are often quite small firms, but they generally offer a range of methodologies. Some operators offer services in techniques, in which they do not have specialist knowledge, because of the easy access to geophysical equipment through hire companies. Details of the contractor's experience should be obtained prior to engagement. The availability and source of equipment should also be determined for the projected timeframe. Potential project slippage needs to be considered, as a contractor may not be able to meet the requirements if project timing changes dramatically.

Larger contracting companies servicing the petroleum and mineral industries may lack the experience of smaller scale projects and the high resolution required for these engineering studies. However, they often have greater resources and flexibility, and are more likely to own the equipment and understand the limitations on its use. This is especially important when larger projects are involved, or where acquisition offshore or from aircraft is required. It is unusual to find contractors who can undertake work in all three environments, as each has its own particular operating conditions and difficulties.

A key point to establish is which personnel will be offered to do the work and to check that they have the relevant experience with the chosen techniques. Timing is significant, as it may not be possible for the contractor to be certain which personnel will be allocated. It is reasonable to ask for the CVs of those who might be assigned and to check them again at the stage of fieldwork commencement.

Nearly all geophysical acquisition methods now provide some form of data presentation on site. This provides a ready means of assessing the value of the data as the work proceeds, but requires a representative on site who understands the results and who can liaise with the contractor. However, it should still be the contractor's responsibility to acquire adequate data. Most geophysical data will require some form of processing or manipulation and plotting to achieve the required data set. Often this is undertaken by the acquisition contractor. For seismic reflection data, the processing and plotting is sometimes carried out by specialist sub-contractors.

Geophysics contractors should, in general, be able to offer an interpretation service. For this to be fully effective they should also have access, in the case of non-seismic methodologies, to modelling programmes. These enable confidence to be established in the chosen methodologies at the inception of the project and allow the evaluation of the dataset on completion of the field acquisition. Such services are also available through the specialist adviser and it may be more appropriate for these elements to be kept within the geotechnical project management team. A well-equipped consultancy will also have access to workstation facilities to enable interpretation of digital seismic records.

3.2.5 Value for money

Value for money in geophysics is unlikely to be achieved if it involves a long and complicated supply chain of consultants and contractors. It is crucial to employ appropriately trained and qualified professionals who understand their client's objectives and the engineering implications of the proposed development. It requires people who are committed to approaching and managing the project in a rational and systematic way, so that they can identify potential hazards, the likelihood of events and corresponding consequences can be recognised. Appropriate strategies can then be incorporated in to the investigation to mitigate or minimise the risks to recognised acceptable levels.

The recommendation that comes from the review of practice in this report is not prescriptive as to the contractual approaches that should be adopted between the various parties, but advocates teamwork with open and clear communication at every stage.

3.3 INVESTIGATION PLANNING

All projects ought to begin with a desk study at the feasibility stage. In too many cases there is no desk study, or it is prepared inadequately.

A desk study can have several purposes, but it is usually focused specifically on a particular construction project, (see 11.2.1). It should present a summary of the historical development of the site, which may highlight potential hazards associated with underground obstructions or contaminative past usages. The study should collect together the geological, hydrogeological and geotechnical information about the site and its surroundings. This should include reference to the most recent, largest scale geological plan of the area (usually 1:10 000) and to other information held by the British Geological Survey. An essential element of the desk study for onshore projects is the accompanying site reconnaissance, which should take account of geomorphological and man-made features. The desk study should draw together the information as a model or statement of the likely ground and groundwater conditions, the nature of any associated hazards and the likelihood of primary risks and their consequences upon the project or to the client. It should identify the likely implications of the ground and groundwater conditions for the design and the construction of the project, as well as the impact of the project on the adjacent area. The overall environmental impact is usually studied separately.

For the investigation of old structures, the desk study is particularly important, but tenacious enquiries may be needed to reveal useful historical plans, documents and construction drawings.

3.3.1 Design of investigation

Geophysical methods measure the vertical and lateral variation of physical properties of the subsurface, so it is necessary to have an initial appreciation of the likely ground conditions at the site and the broader geological context in which the site is located. The processes described above will assist in this, but it is important to identify the constraints, as well as the benefits of a given geophysical technique. These need to be established as early as possible in the process, as any indication that a particular approach may subsequently fall short of expectation, could have a significant effect on the ability to meet the objectives. A site visit is therefore essential. Changes to the methods, scope of investigation and data processing will affect the budgeted price.

Early discussions between the client's GA and the EGA should establish the objectives of the investigation and may be able to identify geophysical techniques and methods, which will considerably reduce the overall investigation cost. Preliminary geophysical investigations may be an ideal way of identifying locations for subsequent intrusive investigation. Such scoping investigations are often more concerned with establishing continuity of lateral and vertical conditions rather than hazards. However, at an early stage these investigations can highlight those locations, which may require a specific borehole or trial pit to investigate a particular feature.

Within subsequent phases of investigation, it may be possible to delineate particular features with detailed geophysics. Here it is essential to determine the degree of detectability that is satisfactory to the geotechnical engineer and the resolution that is needed to meet the objectives of the investigation. At both the reconnaissance and detail stages it is necessary to determine the coverage and density of stations to achieve the objectives. The required depth of investigation needs to be established with the engineer; and the effectiveness of a 1-, 2- or 3-dimensional approach should be reviewed.

In all these aspects, the management of the programme and the timeframe in which it sits are of considerable importance. In many cases it may not be possible, for either cost or timing considerations, to use the most appropriate technology. However when these limitations are understood it is frequently possible to modify the ideal approach to provide subsurface information, which will still be of value.

An investigation is exploratory by nature and its full extent cannot be defined at the outset. Hence, a phased approach to investigation is recommended. It is also helpful to include in all budgets for each stage, an allowance of about 15 per cent for additional works. This is particularly so in fieldwork, where savings on re-mobilisation can be made by extending the investigation programme in the light of information obtained. The recognition of the exploratory nature, underpins the need for the designer of the investigation to be involved in the supervision of the works. The designer needs the freedom to alter, modify or extend the investigation to obtain the required information, in light of the conditions revealed.

3.3.2 Constraints on methodologies

Descriptions of the various methodologies are given in Chapter 5 and include operational requirements. This section presents a general view of constraints, which apply to geophysical studies in particular.

For land projects, the main concerns are access to the site and any disturbing influences that are present. These may not be immediately obvious. Where a site is being redeveloped, it is not unusual to find that the site levelling process has obscured basements and foundations. In a greenfield site, access for particular systems may be affected by steep slopes or acute changes in level. Dense surface vegetation may prevent easy access to the site, requiring either site clearance or abandoning a planned swift reconnaissance. Although many of these factors can be established by careful inspection of site plans and aerial photographs, nothing can replace the specialist visiting the site.

Other factors will determine the potential effectiveness of differing methodologies. Soil conductivity will considerably influence the results from ground-probing radar and other electromagnetic techniques. Site boundary fences, metal pipes and cables affect the viability of the latter methods. Heavy machinery and other sources of audible noise can present severe limitations to seismic data acquisition. Lower frequency vibrations can severely curtail periods in which gravity observations can be made. The presence of ferrous materials, while possibly one of the targets for a survey, can also mask a more critical hazard, such as a mineshaft. Microseisms and sunspot activity can disturb gravity and magnetic observations respectively and affect the productivity of the contractor.

Physical conditions also affect working over water and taking measurements from the air. For work over water, poor weather conditions, strong currents and frequency of shipping can extend periods of survey beyond that originally planned. Weather is also a critical factor for airborne operations. In both situations there is the need to obtain permits, not only to operate in the area, but also to possibly use radio-navigation systems. The latter has become less critical with the availability of accurate positioning using satellites (GPS).

3.3.3 Specification

The above factors should be taken into consideration when preparing a specification. It is particularly important that the engineer states clear objectives, and they should be identified when in consultation with the EGA.

It will not only be the objectives that determine the methodologies to be recommended. Depending on the programme and the amount of detail needed at a given phase, different approaches can be used to fit the timing. A detailed scope of work will usually be prepared in order that tendering contractors can cost the geophysical work. While hopelessly inadequate just to state that "a geophysical survey is required", it can also be counterproductive to overspecify and preclude scope for alternative proposals. It is therefore better to provide a framework within which a contractor can understand what is wanted and cost it, whether on a time basis or unit rates, but allow for the offer of additional methodologies.

In many cases, there should be a specialist providing technical supervision on site during the data acquisition, representing the interests of the client. This could be the EGA or someone working for the EGA. The work can then be modified in the light of what is found. Such an arrangement would need the specification to be clear as to the scope for amendment to the programme; how much, if any, of the flexibility will be at the discretion of the contractor, or if it is only when instructed by the on-site supervisor. With the widespread use of powerful portable PCs, which enable results to be seen in preliminary form soon after their acquisition, this type of arrangement is increasingly necessary. Changes to the programme are often desirable, but can cause subsequent difficulty in establishing legitimate costs if the authority and criteria for change are not properly defined beforehand.

Most geophysical data require reduction, processing and plotting in order to provide a useful image for subsequent analysis. Most data are in digital form and their presentation and format should be specified at the project outset.

The person responsible for interpreting and evaluating the data and what is to be done, should be specified clearly. Sometimes it may be convenient for the contractor to provide only data, which another party would be employed to interpret. In other cases there could be a requirement for a provisional interpretation, pending the provision of boreholes or other ground truth. Integration of this information may be best handled by the geotechnical adviser in conjunction with the EGA.

3.3.4 Contract and sub-contract

The investigation design (which includes the type, location, depth and order of particular investigative techniques and a corresponding methodology to suit the purpose of each location or technique type) is translated into tender documents. The tender documents comprise the conditions of contract, specifications, drawings and bills of quantity. Due to the exploratory nature of the work, it is recommended that the bills should include re-measurable items. These items should properly reflect the nature of the components of work to be done and should be straightforward to measure. In addition, there should be a mechanism for varying the work to suit conditions at the site, in order to obtain the appropriate information in a timely manner without having to re-tender. The geotechnical adviser should agree appropriate contingency budgets with the client that allow for the possibility of the work being varied.

It is often at this translation stage that many of the reasons for and objectives of the survey are overlooked, omitted or subsequently misconstrued. This can be prevented by the involvement of the geophysics contractor in the planning and investigation design process or as a partner within the project team. As much information as possible about the purpose and rationale of the investigation should be given in the tender documents, including the desk study results, the conceptual ground model and the methodology. The availability of the desk study will allow the tenderers to carry out their qualitative risk assessment and develop their fieldwork construction health and safety plan, as well as prepare their method statements. It is important that tenderers comply with the Construction Design and Management Regulations (Health and Safety Commission, 1994), if they apply. This will provide a uniform basis for the tenderers to assess the project and the intentions of the investigation. It is good practice to encourage innovation and to allow tenderers to submit alternative proposals, which could save money or add value. There are also situations where it would be appropriate to negotiate a contract directly with a specialist contractor to provide particular services.

Wherever possible, standard unamended forms of contract should be utilised, even though they may not be specifically designed for the geophysical element of the site investigation. Consideration should be given to the geophysical works being contracted separately from the main geotechnical or geo-environmental survey so that only appropriate geophysics contractors would be bidding. This would not be practical with downhole geophysical logging as it is linked to the progress of the borehole so that it is inevitably let as a sub-contract to the main borehole investigation contract.

In all cases the geophysical survey should be quantified into elements that can be remeasured according to the actual quantity of work satisfactorily performed. Typical items could be items of metreage for borehole logging, arrays at a number of specified locations for land resistivity survey, or day rates for offshore seismic profiling. In such cases it will be necessary to define performance and corresponding acceptance criteria for satisfactory work as well as for payable standing time.

The method of engagement of the geophysics contractor should be appropriate to the type and scale of investigation. In all cases it is essential to identify objectives and expected deliverables. Small-scale works do not need to be weighed down with a complicated and onerous contract. A letter of engagement that outlines the project and sets out the details for remuneration, should be sufficient when dealing with a competent organisation.

The geophysics sector of industry would help itself if it prepared and maintained a register of specialists and specialist contractors. The Geologists Directory published by the Geological Society goes some way towards this.

3.3.5 Quality assurance

Most small UK geophysics contracting companies operate in a professional manner regarding the technical requirements of a project. They will have developed an approach to project management, which enables the work to be undertaken with a minimum amount of paperwork, concentrating on the acquisition of data and its subsequent manipulation to produce an output. However, this framework will, in most cases, not have been brought to formal certification by an outside registration body. This lack of such registration should not be taken as any lack of quality standards on the part of the contractor. Indeed for contractors who have successfully traded for a number of years it is likely that an informal quality system is already in place enabling the company to operate successfully.

Where there is a requirement for a contractor to operate within the ISO 9000 (BSI, 1994) standard there should not be a difficulty if the work is being handled through a consulting engineer who is already registered. Providing the contractor can agree to operate within the engineer's system, there can be an acceptance of working to the standard. This situation is likely to apply to engineering geophysics advisers as well. In some instances this arrangement has provided the necessary encouragement to quantify existing procedures and move forward to certification. Help can be provided to the contractor to understand the requirements for traceability in internal procedures and for records to be made to confirm that standards have been achieved. However, pure adherence to the ISO 9000 standard does not in itself guarantee the work is being undertaken in the best way with regard to the project objectives. Full enquiry is required at the tender stage by the EGA to check that this role is understood in relation to:

- The Client's QA requirement for record keeping, traceability and deliverables.
- Quality control during the acquisition, processing and reporting.

There needs to be an established system of recording requirements and decisions, and this information needs to be circulated to all parties. The responsibility of the EGA, and the level of decision-making when acting as the engineer's representative on site, needs to be carefully considered and documented. A diary of events and confirmation of all decisions in writing to both the contractor and the engineer is essential.

3.3.6 Data processing, modelling and interpretation

Although the data acquisition phase is usually the most expensive part of a geophysical investigation, it is just as important to make sure that the acquired data are adequately and correctly manipulated, to remove geophysical artefacts, if the final product is to be useful. As different geophysical methods require different amounts of processing in order for the information to be of value, the EGA should be consulted about the degree to which such processing is required.

In the case of passive methods, eg magnetic and gravity surveys, where an ambient property of the earth is being measured, the data have to be corrected for diurnal variations and other disturbing influences before a true value of the local field is produced. Providing the way in which the contractor has arrived at the final values has been verified, the data-reduction process is routine. In the case of active methods, where a signal is being imposed on the earth (such as with electromagnetics, resistivity, seismic tomography and downhole geophysical methods), the processes of data manipulation are more complex and should be observed and checked at various stages by the EGA. This is particularly relevant to the manipulation of airborne data, which are now used in some major engineering programmes.

The process, by which seismic reflection data are transformed from raw seismic arrivals into a pseudo-geological cross section, is highly sophisticated and requires close monitoring by the EGA at key stages. Many geophysics contractors specialising in reflection seismic acquisition, found that the oil exploration processing houses did not have the understanding of the more variable, high-frequency shallow section of interest to the engineers, and now tend to carry out their own processing. There are specific points in this processing at which it is valuable for decisions to be made in conjunction with the EGA.

With seismic reflection data sections, it is possible to gain a general understanding of the structural nature of the subsurface. With non-seismic methods however, the nature of the results can often only be understood by comparison of the field results, with that produced by an idealised earth model. It is not uncommon for several models to fit the dataset. This does not mean that the data are faulty. A given set of measurements taken at the surface, remote from the changes in physical parameters in the subsurface, can arise from differing subsurface conditions. It is necessary in these circumstances to provide constraint in the interpretation, either from additional geophysical sensors, or from the results from intrusive investigation (ground truth). Some investigation of this possibility can be beneficial, prior to the use of a particular method, to ascertain the detectability of subsurface features.

The contractor's geophysicist should present the geophysical data in an appropriate way, to take account of the engineer's objectives for the project. The presentation methods should be scientifically rigorous and the results, where appropriate, should be numerical with the provision of specific values and accuracies or error bars. In the case of seismic reflection data, these should be interpreted by someone who is familiar with the type of structures encountered at the site and transformed into depth information through the use of boreholes, in which check-shots and sonic logs have been obtained. The EGA can play a particularly useful role in all these areas.

3.4 INTER-RELATIONSHIPS IN MANAGEMENT AND REPORTING

3.4.1 Team structure

Good communications are essential within any team structure, especially as the team is likely to change throughout the project life. A lack of communication presents a significant risk. In establishing any team, the facilitation of good and open communications between team members is very important. Just as the geotechnical adviser (GA) needs to be fully integrated within the overall project team, so too should the EGA and any other specialist advisers. Site investigation is too often treated as a stand-alone product assigned as being of little value. There are many benefits of properly integrating the EGA into the feasibility team, which may have far-reaching, cost-saving implications when design options are being tested, particularly for those applications intimately associated with the ground conditions. However, these benefits can only be enjoyed when individuals with the appropriate skills and abilities are selected. They can then demonstrate their proficiency through leadership, example and performance within the client's budgetary and financial criteria.

When difficulties are experienced in progressing the survey, or changes to the survey are required – which are common occurrences – the need for regular dialogue is increased. Experience indicates that this is often overlooked, leading to distrust within the team, which compounds the impact of difficulties on cost and programme. The increased use of a partnering approach, where there is collaboration and co-operation between all parties, should lead to improvements in teamwork and communications.

3.4.2 Supervision

Although there is a move towards "self certification" in construction contracts, ie supervision of the works by the contractor's own staff, experience has demonstrated that this is neither cost-efficient nor effective as a risk management strategy for ground investigation. A risk management strategy is exploratory and needs to be directed, ie modified, altered, expanded or extended to reflect the conditions recorded. However, the partnership approach can be successfully applied where there is a collaborative and a non-adversarial approach to supervision. The establishment of a team that has members from both the contractor and the consultant – particularly if they were both involved in the planning process and are then involved in the fieldwork – can provide a highly self-motivated environment where the project objectives dominate.

Many geophysical techniques are highly specialised and require an in-depth knowledge of electronics, so there can be a tendency to over-focus on technical minutiae. Hence, at least one individual within the team should be able to consistently view the overall performance of the survey and provide balanced, clear, objective reports to the client's team. The level of supervision should be prescribed and identified by both parties and the associated costs should be separately identified and paid for on a time basis.

3.4.3 Deliverables

The definition of deliverables is often given insufficient consideration in relation to their purpose, format, content, scale, style, staging and timing. Sometimes this stems from the specifier or procurer not having a technical understanding of the particular technique or because the specialist contractor does not appreciate the needs of the project team.

Specifications should detail what is required, its timing, differentiating stages of preliminary information, drafts and final reports. There should be clear statements of time periods for corresponding approvals. The ability and need to exchange data in digital format also requires clarity about what is required and the status of the data.

The procedures of internal and external checking, approval and review should be formalised in the specification. These responsibilities should be linked to the grades of the staff and their qualifications.

Usually the geophysics fieldwork contractor prepares a factual report. This report should describe the techniques used, discuss any limitations and highlight particular difficulties experienced at the site. It should include all the calibrations as well as the factual data. In civil engineering applications of geophysics, the specialist contractor also provides an interpretation of the data. Reports should be divided into sections that differentiate between fact and interpretation. While colour helps visualisation of the data, its application has to be tempered to avoid over-emphasising features that may be tenuous. It may be necessary to associate various colours with various geological strata in a pre-determined, systematic way.

3.4.4 Control and communication

Figures 3.1 and 3.2 represent two models of the relationships in geophysical investigations and which are discussed above. The main difference is whether the geophysical investigation is a stand-alone contract or a sub-contract under the main site investigation contract. Either model can be appropriate, but the Geotechnical Adviser has a key role in the site investigation as a whole, and the Engineering Geophysics Adviser is needed when there is a geophysical investigation. There are complex communication routes in either case, for instructions, variations of the work, reports and interpretation. It therefore, needs careful attention when setting up these control and communication systems before procurement of the geophysics.

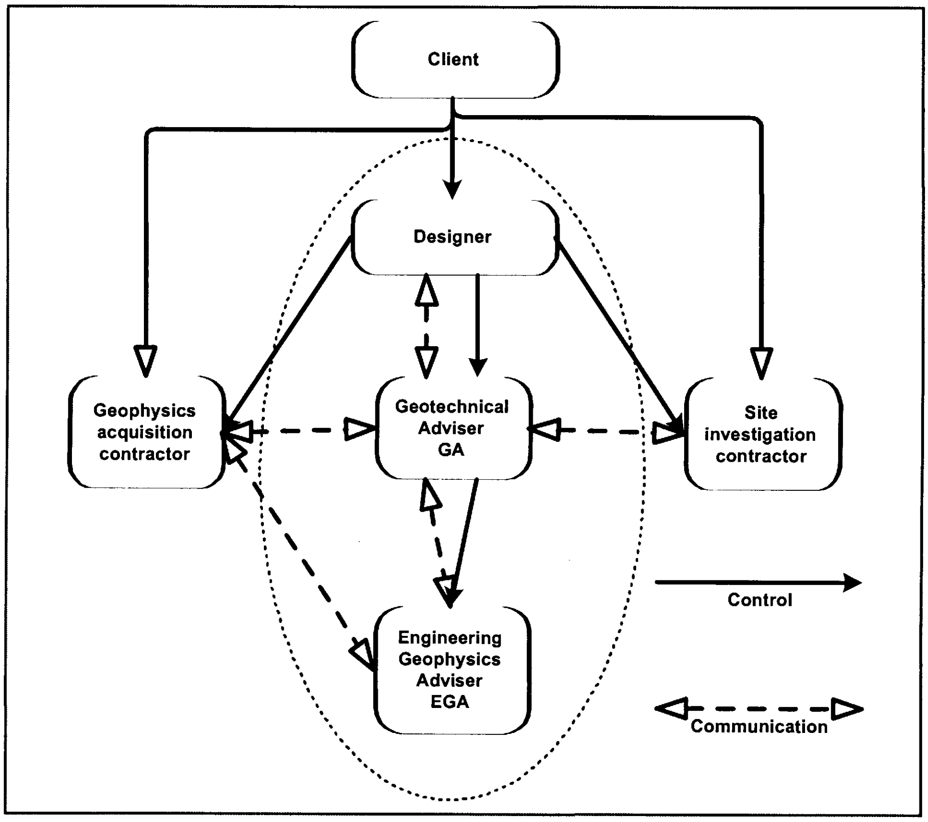


Figure 3.1 *Control and communication with a separate geophysics contract*

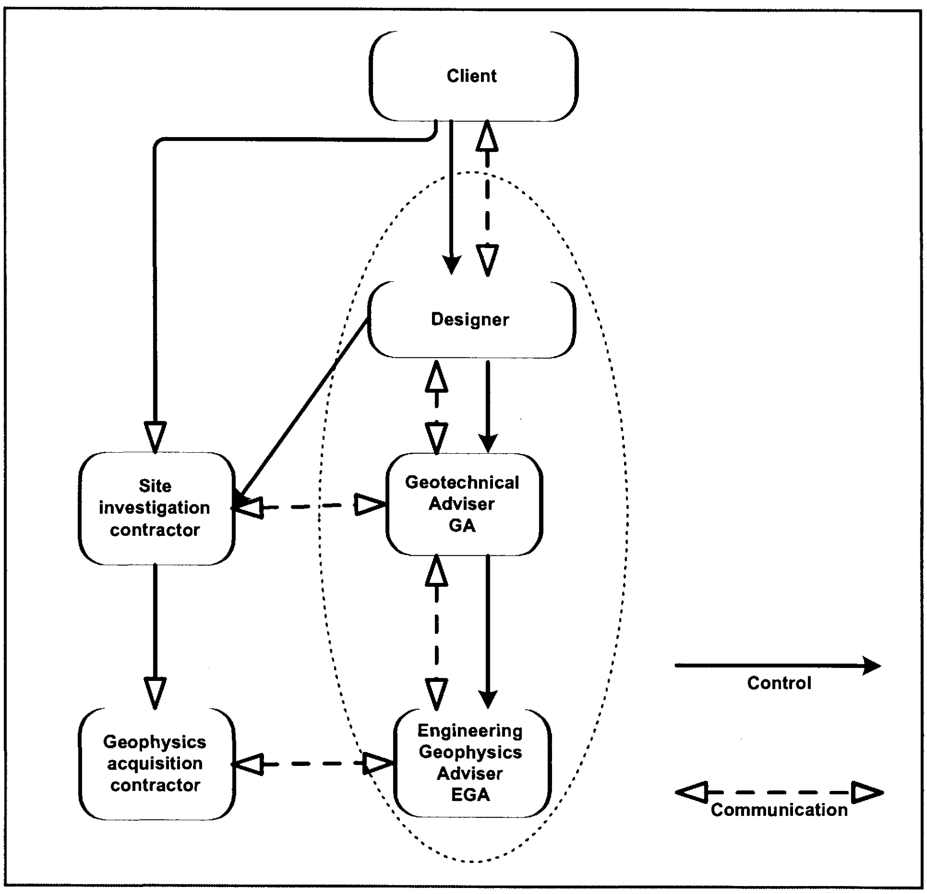


Figure 3.2 *Control and communication with the geophysics as a sub-contract*

Geological Society, London, Engineering Geology Special Publications

The conceptual ground model

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 51-59
doi:10.1144/GSL.ENG.2002.019.01.04

4 The conceptual ground model

The range of possible subsurface conditions that can be predicted, knowing the geological processes that formed the ground beneath a site, is self-evident to the geological or geotechnical advisor. This information underpins the conceptual ground model. Many construction cost over runs are caused by unforeseen ground conditions. Avoiding this requires a better desk study and ground investigation (including geophysical survey), as well as the development of a ground model that includes the known and suspected features on, below and adjacent to an engineering site. Such a model will assist in identifying the likely implications of the ground for a proposed engineering project. It is helpful to portray the conceptual ground model as a three-dimensional block model that allows the scale of the features, in relation to the size of the project, to be appreciated. In addition, the geology should be characterised in engineering terms by the geological/geotechnical advisor, which means that geotechnical properties and their likely lateral and vertical variation, must be assessed within the context of the model.

The difficulty in understanding the ground conditions at a construction site has its origin, in part, in the way that geological knowledge advances. Geological mapping has been carried out in Britain since the late 18th century when the canal network was constructed. The process of updating British geological maps is still continuing (see CIRIA Special Publication 149, *A guide to British stratigraphical nomenclature*, Powell 1998). The geologist has to interpret the information as it is made available from boreholes, trenches and various exposures of rocks seen in cuttings, quarries and cliff sections. The geologist will then construct models from the data, such as the geological map and the geological cross-sections. The relationship of these models to the true geological structure below the ground surface is a function of the available data. It is the ability of the geologist, which enables the interpretation of the models, to show how a block of ground was formed and subsequently modified, by geological processes. However, the geological structure in many places is extremely complicated and there can be great difficulty in proposing a geological model, which genuinely represents the ground conditions. The initial model will be used to assist in designing the investigations for the site and as the basis for the iterative development of improved models, as further data become available.

4.1 ELEMENTS OF THE GROUND MODEL

The basic geological concepts described in this chapter, were summarised and developed by Professor Peter Fookes in the 1st Glossop Lecture (Fookes, 1997):

> Considered simply, the bedrock and superficial geology at any one site is the product of its geological history, that is, the formation of the component rocks; diagenetic, tectonic and weathering disturbances it has received, together with any overlay of alluvial, colluvial, windblown, or other superficial materials. These in turn may have been affected by diagenesis, tectonism and weathering.

In summary, the three-dimensional geology of a site is shaped by a series of rock-forming and rock-modifying processes.

4.2 ROCK FORMATION

Figures 4.1, 4.2, 4.3 and 4.4 present examples of how the rock-forming and rock-modifying processes can result in different rock, soil and discontinuity relationships in the ground.

Figure 4.1 (Fookes, 1997, Figure 19) shows some possible igneous rock associations in a wet temperate climate. A granite body has intruded into a sedimentary sequence, causing local contact metamorphism and a steepening of the dip of the sandstones and mudstones. Later, the sediments have been intruded by andesitic and basaltic dykes, the latter from a gabbroic body. The variability of the composition, hardness and strength of the rock types present has resulted in differential weathering.

Sedimentary rocks are formed at, or near, the earth's surface as a result of erosion and deposition, chemical precipitation and organic accumulations. Figure 4.2 (Fookes, 1997, Figure 21) shows a typical tropical or sub-tropical coastal environment, in which mainly carbonate-rich materials are being deposited. The block diagram shows how the deposits, and hence the rocks that form from them, can vary in lithology and thickness over relatively short distances.

A typical model of metamorphic rock associations in a wet, temperate climate is shown in Figure 4.3 (Fookes, 1997, Figure 20). One of the most important effects of the high pressures and temperatures, and the earth movements is the creation of a rock mass that is often hard and strong but highly fractured, cleaved and sheared.

4.3 ROCK MODIFICATION

These basic rock associations are further complicated by the geological processes that act upon them. The rocks may be weathered, sheared or overlain by superficial or man-made deposits. The superficial deposits (which will, ultimately, form sedimentary rocks, if not eroded) are characterised by usually being bedded, while the man-made deposits are characteristically heterogeneous. These deposits can be variable in their thickness and their lateral extent.

Figure 4.4 (Fookes, 1997, Figure 33) shows what can happen if the rocks shown in Figure 4.1 were subsequently exposed to a wet tropical environment, where the weathering would be intensified, resulting in a deeper soil profile. The return to temperate climatic conditions would expose the weathering profile to new processes that would result in further modification.

The range of geological processes that can modify the original rock type includes:

- burial (compaction – moving particles closer together; diagenesis – rock formation including lithification, metamorphism)
- tectonic activity (folding, faulting/shearing, metamorphism)
- volcanic activity (hydrothermal – chemical alteration, baking – thermal hardening)
- weathering (chemical and physical rock alteration in a range of climatic environments)
- erosion (physical removal of rock or soil material)
- solution (of more soluble materials)
- subsidence (ground movement due to a variety of causes)
- sea level change
- seismic activity.

The result of these processes on the rock mass can be summarised as hardening (eg by lithification, cementation or baking), breaking (eg by faulting or de-stressing) and weakening, a chemical and/or physical alteration by weathering, for example.

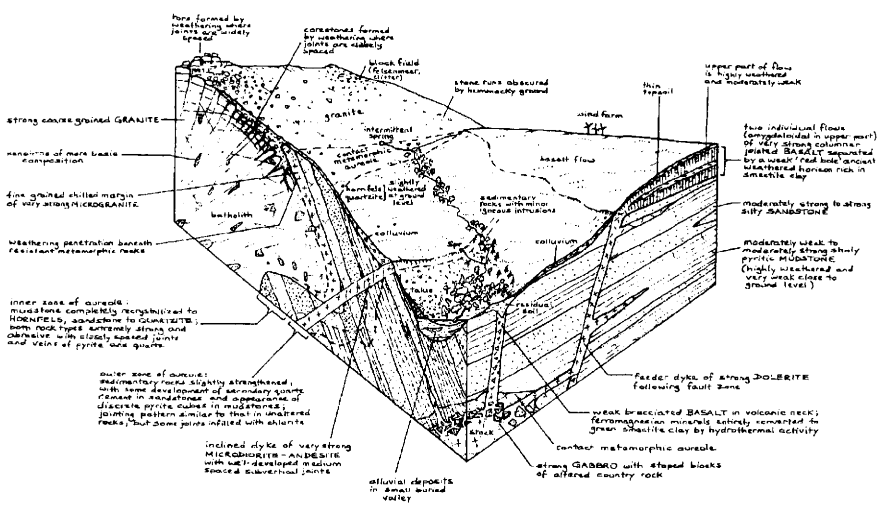


Figure 4.1 *Igneous rock associations (wet temperate climate) (after Fookes, 1997)*

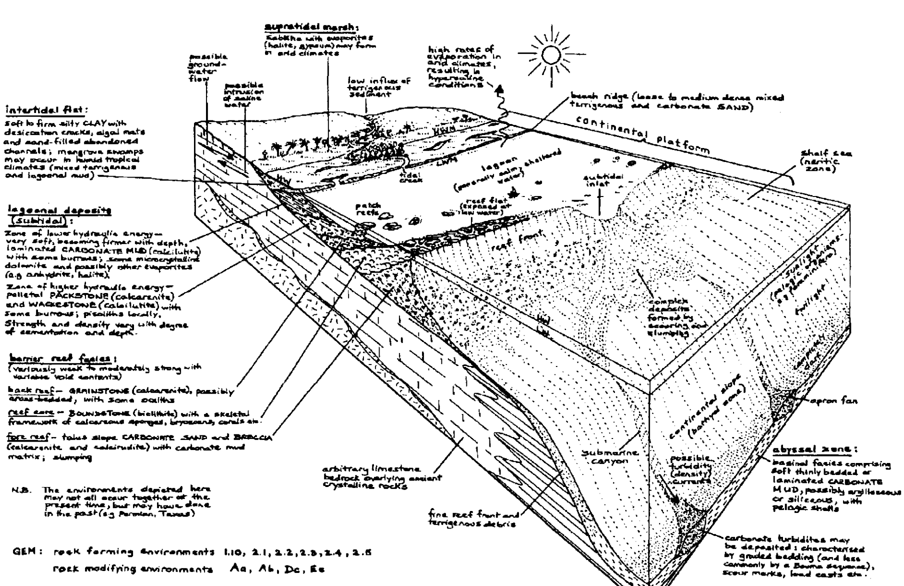


Figure 4.2 *Tropical / sub-tropical carbonate shelf facies (after Fookes, 1997)*

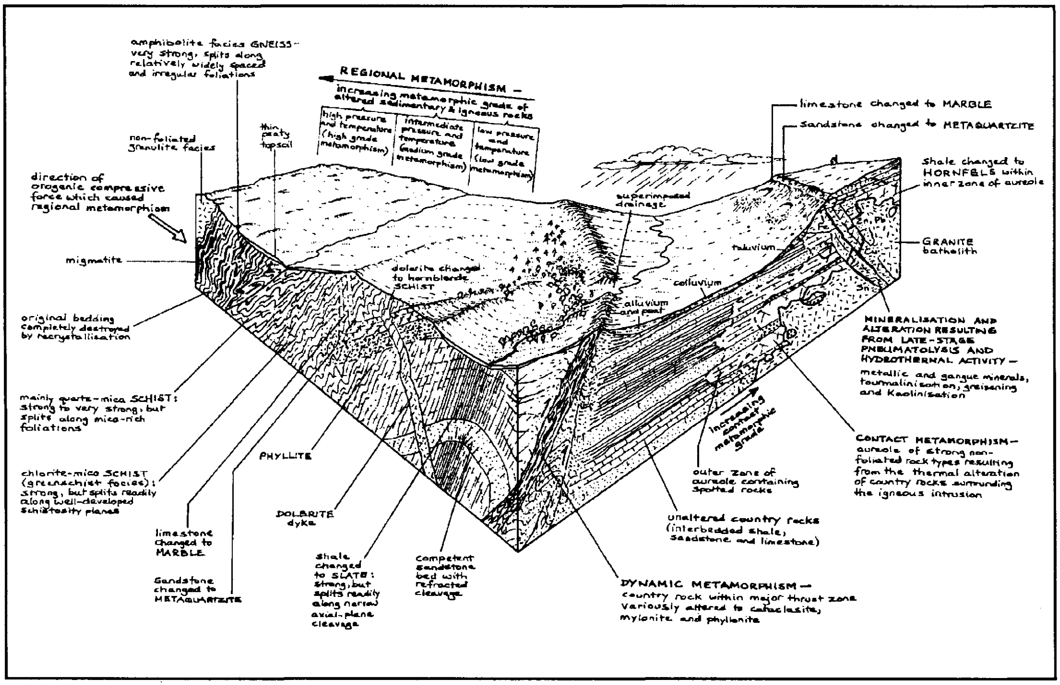


Figure 4.3 *Metamorphic rock associations (wet temperate climate) (after Fookes, 1997)*

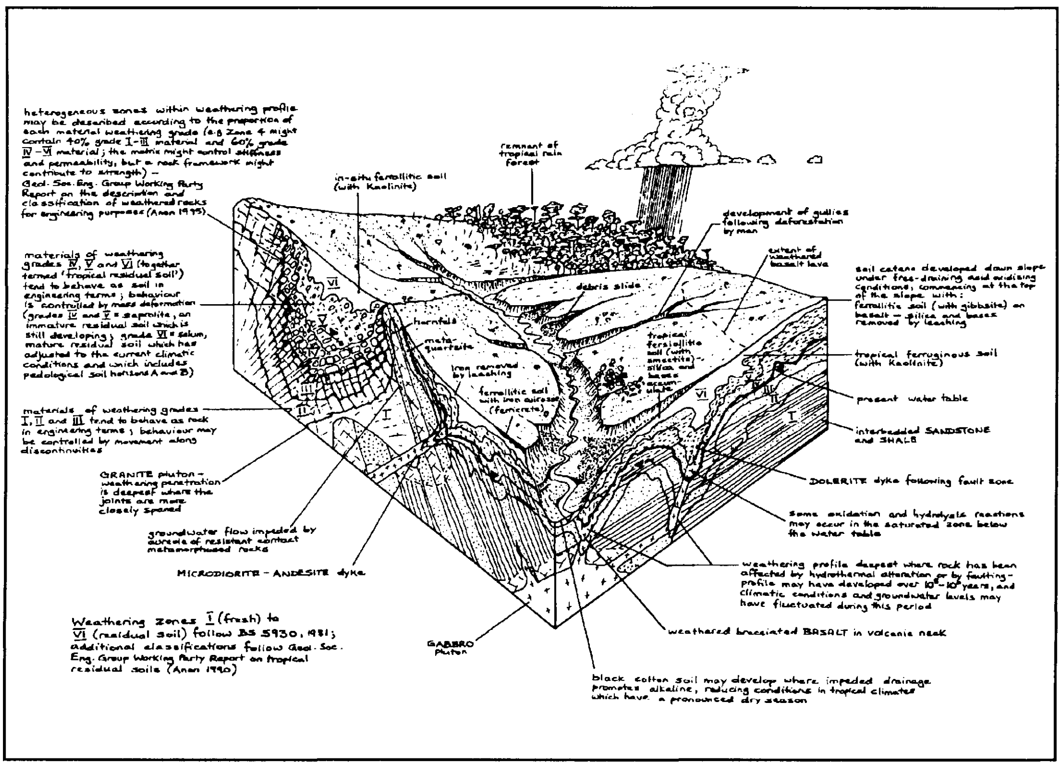


Figure 4.4 *Wet tropical weathering (superimposed on geology shown in Figure 4.1) (after Fookes, 1997)*

The rock-forming and rock-modifying processes that may have affected a site should be considered when developing the geological model. In addition, the groundwater conditions should also be assessed for incorporation into the model. These have a considerable impact on the interpretation of data from many of the geophysical techniques. An idealised model of near-surface hydrological environments is presented in Figure 4.5 (Fookes, 1997, Figure 28). This shows how water can move through a surface zone of infiltration to a capillary zone and ultimately the saturated zone. The boundaries between these zones vary depending upon the availability of surface, the groundwater to the system and their movement within it. The ground model may need to be modified in urban areas. Rising groundwater levels are perceived to be a major problem for the future in many areas of the UK (See 9.2.5). The interpretation of geophysical investigations is affected by the presence of buried objects or voids, the placement of fill and the contamination of soils and groundwater.

4.4 INTERPRETATION OF THE GEOPHYSICAL DATA

The success of geophysical surveying techniques in the search for oil, gas and minerals has been so great, that they are used extensively and routinely in these industries. While the principles of these techniques remain unchanged, their application to construction requires careful consideration of how they are incorporated into site investigation practice.

Typically, the initial conceptual model of the ground is constructed on the basis of a desk study (see 11.2.1) and some form of investigation at the site (eg site visit, drilling). **The objective of any subsequent geophysical survey should be to improve and refine the developing conceptual ground model, rather than to create a competing one based predominantly on new geophysical data.** This approach focuses geophysical surveys directly on what knowledge is needed at a site. For example, the continuity of rock between two boreholes may be established rapidly and cost effectively using surface surveys, when characterising the whole inter-borehole region would be far too costly.

Geophysical surveys on their own merely provide a **measure** of the vertical and lateral variation of the physical properties, such as electrical conductivity or seismic velocity, of the geological materials. The modelling of geophysical data is generally based on the assumption that the geological units present in the ground are isotropic and homogeneous, and that sharp boundaries exist between them. It is also often assumed in the modelling process, that the geophysical properties are constant both laterally and vertically within a specific geological material. Geological situations are rarely this simple. The results of geophysical surveys can only be **interpreted** in the light of knowledge of the range of likely ground conditions that could give rise to the data set measured. Hence proper interpretation of the geophysical data has to be made within the context of a realistic model of the likely geological ground conditions, ie the ground model (See Chapter 6)

In most cases, the data collected during the course of a geophysical survey, only represent the variation of a particular geophysical parameter, such as the earth's gravitational field or seismic travel time, within the survey area. It is not until the data have been processed that they can be interpreted to assist in the development of a model of the geological structure under the survey area. Without a ground model to guide the geophysical interpretation, the geophysical model cannot be calibrated or evaluated confidently, in practical terms. For example, a modern seismic reflection record section is very similar in appearance to a geological cross-section. It cannot however, provide real depth information until the time section has been converted to a depth section, by using the appropriate seismic velocities in each of the resolved layers.

Geophysical measurements, in themselves, are unambiguous and precise. In their interpretation however, there may well be several possible models that could equally fit a given data set. The geophysical properties of a particular lithological unit in the geological sequence may also vary with depth. For example, a gradual increase in seismic velocity, with water content above the water table, is often observed in superficial materials. Sloping interfaces in the geological sequence do not appear in their correct position in a seismic reflection, or ground penetrating radar record, and their orientations have to be changed in order to represent the true geological situation.

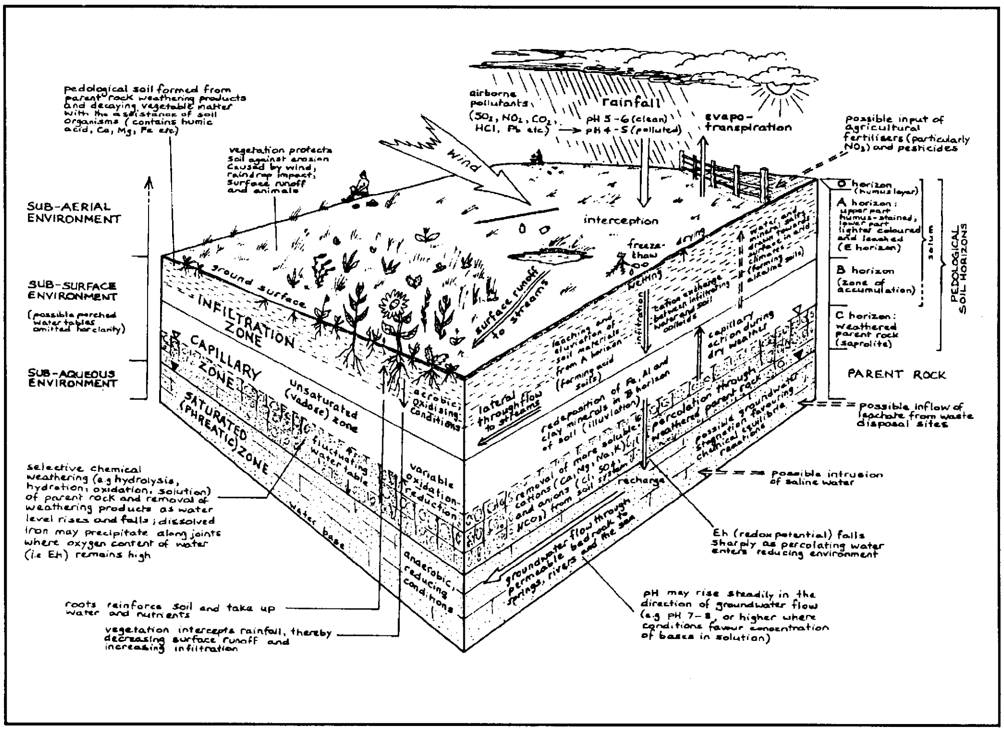


Figure 4.5 *Idealised characteristics of near-surface hydrological environments (after Fookes, 1997)*

A typical example of how essential the geological information is to the interpretation of a geophysical survey is in the commonly used application of seismic refraction techniques, to the mapping of bedrock. A refractor of seismic velocity in the range 4000 to 5000 m/s may be confidently identified as "bedrock" or "engineering rockhead", while the identification of material type with velocities of 1800 to 2500 m/s is often ambiguous. It could represent either a weathered rock or a stiff clay for example, materials that have quite different engineering properties. This situation is one of the more frequent sources of discrepancy between bedrock depths determined in boreholes and from seismic refraction surveys. The situation is compounded further by inconsistency in exploratory borehole practices in these intermediate materials. It is essential, therefore, that the interpretation of the geophysical data is made within the conceptual framework that a ground model provides.

A geophysical survey is only one part of the whole site investigation. The interpretations produced from it should improve and refine the developing ground model. The advantage of the geophysical survey is that it enables information to be obtained for large volumes of ground that cannot be investigated by direct methods because of the costs involved.

4.5 GEOLOGICAL CONSTRAINTS ON THE DESIGN OF THE GEOPHYSICAL SURVEY

The development of a ground model is necessary in determining the coverage and depth of penetration required from the investigative techniques. In most areas, it is usually possible to assign a realistic average, or at least a bandwidth, of strength and stiffness properties of the various soils, rocks or man-made features. This will allow assessment of the relative ratio of contrasting properties that influence selection of geophysical techniques, as well as selection of probing, boring or coring for intrusive exploration. The position of the water table is likely to be of considerable significance. For an engineering investigation, the ground model should take account of the proposed construction and its foundation. Thus there may be a need to investigate the deposits, in which piled foundations would take their bearing, or deep-seated geological features, such as faults, which could have implications for design against seismic activity and the possibility of rising groundwater (See 9.2.5).

Pitfalls can arise when the partially-developed ground model is taken to be a true representation of the subsurface. Figure 4.6 illustrates a case where the ground model has been constructed from borehole data without regard to the geological setting (contrary to sections 11.2.1 and 11.2.2). The conditions found during construction corresponded with a well-developed solution-weathered environment, having pinnacles, dolines and extensive filling of cavities and joints (Fookes, 1997).

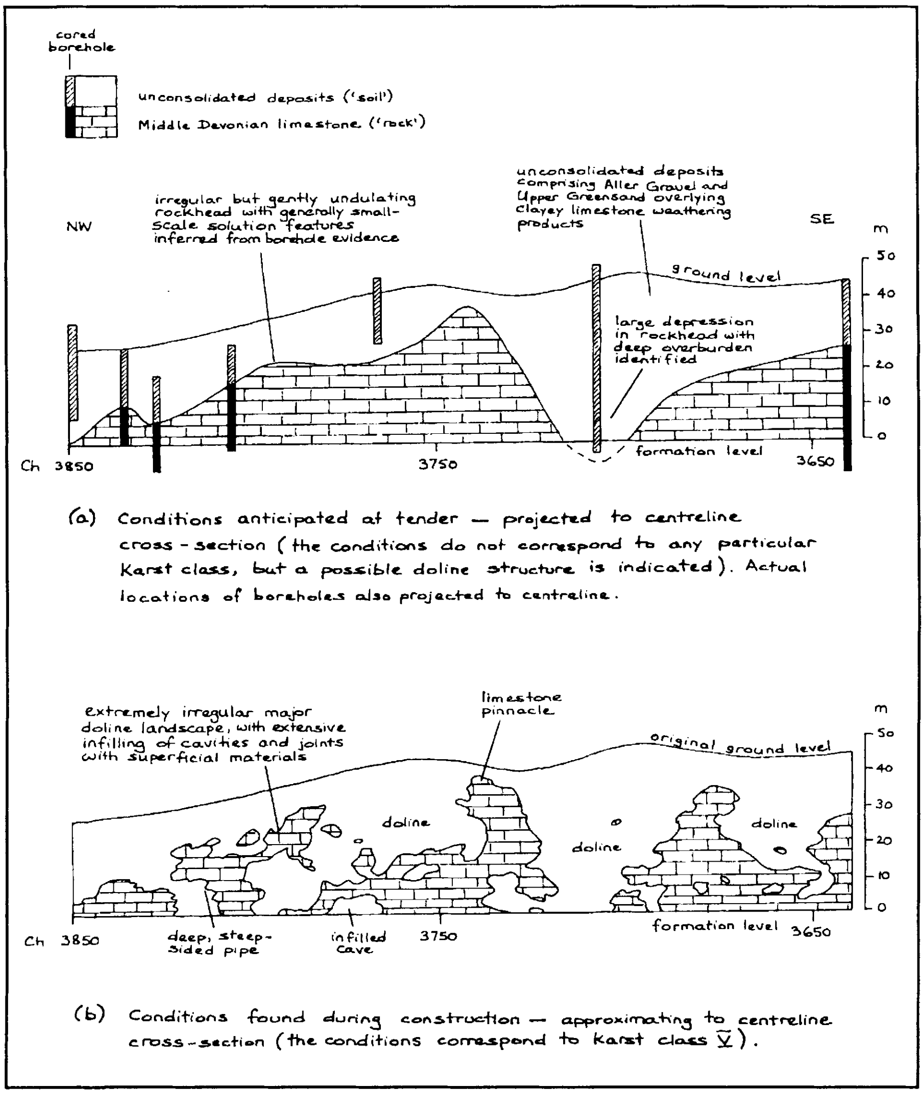
A second example is shown in Figure 4.7, where sites of bridge piers for a river crossing are considered (Fookes, 1997). While a karstic setting had been identified, the initial conceptual model (a) was constructed showing limestone extending between boreholes near the ground surface. During construction, the site investigation boreholes were found to lie within pinnacles of limestone (b), the solution-weathering being far more advanced than had been anticipated in (a). While model (a) was taken to be the most likely given the information available following the site investigation phase, model (b) could also have been possible. A combination of resistivity imaging from the ground surface, and horizontal seismic scanning between boreholes, provide a means of testing the hypothesis inherent in model (a) that limestone extends between adjacent boreholes. Knowing the water table is above the limestone in the centre of the valley, low resistivity and low velocity estimates for the inter-borehole region would suggest the presence of sediment rather than extensive fracturing. Improving ground model (a) by incorporating such geophysical knowledge, would have strongly suggested the presence of in-filled voids and greater dissolution, which were subsequently proved during construction (b).

The development of a ground model will assist in the selection of the most appropriate geophysical technique(s) to be used and in their specific design. Various physical factors limit the likely effectiveness of the available geophysical techniques:

1. *Penetration.* The depth of penetration into the geological formation or anomalous material that is possible. For example, the depth of penetration of a ground probing radar survey in saturated clay is considerably less than in dry sand.
2. *Resolution.* The vertical and lateral resolution required for the anticipated targets. For example, it may be possible to resolve a 1 m diameter void at a depth of 10 m using electrical resistivity, but not if the void is at a depth of 100 m.
3. *Physical property contrast.* The contrast in physical properties between the target and its surroundings. For example, it is not possible to identify a low density/low velocity layer beneath a higher density/higher velocity one using seismic refraction.

4. *Signal-to-noise ratio*. The ratio of the signal for the physical property being measured at the site under investigation to the environmental noise level. For example, the close proximity of a high voltage electrical power cable emitting strong electromagnetic radiation might make the use of electromagnetic methods impossible.

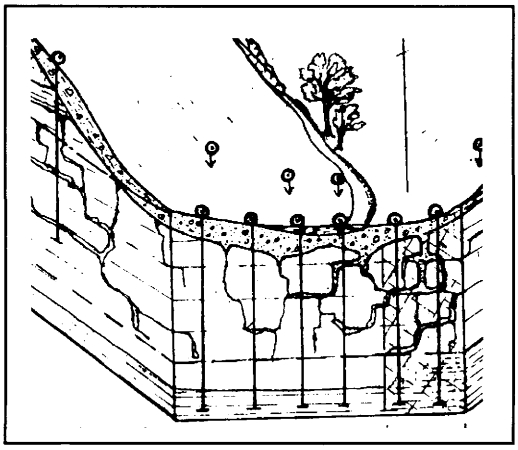
By developing a geological model of the ground, it is possible to decide which geophysical methods are likely to identify or quantify the investigation target and those that are less likely to be successful. Table 2.2 gives preliminary guidance on methods appropriate to various ground conditions. More information is given in chapters 5 to 9.



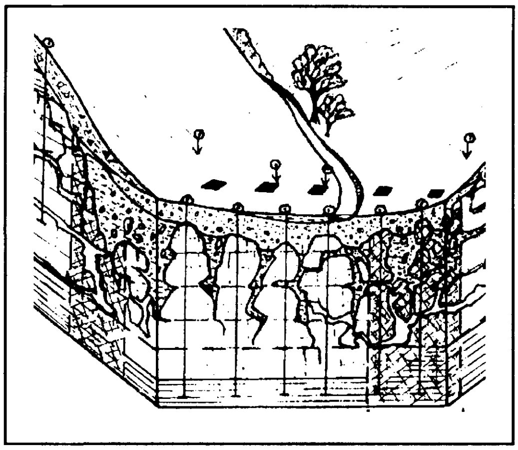
(a) Conditions anticipated at tender — projected to centreline cross-section (the conditions do not correspond to any particular Karst class, but a possible doline structure is indicated). Actual locations of boreholes also projected to centreline.

(b) Conditions found during construction — approximating to centreline cross-section (the conditions correspond to Karst class V).

Figure 4.6 *The conceptual ground model based on site investigation boreholes (a) has not anticipated the presence of the dissolution identified during construction (b) (after Fookes, 1997)*



(a) Conceptual ground model following the site investigation phase, showing boreholes where the presence of Karst dissolution features has been identified



(b) Conceptual ground model following construction of bridge piers, showing Karstic features to be far more developed than had been anticipated

Figure 4.7 *Conceptual ground models before and after construction of a river crossing. (adapted from Fookes, 1997)*

Geological Society, London, Engineering Geology Special Publications

Techniques: science and practice

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 61-110
doi:10.1144/GSL.ENG.2002.019.01.05

5 Techniques: science and practice

Geophysical methods can be used at and below, the ground surface, at sea, in the air, and in the laboratory. In this chapter the advantages and limitations of the main methods used in the civil engineering industry are summarised. Other, less familiar, methods are discussed with the objective of familiarising the reader with the range of possible methods, which might be suggested for the solution to a specific problem.

This chapter emphasises land-based geophysical techniques to investigate the ground. There are descriptions of geophysical surveying systems, specifically developed for the marine environment to be rapid and cost-effective. Modern positioning systems, such as the Global Positioning System (GPS) and the Differential Global Positioning System (DGPS), are now in common use and accurate position-fixing of the survey vessel can be achieved.

Airborne geophysical methods are widely used in regional surveys associated with hydrocarbon and mineral exploration. They currently have little application in engineering studies because their overall cost would be prohibitive in most cases. However, in a large engineering project, such as the development of a radioactive waste repository, which involves a significant requirement for regional geological information, information from large-scale seismic reflection, gravity, magnetic, and electromagnetic surveys will be required. In this case the use of airborne methods might well be both practical and economically viable.

Many of the geophysical methods are widely used in the non-destructive testing (NDT) of civil engineering structures and materials. While not strictly geophysics, the testing employs the same physical parameters that control the effective use of geophysical methods in the geological environment. For example, ground penetrating radar is applied effectively to the testing of both masonry-arch bridges and concrete bridges but, in the non-destructive testing industry, the method is more commonly referred to as the impulse radar method. It is therefore appropriate to review the geophysical methods that are common to the testing of structures and site investigation.

Although the emphasis of this chapter is on field geophysical measurements, laboratory tests are also considered. Practitioners should be familiar with safety regulations, particularly those of the Construction (Design and Management) Regulations (Health and Safety Commission, 1994).

5.1 ELECTRICAL METHODS

5.1.1 Resistivity surveying

In electrical resistivity surveying, an electrical current (I) is passed into the ground through two earth connections (electrodes) and the voltage (potential difference (V) is measured across a second pair of electrodes (Figure 5.1). The ratio of voltage to current, is the resistance that when multiplied by a factor which takes into account the spacing between the electrodes, gives a parameter known as the apparent resistivity. When the measurement is made over a homogeneous surface, the apparent resistivity is equal to the true resistivity of the ground. However, when the resistance is made over a complicated subsurface structure, the apparent resistivity is a weighted average of the resistivities of the various rocks below the surface.

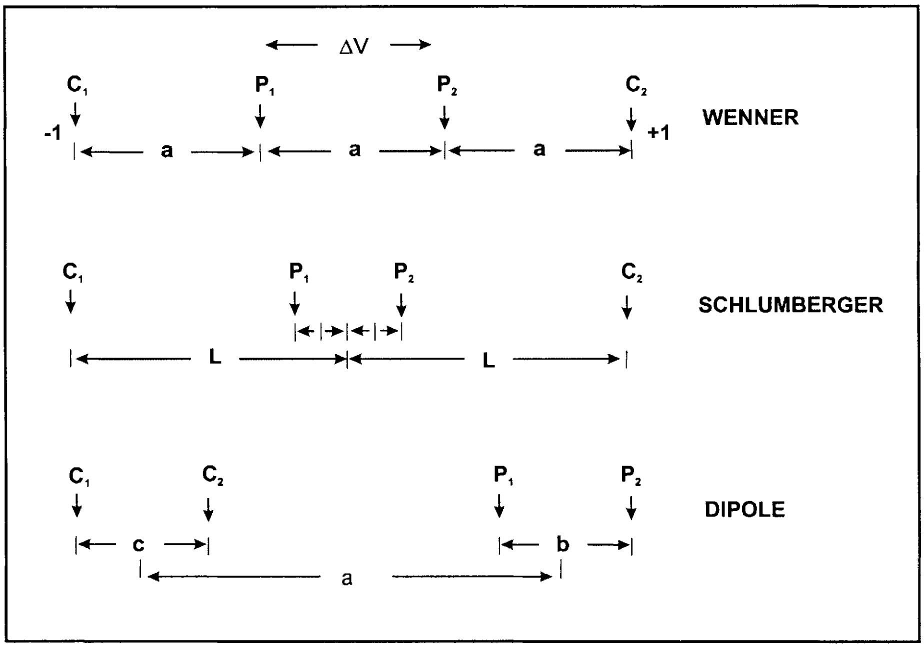


Figure 5.1 *Commonly used electrode configurations (the electrodes are placed in line at the surface of a half space. A current (I) passes into the ground through C1 and C2 and a potential difference (V is measured between P1 and P2).*

In order to investigate the ground structure and determine the individual formation resistivities, a series of measurements must be made with the electrodes in different positions. Three survey techniques have been developed for different applications.

1. *Constant separation traversing*, in which the electrode spacing is kept constant and all the electrodes are moved laterally between measurements, is used to examine lateral changes in the geological structure. These traversing techniques are popular in archaeological surveys but have largely been superseded by electromagnetic traversing methods for deeper investigations.
2. *Vertical Electrical Sounding* (VES, electrical depth probing or electrical drilling) is a technique used to examine the vertical change in resistivity. In this technique, the spacing between electrodes is progressively increased between measurements, while the centre of the whole array is kept constant. As the electrode spacing increases, the current penetrates to greater depths and so a plot of apparent resistivity against electrode spacing provides a picture of the variation of resistivity with depth. In this case the data may be interpreted quantitatively to provide resistivities and thicknesses of subsurface layers.
3. *Electrical imaging* is a recent development, which involves a combination of both traversing and sounding, to produce an image along a section through the subsurface.

Electrical methods use inexpensive geophysical equipment and are relatively easy to perform. When the interpretation techniques are well developed, the whole process can be completed in the field. This apparent simplicity has led to surveys being carried out by untrained personnel, frequently with very poor results. Field measurements should be made using techniques, which produce good quality data (eg the Offset Wenner technique for sounding), using modern digital equipment and making allowances for environmental factors, such as changes in topography, presence of fences, power lines and water mains. Interpretation of the data should allow for the considerable ambiguity, which may be present in the data. The interpretation should be based on a model, which is consistent with the known geology and uses all available controls such as borehole information and outcrop geology (See Chapter 4).

Wherever possible, the final interpretation should be based on geological information. This means that the interpreted formation resistivities should be translated into rock types. Figure 5.2 shows typical ranges of resistivities for broad types of soil and rock. More specific values are given in Appendix 2. Although it may often be easy to differentiate between rock types, eg a clay from a granite, very often the resistivity ranges overlap considerably.

The interpretation of resistivity data can take two routes:

1. Inversion, where a geological model is obtained directly from measured field data.
2. Forward modelling, where an initial geological model is adjusted until it reproduces the observed field data; the model is then a good interpretation.

The second approach gives the geophysicist more control of the geological model that is developed, as more use can be made of other geological information from the site to optimise the interpretation procedure. (See Chapter 6)

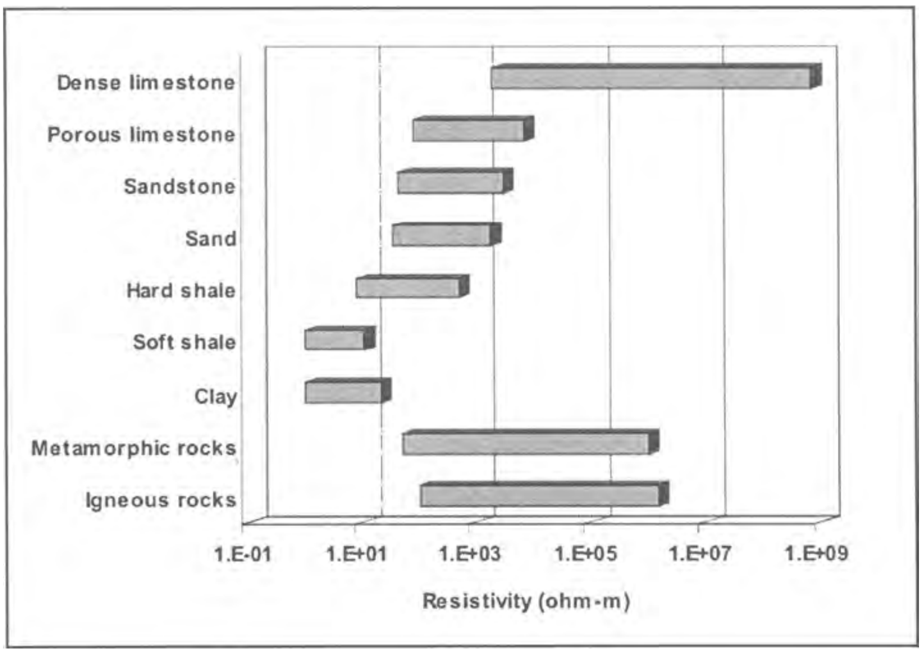


Figure 5.2 *Typical ranges of electrical resistivities of common rocks*

One example of an interpretation from a typical resistivity depth sounding using a Wenner array is shown in Figure 5.3. The electrode spacing (a) for the Wenner array is defined in Figure 5.1 and the measured resistivity values for each spacing are given by the crosses on the graph. The electrical resistivity values, which correspond to the theoretical model of the geological structure, giving rise to this data set, are shown by the dotted lines in Figure 5.2. Although the changes in the theoretical model are abrupt, the measured values of electrical resistivity change more gently, since the electrical current is only confined to an individual layer, when the layer has sufficient thickness. It is clear that other models could be generated that would fit this data set. This problem is known as equivalence and can only be resolved by some additional knowledge of the geological structure at the site from boreholes or trenches.

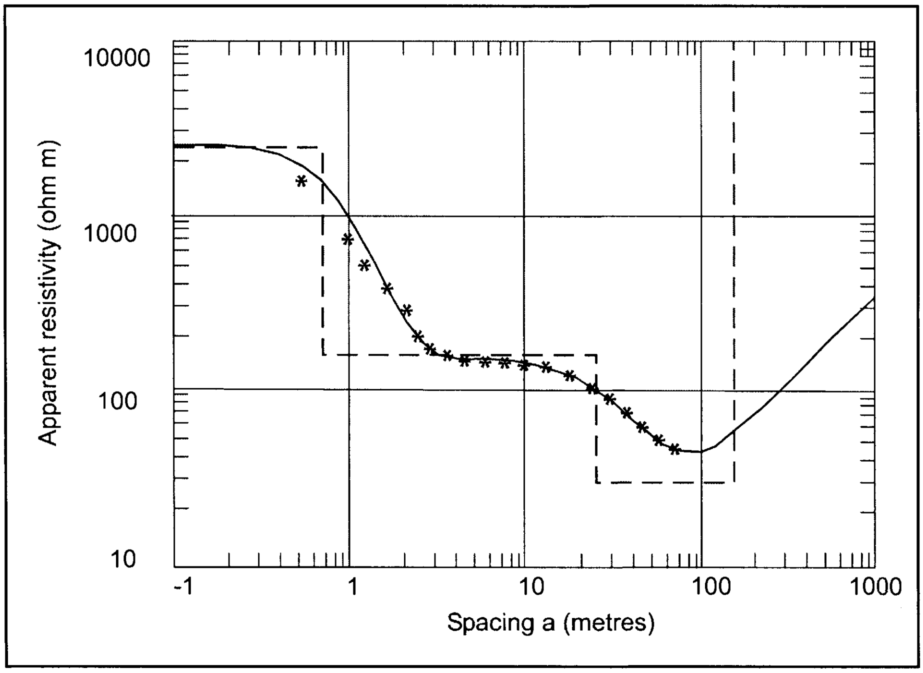


Figure 5.3 *Interpretation of a resistivity sounding curve*

A range of equipment developed in the late 1980s included computer control of the electrode arrays and automatic processing of the data in the field (Griffiths and Barker, 1993). These computer-controlled multiple electrode arrays and iterative modelling techniques can now rapidly produce an electrical image (or tomogram) of the geological strata, (Figures 5.4 and 5.5).

In the marine field, while the natural high salinity of seawater prevents the use of the electrical resistivity method from the sea surface, towed electrode arrays have been developed to measure the variation of resistivity in the near-surface sediments to a depth of 1 m. These arrays have been successfully deployed in marine pipeline studies.

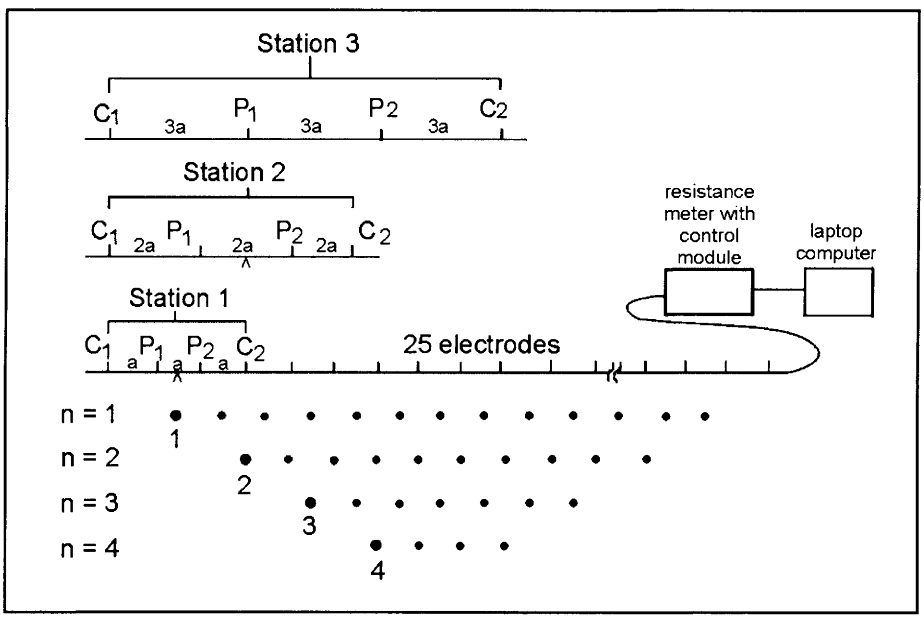


Figure 5.4 *Instrumentation and measurement sequence for building up a pseudosection*

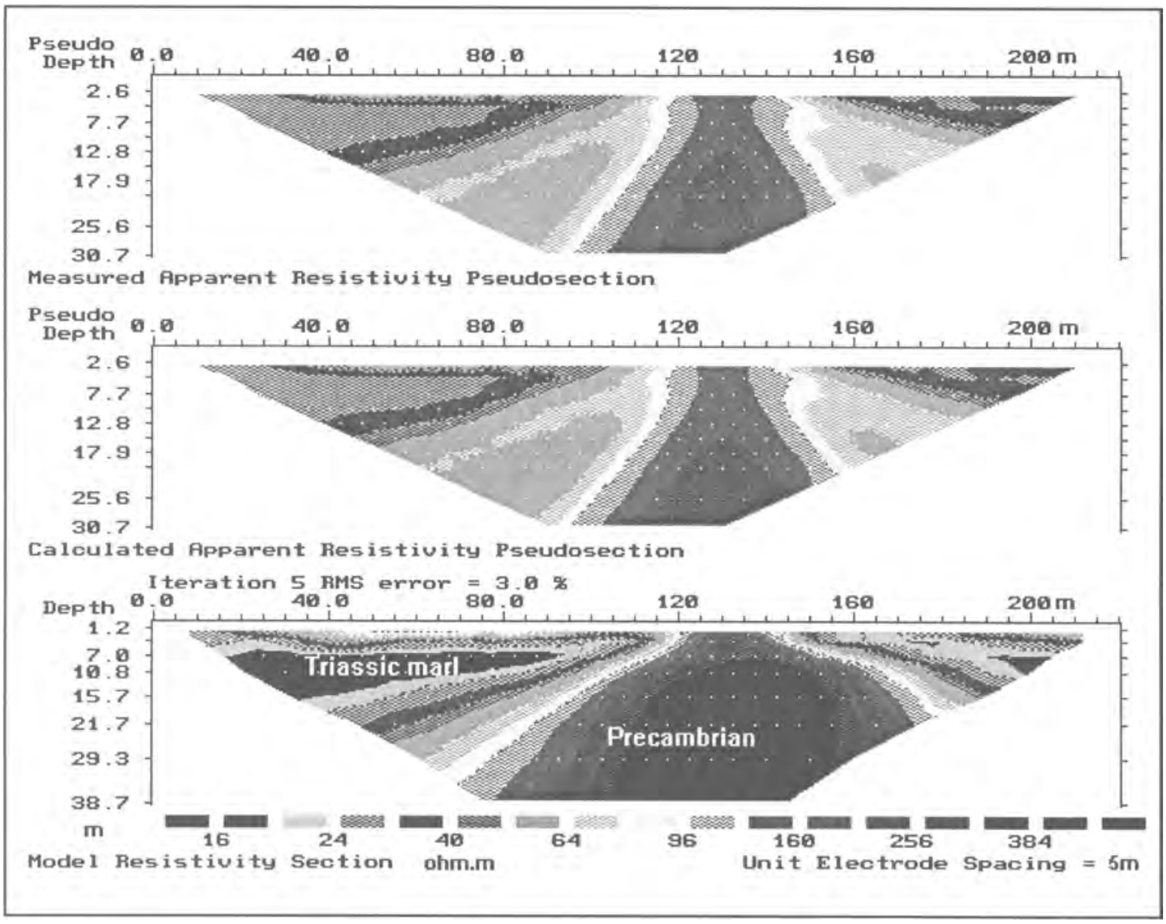


Figure 5.5 *Typical electrical image from computer controlled multi-electrode imaging system (after Griffiths and Barker, 1993)* (for colour version see page 252)

5.1.2 Laboratory measurement of resistivity

The electrical resistivity of rocks and engineering soils can be measured readily in the laboratory with a sensitive AC resistivity meter. A four-electrode system is preferred, ie current electrodes at the ends of the sample and two potential electrodes, in the form of rings, close to the centre of the sample. In this way polarisation and contact resistance effects are minimised and a uniform current flow exists between the potential electrodes. The contact resistance at the current electrodes can be reduced further by coating the ends of the rock sample with conductive paint, or placing brine-soaked paper between the electrode plates and the sample. This is particularly important for dry, porous, granular rocks. Engineering soils are usually placed in a soil-cell, ensuring that the cell is completely full and the soil is in contact with the current electrodes. Electrical resistivity will vary dramatically with the degree of saturation and the conductivity of the pore fluids. With engineering soils, compaction will also influence the results.

Electrical conductivity bridges enable the electrical conductivity of water samples to be measured with relative ease. The main sources of error arise from cells not being adequately washed with distilled water and a lack of consideration being given to conductivity variation with temperature. Confusion often arises with the units of conductivity, which should be expressed in Siemens per metre (S/m) or the submultiple (mS/m).

Where original pore fluids are not used, a standard fluid of known conductivity can be substituted and the resistivity quoted together with a "Formation Factor".

5.1.3 Other electrical methods

Spontaneous potential (SP) method

When groundwaters of different chemistry come into contact, small currents flow as the ions move in an attempt to establish equilibrium conditions. The resulting potentials may be measured on the surface using special (non-polarising) electrodes. Similar effects are produced by moving subsurface fluids. The method, variations of which are termed "self-potential" or "streaming potential", has been used to study water leakage from dam sites (see 8.5.3) and to locate boundaries in landfill sites (see 9.3 and 9.6).

Voltage mapping

Leaks in plastic lined tanks and landfills may be located by passing a current from one side of the liner to the other and mapping the voltage distribution over the liner. The voltage may be mapped using a grid of electrodes permanently emplaced below the liner, or moving the electrodes above the liner (Taylor *et al*, 1999). A voltage high will be measured in the region of the leak.

Induced polarisation (IP)

When electrical current flows in the ground some parts of the rock mass become electrically polarised. If the current is abruptly interrupted, polarised cells will discharge and produce currents, voltages, and magnetic fields, which may be detected at the ground surface. This method is used mainly in the mineral exploration field, but may have application in the study of contaminated land. Work in this area is currently at the research stage.

Electrokinetic sounding/surveying (EKS)

The phenomenon of electrokinesis (EK) was first described in the late 1930s, but its potential was not explored until the mid 1980s. The EK concept is particularly intriguing because unlike conventional hydrogeophysical techniques, it promises the direct detection of abstractable groundwater. The theory underpinning EKS is straightforward. Electric charge separation occurs naturally in groundwater contained in porous materials and the displacement of this water, relative to the pore surface, creates an electric field that can be measured on the ground surface. In practice, the relative rock / fluid motion is induced by a down-going seismic pulse that is generated by a sledgehammer blow on a steel plate. The resulting time-varying electric field is measured with two short-grounded dipoles placed symmetrically about the shot point. The rise time of this EK signal gives a measure of permeability (although other variables have to be considered), while the depth of the permeable horizon is estimated by assuming realistic seismic velocities in the geological strata above the horizon. The technique has potential for applications in hydrogeology, but requires a means of discriminating between the EK signals caused by vertically and horizontally propagating seismic disturbances.

5.1.4 Borehole electrical methods

Spontaneous potential log

The spontaneous potential (SP) log is a recording against the depth of the natural voltages, which exist in the borehole mainly at sand/shale boundaries where fluids of different salinities come into contact. The log is used mainly to differentiate between sands and shales. It provides similar, but less detailed, information to the natural gamma log. In a low porosity rock mass, such as granite, variations in spontaneous potential will be related to zones of fractured rock associated with joint and fissure patterns. The measured values however, cannot be applied in a quantitative manner to obtain formation porosity or permeability.

Single point resistance log

This is the simplest of the electrical logging systems. It is a two-electrode system, in which a lead electrode is lowered down the borehole on an insulated cable and a return electrode is buried at the surface. The measured resistance is a function of the formation resistivity, so that variations are related directly to changes in lithology. As it cannot be calibrated, it is used qualitatively. The log has been used as a lithology tool for geological correlations between boreholes. Although the depth of investigation (into the borehole wall) is only a few centimetres, the log has a high resolution and will respond to fractures in the borehole wall. For this reason it is often used in conjunction with the calliper log, to investigate fracturing in the rock mass. It is strongly affected by the borehole fluid and changes in borehole diameter.

Normal logs

These are four-electrode devices, in which a current and potential electrode pair is lowered down the borehole. The return current electrode and the second voltage electrode are planted at the surface. The measured resistance is converted to resistivity by multiplying by the electrode spacing, the magnitude of which determines the depth of investigation from the borehole into the formation. The basic tool is simple and easy to use, and can provide useful lithological and porosity information. In low porosity rocks, such as granite, the resistivity of the rock mass is very high and the major factor influencing the resistivity log will be the joint pattern. The effects of fractures and joints in the rock mass can be observed in a qualitative manner by the comparison of normal logs with different electrode spacings.

Focused logs

The resistivity sondes described above are all strongly sensitive to the borehole fluid. This results in poor resolution of the bed boundaries and the measured resistivity is not representative of the formation resistivity. This limitation has been overcome by the introduction of multi-electrode focused resistivity tools. The voltage across different electrode combinations is varied, so that a current from a central electrode is forced directly into the borehole wall with very little influence from the borehole fluid. This results in resistivity measurements, which accurately reflect the formation properties.

Micro-resistivity dipmeter

A dipmeter is usually a 4-arm (but may be 3 or 6-arm) side-wall micro-resistivity device, which measures small variations of resistivity in the formation with such a high resolution, that the relative vertical shift of characteristic patterns of variation on the traces can be used to derive the attitude of a plane intersecting the borehole. Such patterns can be caused by bedding planes, changes in lithology, or fractures and joints in the rock mass. The patterns are arranged across the traces as sinusoids. Computer analysis can identify the patterns by cross-correlation, and perform a trigonometrical solution to derive the dip and strike of the planes.

Formation scanning log

The basic principle of the formation micro-scanner is to map the resistivity of the borehole wall with a dense array of sensors. The sonde was originally a development of the dipmeter in which each of the dipmeter pads carried an array of button electrodes. The sonde obtains a number of closely spaced microresistivity traces, which are processed to produce a very high-resolution electrical image of two strips down the borehole wall. The data are produced in digitised form and can be processed by a computer-based interpretational package for direct comparison with the records from a borehole televiewer. Recent tools can provide over 80 per cent coverage of the borehole wall. This form of electrical imaging generally penetrates a few centimetres into the formation and the resulting image bears a striking resemblance to recovered core. In addition, a wealth of data is produced on subsurface fracturing. This is an expensive type of log, which is unlikely to be used in normal engineering site investigations but has been used in major projects such as the evaluation of possible nuclear waste depositories (See 9.4.2).

5.1.5 NDT electrical methods

Resistivity measurements

A miniature version of the electrical resistivity arrays described in Section 5.1.1, can be used to assess the likelihood of significant corrosion within a reinforced concrete structure. The electrodes are deployed in a constant separation Wenner array and are used to map the variation of electrical resistivity over the surface of the structure or beam. These changes can be related to the ability of corrosion currents to flow through the concrete, which is a function of water:cement ratio, the moisture content and the salt content. The major problem associated with this method, is achieving good electrical contact between the electrodes and the concrete structure and it is usually necessary to drill small holes to provide effective contact.

Half-cell potential measurement

The more popular method for assessing corrosion of the reinforcing rods is the half-cell potential system, where the potential of the embedded steel reinforcement rod is measured relative to a reference half-cell placed on the concrete surface. Zones of varying degrees of corrosion risk can be identified by preparing potential contour maps on the concrete surface and these are particularly applicable for assessing maintenance and repair requirements. It is most valuable in the comparison of areas where corrosion has already been evaluated, with those where the corrosion risk has yet to be established. Contact is necessary with the steel reinforcing rod and a small hole has to be drilled through the concrete. Generalised corrosion risk is reflected by uniformly low potential measurements, while localised corrosion is indicated by high potential gradients, which appear as a "whirlpool" effect. Interpretation and presentation of the data obtained are similar to techniques described for geophysical methods and the data could, for instance, be displayed in a shaded relief format.

5.2 GRAVITY METHOD

5.2.1 Gravity surveying

The gravity method involves the measurement of variations in the gravity field of the Earth caused by local differences in the density of the subsurface rocks. Figure 5.6 gives the broad range of density values associated with a range of rocks and sediments (a more extensive list is given in Appendix 3). Figure 5.6 indicates that, except in the case of air-filled voids, density contrasts are likely to be small, and that significant anomalies will only be recorded when the size-to-depth ratio of targets is large (Section 2.2 and Figure 2.1).

The technique is usually associated with large-scale regional geophysical surveys investigating geological structure to considerable depth. Measurements of gravity can also be made from the air or at sea.

Originally, in ground investigations, gravity data were mainly used to produce contoured maps, which located anomalous zones associated with a density reduction in the near-surface material, resulting from the presence of a cavity or mineshaft for example. For particular applications, such as locating near-surface voids, the gradient in the Earth's gravity field can be measured. In larger scale engineering surveys, the method has been used to locate large fault zones, deep buried channels, and rock faces in back-filled quarries.

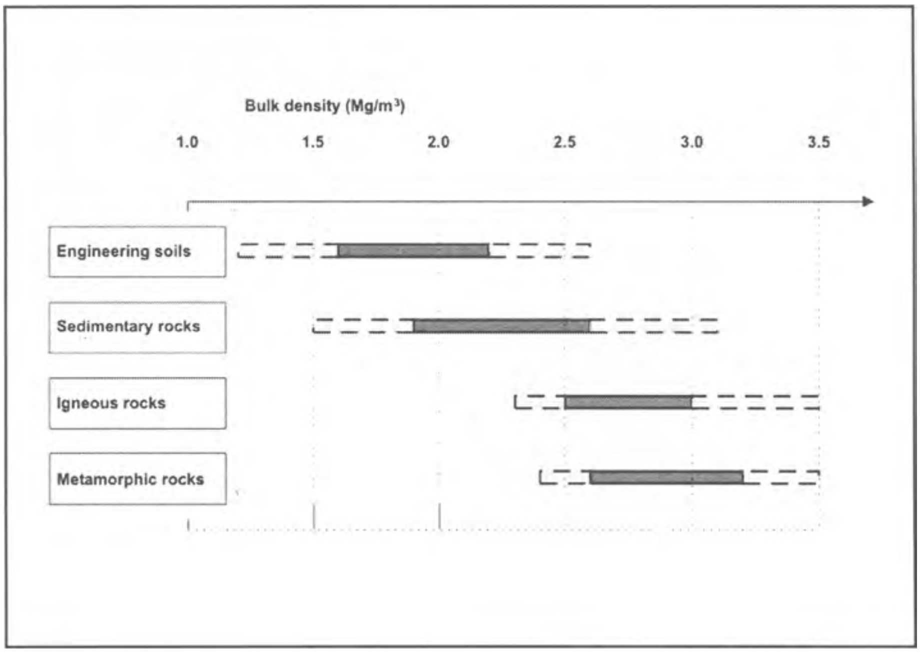


Figure 5.6 *Typical bulk density ranges*

High-resolution microgravity surveys are employed in engineering investigations. They use extra-sensitive gravimeters (microgravimeters) having a precision of 2 μGal. Microgravity surveys require precise determination of the height (< 20 mm) and position (< 10 m) of each measurement, so high precision surveying is needed. A digital terrain model is ideal for computing the topographic variations and effects of gravity on local buildings. Such surveys are often carried out for shallow cavity detection where other techniques are unsuitable.

Significant developments in the mathematical modelling of gravity data enable the geophysicist to produce 2 D geological models, from data recorded along profiles in the field. A typical example is shown in Figure 5.7 where a series of gravity measurements have been made on the ground surface above a cavity system in a Karst limestone environment. Using a modelling program the theoretical geological structure is adjusted until the predicted gravity cross-section fits the measured data points.

Gravity surveys are expensive because of the relatively slow rate of data acquisition and the variety of corrections, which need to be applied to the observed data. Its application should be tested before embarking on a large-scale survey. Fortunately the software for this is easily available.

Ambiguity remains a particular difficulty with the modelling of gravity data, as the gravity profile can be represented by a large number of possible geological solutions. Additional information is required to set bounding limits which the model has to fit. It may however, be the most suitable geophysical method, for the applications mentioned, particularly in an urban environment.

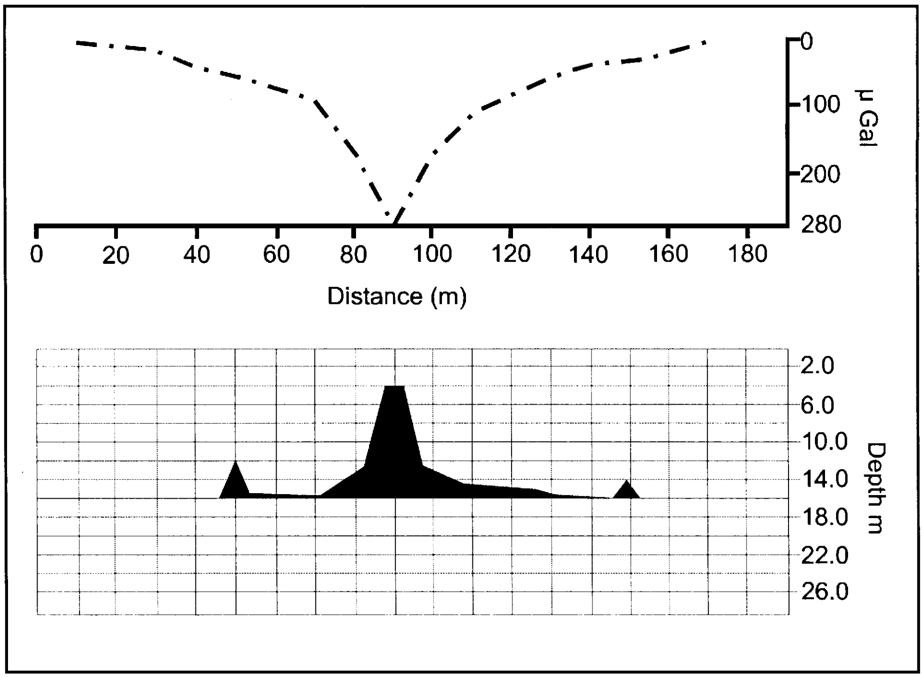


Figure 5.7 *Theoretical modelling of an observed gravity traverse across a buried cavern*

5.2.2 Measurement of density

Interpretation of gravity data requires some knowledge of the density of the rocks present in the geological structure underlying the survey area. This information can be obtained from laboratory measurements made on rock specimens collected either from rock outcrops, or boreholes in the survey area. Measurement of density in the laboratory is based on the procedures described in Anon (1981).

Alternatively density can be obtained from the gamma-gamma or formation density borehole log described below (see 5.6.2).

5.3 MAGNETIC METHOD

5.3.1 Magnetic surveying

The magnetic method involves the measurement of variations in the total magnetic field of the earth, caused by local differences in the magnetisation of the subsurface rocks and soils. Figure 5.8 gives the typical ranges of magnetic susceptibility values, of common rocks and sediments (a more extensive list is given in Appendix 4). The standard instrument in use is the proton magnetometer. A major recent improvement made to the instrumentation is the addition of micro-processor control to record the data, for downloading to a computer at suitable points in the survey. Some modern instruments include two sensors within the system, so that measurements of the vertical magnetic gradient can also be recorded. For engineering purposes the data are usually presented in contour form. Significant progress has been made in the mathematical modelling of magnetic data, particularly of the variations in a 1-D visualisation. It is common practice to produce 2-D geological models from the magnetic data.

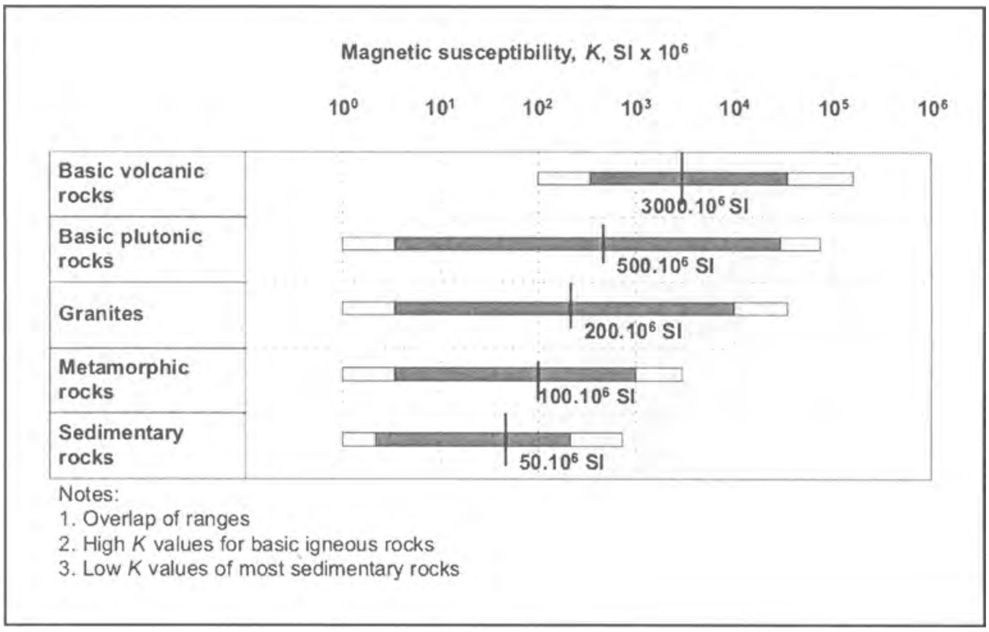


Figure 5.8 *Typical ranges of magnetic susceptibility*

A magnetic survey is rapid and easy to carry out. A site can be surveyed with close grid spacing (often 1 m) at low cost. The only correction required to the observed data, is the subtraction of the temporal (diurnal and secular) variation, which is usually continuously recorded throughout the survey period. This is not required if a magnetic gradiometer survey is carried out, since this measures the gradient of the vertical magnetic field using two magnetometer sensors. These are separated by a fixed distance in the vertical plane and record simultaneously. This is particularly relevant where rapid changes in the magnetic field result from the presence of magnetic bodies, eg oil drums, in the near-surface material. A site with a long urban or industrial history will nearly always be littered with ferrous debris, which may prevent the location of the main magnetic anomaly. Some attention should always be paid to the possible effects of magnetic objects carried by the operator, on the local magnetic field.

The greatest application for this method in engineering studies is in the location of buried mineshafts and adits. It is also widely used in the location of buried metalliferous man-made objects, such as cables or pipelines. In the geological field, the magnetic method may locate boundaries between rocks, which display magnetic contrasts, such as faults or dykes.

A typical example of the use of the magnetic method quoted in Culshaw *et al* (1987) is the investigation of the line of the concealed Armathwaite Dyke, near to its intersection with the M6 motorway in northern England, prior to its construction. The survey was carried out with a series of traverse lines set out perpendicular to the estimated line of the dyke, with a station interval of 7.5m (Figure 5.9 (a)); a typical profile along line E is shown in Figure 5.9 (b). Both the drift cover and the Penrith Sandstone, which forms the country rock, are virtually non-magnetic and the anomaly observed on the magnetic profile can be attributed entirely to the presence of the Armathwaite Dyke.

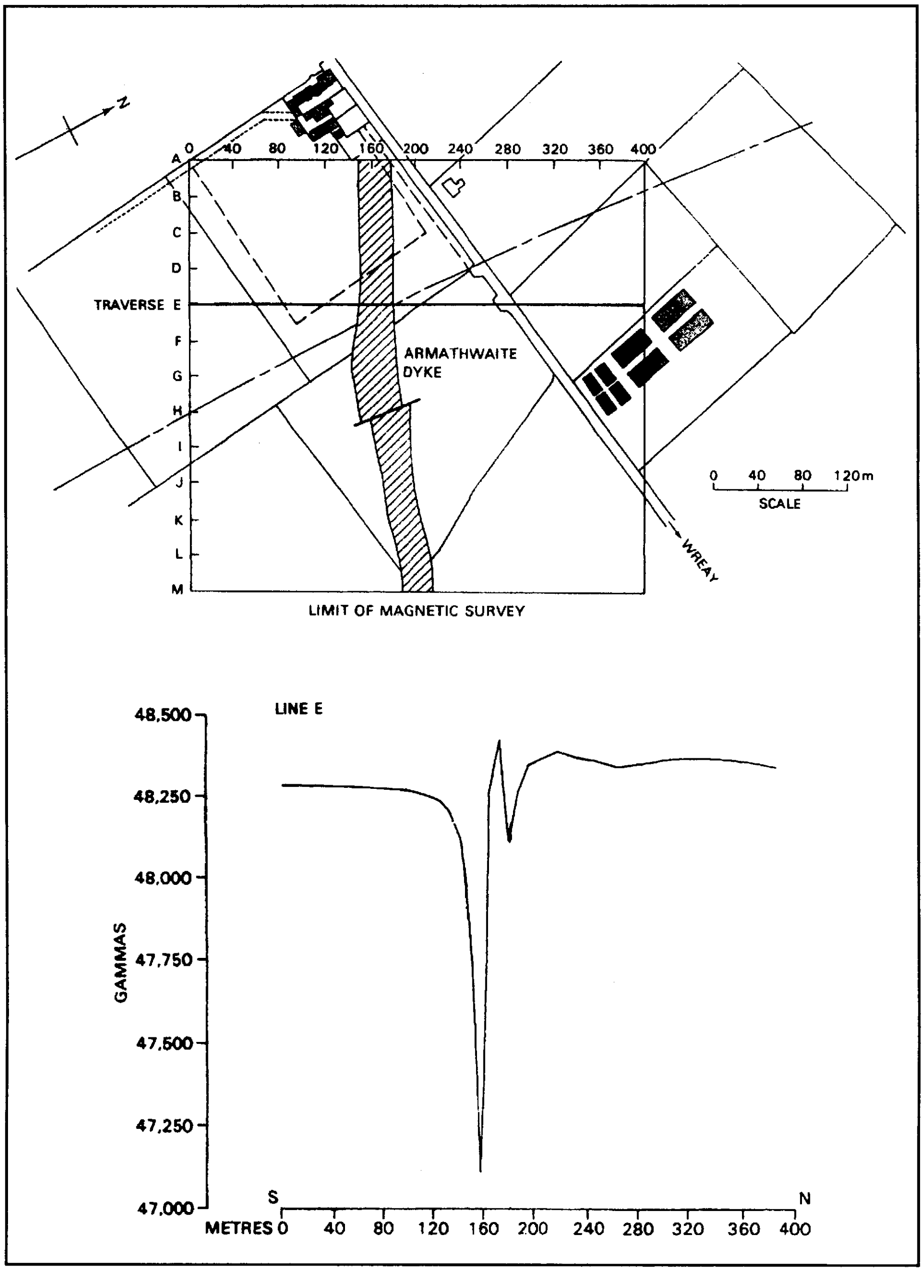


Figure 5.9 *Magnetic survey over a motorway route to locate the position of the Armathwaite Dyke with (a) layout of the survey lines and (b) typical magnetic traverse along line E (from Culshaw* et al, *1987)*

In the marine environment, towed magnetometers are regularly deployed in large-scale regional geological surveys, but they are infrequently used in marine civil engineering investigations. The development of sea-floor instruments and, more recently, deep-tow instruments, may achieve the greater resolution required in shallow, small-scale investigations. These are deployed close to the sea-floor and give continuous measurement of the magnetic properties along a survey line. In the marine environment, magnetic surveys are particularly effective in the location of sunken vessels and the method is widely used in archaeological investigations.

5.3.2 Laboratory measurement of magnetic susceptibility and remanent magnetism

Magnetic susceptibility and remanent magnetisation contribute to the modelling of magnetic anomalies. Evidence of reversal in remanent orientation may assist the dating of intrusions and identifying disturbed ground. Magnetic susceptibility has been used to map the distribution of toxic pollution, because toxic substances are known to be associated with iron particles.

Some instruments are designed to measure magnetic susceptibility directly for rock masses. Such instruments can also be used on large blocks of rock in the laboratory, although careful consideration should be given to sample size and shape. The susceptibility of the rock or soil may vary considerably, both within a sample and within a rock outcrop, due to the significant effect of ferromagnetic minerals by content and distribution. A slim-line borehole logging tool is now available for continuous determination of magnetic susceptibility.

Magnetic susceptibility K is the ratio of the intensity of magnetisation to the magnetic field strength, and therefore can readily be measured with laboratory magnetic susceptibility bridges. Usually, the sample is tested, as a rock core or chippings, and correction factors have to be applied for variations in sample diameter and the volume of air spaces between the chippings. These meters use alternating current and therefore do not measure, and are not affected by, remanent (permanent) magnetisation. Care should be taken in these measurements to distinguish between the SI units and cgsemu (electromagnetic units in cgs terms) units of volume magnetic susceptibility, as a 4π factor is used to convert cgs to SI units. Magnetic susceptibility of soil cores has been measured by slipping a coil over the soil, which has been captured and retained in a plastic liner.

Magnetic remanence measurements are usually made on small cylinder cores or cubes prepared from larger drill cores or bulk samples, using specially designed magnetometers, and are labelled with the original orientation of the borehole core. The possibility of demagnetisation by weathering processes, the drilling action and careless storage should be fully appreciated and taken into consideration. To determine the stability of the remanent magnetism, samples should be subjected to demagnetisation in an alternating strong magnetic field. After removal of the secondary magnetisations, the intensity, inclination and declination of the true remnant magnetisation can be ascertained, with the spinner magnetometer. Remanent magnetisation can vary considerably in orientation and magnitude from induction, due to the earth's present magnetic field, and there can be complete magnetic reversal.

5.3.3 Aeromagnetic survey

A regional magnetic survey can be carried out from an aircraft or helicopter by either mounting the magnetometer on the side of the aircraft, or towing it behind in an "aerodynamic bird". The latter approach has the advantage that no compensation is needed for the magnetic effect of the aircraft, since the towing length of the cable varies between 20 and 30 m. The survey area is usually covered with a grid of parallel flight lines separated by distances of between 50 m and 2 km depending on the size of the area to be covered and the resolution required. The aircraft usually flies at a height comparable to the line spacing, but this is dependent to a large extent on the ground topography. The height of the magnetometer above the ground surface is measured with a radar altimeter and the position of the aircraft needs to be accurately monitored. The daily variation of the magnetic field at a base station has to be monitored during the airborne survey and used to correct the recorded data at the interpretation stage of the project.

5.4 SEISMIC (ACOUSTIC) METHOD

Seismic exploration is based on the generation of seismic waves on the ground surface and the measurement of the time taken by the waves to travel from the source, through the rock mass to a series of geophones, which are usually laid out along a straight line from the source. Table 5.1 gives the compressional (*P*) and shear (*S*) wave velocities for of a range of rocks and sediments. Explosives and other energy sources are used to generate the seismic waves in the rock mass, and geophones are used to detect the resulting ground motion at the surface. Further values of wave velocities for rocks and soils are given in Appendix 5.

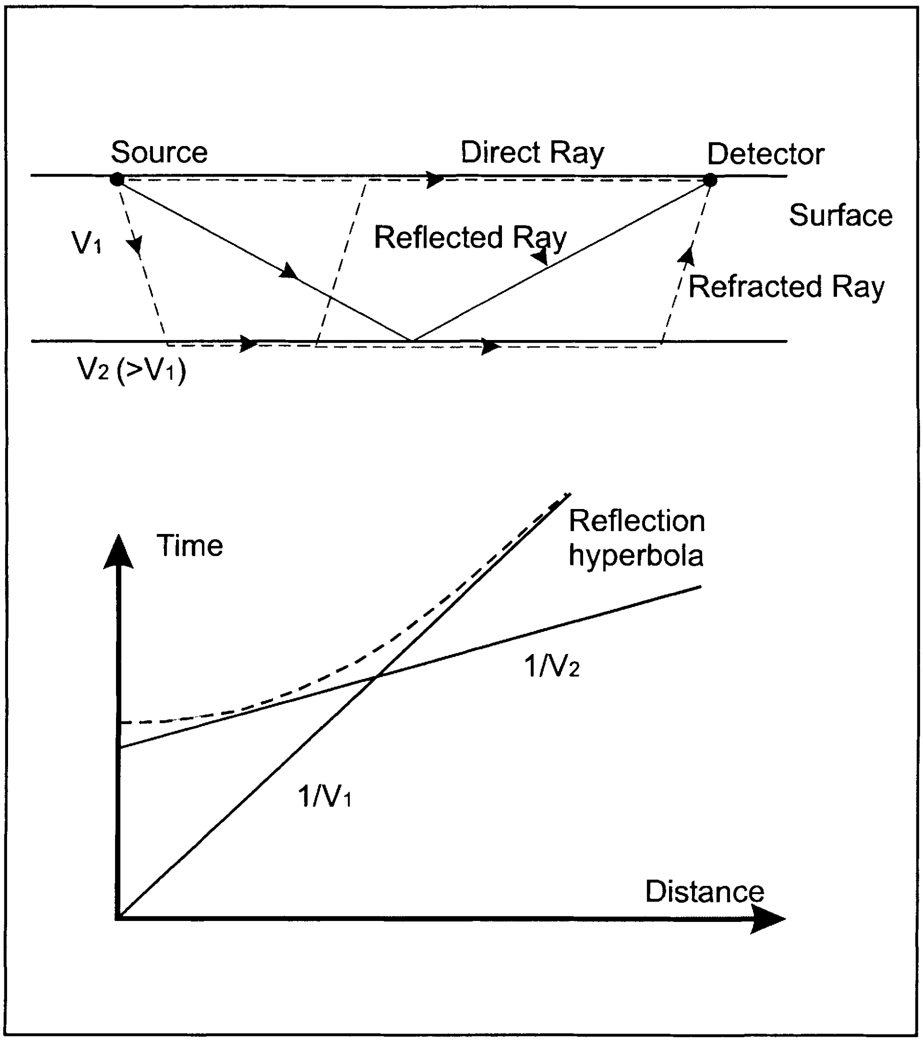


Figure 5.10 *Seismic survey line showing (a) the path of direct, refracted and reflected seismic rays in a two layer soil/rock system and (b) the travel time/distance plot for the seismic line*

From Figure 5.10 it can be seen that apart from seismic energy travelling directly through the rock mass to the geophone array two other main paths are possible:

1. The refracted/head wave that travels along the interface between the two rock types
2. The reflected wave from the interface between the two rock types.

Figure 5.10 shows a plot of the travel times of the direct, refracted and reflected seismic pulses against the distance to each geophone along the seismic line. From the travel time/distance plot it is possible to calculate the depth to the surface of the refracting/reflecting interface.

Other waves exist. Surface waves may be generated and their dispersion properties used to derive the vertical 1-D profile of shear wave velocities (Section 5.4.1).

5.4.1 Seismic properties

Seismic wave propagation

Sudden application of a point force to the surface of a homogeneous elastic earth generates body waves and surface waves. The body waves are compressional *P* waves and shear *S* waves. There are two types of shear wave; vertically polarised S_V and horizontally polarised S_H waves. In a homogeneous isotropic earth, the velocities of the two waves are the same. Where there are material boundaries or artefacts that affect the wave transmission from the source, the waveforms are different. Along boundaries they are called "Love" waves; those responding to the borehole shape are called "tube" waves.

If the source is within the medium, the waves generated will depend upon the character of the motion at the source. A pure spherical expanding source will generate *P* waves, but any non-spherically symmetric disturbance will generate both *P* and *S* waves. In reality, the necessity for finite source dimensions complicates the type of wave produced. Furthermore, inhomogeneities give rise to wave conversions, whether the source is at the surface or at depth. To derive the physical properties from wave velocities the type of wave has to be identified.

Table 5.1 *P- and S-wave velocities of some rocks and other materials*

Material	Compressional velocity (m/s)	Shear velocity (m/s)
Air	330	
Water	1450	
Sands and clays	300–1900	100–500
Glacial till	1500–2700	600–1300
Gravels	1000–2000	
Chalk	1700–3000	600–1500
Strong limestones	3000–6500	1500–3500
Weathered granite	100–3000	500–1500
Fresh granite	3000–6000	1500–3000
Slate	5000–7000	2500–3800
Weak sandstones	1000	

Material anisotropy arising from sedimentary features or the geometry of discontinuities can affect the propagation and character of the signal, as can anisotropy of *in-situ* stress. This is a major research area and the interpretation of field measurements may be difficult. In addition to the differences between vertical and horizontal velocities there can be azimuthal differences.

Propagation velocities are often used to provide information on elastic parameters, although signal levels, wave shape and frequency signature may also be used to estimate anelastic absorption indices. (Anelastic is when any deviation from the ideal internal structure of a body is present that would dampen or attenuate an elastic wave therein.) In current engineering practice most attention is given to measuring the propagation velocities of both P and S waves and is assumed that the ground is a single-phase material, although this introduces some uncertainty. Seismic methods involve frequencies in the range 100 to 500 Hz while higher frequencies, in the range

10 to 30 kHz, are used in "acoustic" techniques with piezo-electric sources. The differences in the effective rates of strain imposed on the soil have been seen as a reason for differences between the parameters derived from different techniques (Lo Presti *et al*, 1997).

The seismic signal is reduced in amplitude with distance from its source, both as the energy is spread over a greater surface and by internal material damping such that the energy is ultimately dissipated as heat. The change in signal level with distance from the source depends upon the wave type and its spreading geometry, the inhomogeneities of the pathway and the anelastic absorption of the intervening materials. If allowance is made for the effects of geometric spreading, both the reduction in vibration amplitude between separated measuring points and changes in signal character, can carry information on the damping properties of the ground material.

The fundamental material damping term is the "specific damping capacity", which is defined as the energy dissipated in a specified work cycle, as a proportion of the maximum strain energy during that work cycle. The index most often used by engineers (strictly a system dependent term) is "Damping Ratio" D. This is the ratio between the actual damping and the least value of damping which would prevent oscillation in a system. In seismology it has become the practice to use the term Q; defined as the reciprocal ratio of energy lost per cycle to maximum strain energy, divided by 2. For example in a system with one degree of freedom $D = 1/2Q$. Although Q is often quoted without an associated frequency, recent work has shown that for shallow soils it is frequency dependent. Depending upon methods of interpreting field data, Q can range from two to nine in an example of unconsolidated Quaternary sediments 22 m thick with V_s ranging from 100 to 200 m/s. Tables 8.4 and 8.5 provide ranges of Q values in different rocks.

Field measurements

Current field techniques may involve continuous or impulsive sources, either at the ground surface or in boreholes, with measurements being made at ground surface or adjacent boreholes. Measurement of arrival times from surface sources is carried out using clamped triaxial geophone assemblages in boreholes, at intervals down to 150 m. Downhole sources are also commonly used with measurements made in co-linear holes, using clamped triaxial sensors.

There has been much ingenuity applied to shear wave generation, with directional sources at the ground surface and in boreholes, but adequate shear waves can sometimes be generated by compressional wave sources, such as the "Sparker" source, in boreholes with conversion of P- to S-waves at the borehole wall or hole casing. The suspension log uses the similar property of wave type conversion at the boundary from a piston source generating waves in the frequency range 50–500 Hz and measuring over intervals of 1 m. In principle, because it does not rely on clamping to the sides of a hole, there is no limit on the depth at which it can be used. The wide variety of methods available is shown in the table in Appendix 5 and Figure 5.11.

For satisfactory field measurements the following points need considering:

1. Hole formation – the boring methods should minimise the possibility of forming an irregular hole and produce a bore with minimum deviation.
2. Acoustic coupling – the hole liner (if needed) should be well grouted in, the wave velocity in the grout noted, and invasion of grout into permeable ground avoided.

The geometry of source and detector should be arranged to give a sufficient time interval and predictable travel path. Where a surface source is used it should be adequately offset from the borehole to minimise a casing transmission path or "tube" waves.

Although two-hole systems have been widely used for cross-hole shooting, the use of a minimum of three holes (with one source hole and two receiver holes) is essential for the determination of *in-situ* values of Q. Problems may arise when only two holes are used, one for the source and the other for the receiver. This is due to the broadening of the pulse in some materials, which provides a way of measuring damping, but introduces uncertainty in the timing. Errors may also be introduced by timing delays arising in filter circuits. The use of three or more co-linear boreholes enables refracted and reflected events to be distinguished from direct events, in layered ground.

Identification of both a P- and an S-wave is the first aim. In very favourable circumstances this may be achieved by inspection of the time history of the signal, either in a single trace or with multiple stacked traces. First motion reversal may identify the

S-wave, but the results sometimes give ambiguous answers. Alternative methods include representations of particle motion by hodograms (a curve used to determine acceleration), frequency analyses and correlation procedures. A common feature of most impact methods is the facility to reverse the sense of first motion and thereby assist in the identification of shear wave arrivals.

The objective is to measure time differences between the arrivals of identified wave types. The compressional P-wave is first, followed by shear S-, and reflected and refracted waves. The necessary time discrimination for different configurations of source and detectors is considered later, but generally it is now possible to achieve an accuracy of $\pm$ 50 µs. A modern digital seismograph with stacking capacity and interfacing to a microcomputer is a favoured arrangement. Storage of the signal on an instrumental tape recorder enables subsequent analysis to be made, although this should not be necessary if digital storage is adequate.

Surface (Rayleigh) waves have been used to deduce the velocity/depth profile. The surface wave velocity is similar to the shear wave velocity. It is dispersive, ie its velocity is a function of frequency, and experimental observation of dispersion can be matched to a similar layered ground model. The wave can be generated at the surface or ambient noise can be used. A widespread technique is the use of a transient surface source, such as hammer or a dropping weight, followed by spectral analysis of the surface waves (SASW). Rayleigh waves generated by large sources, such as Vibroseis generators, are being used for the characterisation of larger volumes for special projects, eg radioactive waste storage.

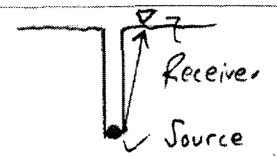
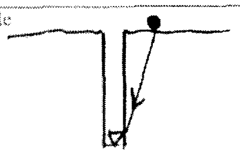
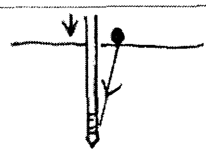
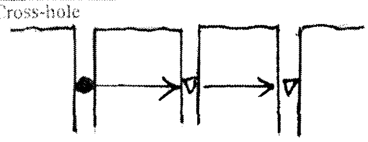
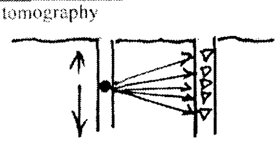
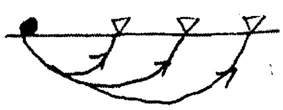
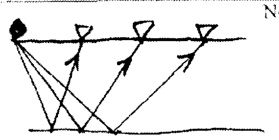
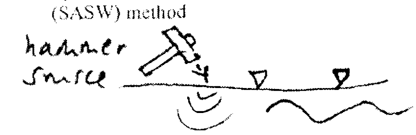
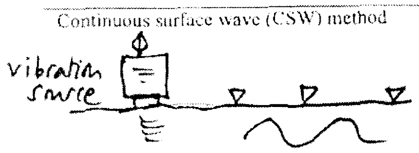
Method	Advantages	Disadvantages
Up-hole 	Only single borehole required. Tests can be carried out is all soil and rock types. Average velocity is measured in layered materials.	Need to install plastic casing to provide stable borehole.
Down-hole 	Only single borehole required. Tests can be carried out in all soil and rock types. Average velocity is measured in layered materials. Higher energy sources (e.g. explosives) can be used without damaging the boreholes.	Need to install plastic casing to provide stable borehole.
Seismic cone 	No borehole required; probe is pushed into the ground. Provides other geotechnical parameters in addition to stiffnesses. Average velocity is measured in layered materials.	Penetration limited by strength of ground. Not suitable for rock.
Cross-hole 	Can detect low velocity (in low stiffness) layers, provided they are thick compared to borehole spacing. Tests can be carried out in all soil and rock types.	Quality of data diminishes all shallow depths. Maximum velocity is emphasised in thinly layered soils due to head waves.
Cross-hole tomography 	Gives two-dimensional distributions of stiffness. Tests can be carried out in all soil and rock types.	Expensive. Artefacts make interpretation difficult. Specialist processing facilities required.
Refraction 	No borehole required.	Cannot detect low velocity (low stiffness) layers below higher velocity layers. Cannot detect thin layers. Problems with interpretation of continuous velocity increase with depth. Cannot use in situations of continuous velocity decrease with depth, although much cases are rare.
Reflection 	No borehole required.	Expensive: high resolution seismic reflection is required for engineering surveys. Method only effective in layered ground.
Spectral Analysis of Surface Waves (SASW) method 	No borehole required. Field method is quick and relatively simple.	No selective control over the frequencies generated; therefore measurements are limited to those frequencies which can be generated in the medium by a given impulsive seismic source. It may be necessary to use a number of different impulsive energy sources.
Continuous surface wave (CSW) method 	No borehole required. Selective frequency control of vibratory seismic source. Field method is relatively quick and simple. Preliminary stiffness-depth profile may be viewed on site.	Depth of investigations is currently limited to about 10 m unless large lorry mounted vibrators are employed.

Figure 5.11 ***Seismic methods for the determination of stiffness-depth profiles***

P- and *S*-wave velocities may also be derived from acoustic logs in single boreholes, ie continuous velocity logging. Usually only a relatively small volume of ground is involved however, and care has to be taken in interpreting the elastic parameters, which may be derived from such measurements

Methods of determining the shear wave velocity depth profile from non-invasive surface seismic procedures have obvious economic attractions. However, all non-invasive surface seismic techniques use pre-defined models with which to obtain the depth of propagation of the waves. These models work best in "ideal" ground conditions which rarely exist in practice. A cautionary note has been sounded by Wills (1998), following a set of comparisons between shear wave velocities, determined from inversion of surface wave phase velocities and downhole measurements (Boore and Brown, 1998). Where use is to be made of surface seismic methods using proprietary software, it is prudent to verify the results by comparison with crosshole or downhole measurements made in representative soil profiles.

Reconciliation of soil and rock dynamic attributes, derived from the diversity of methods (field seismic, laboratory testing) has long been a matter of concern

(Hardage, 1987). Until recently, the engineering profession has been slow to discard static tests and "factors". The identification of rock attributes, eg fracture characterisation and permeability, from the properties of a seismic wave field is a lively current issue, especially in the hydrocarbon industry and for radioactive waste repositories.

Laboratory measurements

Dynamic parameters of soils and rocks may be determined in the laboratory by, either resonance or pulse velocity methods. Resonance under axial sinusoidal loading of a rock core may be used to calculate the "bar velocity". Resonance is obtained as the excitation frequency is changed. A sensor can explore for nodes. The "resonant column" test for reconstituted soils is well known in soil dynamics studies and its procedures have been largely standardised. Torsional strain of 10-2 can be achieved in the resonant column test in soils.

Pulse methods to measure *P*- and *S*-wave propagation velocities through specimens use ultrasonic frequencies. V_{lab} is defined as the velocity of bulk compressional wave events through rock or soil samples by ultrasonic pulse techniques in the laboratory. The *in-situ* stress and moisture content should be simulated as closely as possible and the tests carried out with appropriate equipment and transducers. Saturation of samples for testing is also recommended. Argillites are usually tested at "natural moisture content", but may be saturated under back-pressure in special triaxial cells, in which the transducers are mounted in the loading platens. The frequency of transducers and the dimensions of the samples should be selected to avoid the possibility of the measurement of bar, rather than bulk compressional wave velocities, and to minimise internal scatter. *S*-wave velocities are rather more difficult to measure in the laboratory. The error in the measured shear wave velocity is often high when direct methods are employed, ie when the shear wave transducers or wedges are mounted on opposite parallel faces of the rock sample. These difficulties can be overcome to some extent by indirect surface testing, ie with axially polarised transducers mounted on the same flat surface (McDowell and Millet, 1984).

The direct measurement of *S* waves in soil samples using piezo-ceramic bender elements has been refined from the original concept (Dyvik and Madshus, 1985) to sophisticated systems that can measure S_V and S_H, which propagate axially and diametrically through the samples (Pennington *et al*, 1997 and Kuwano *et al*, 2000).

Damping can be measured by observing the width of resonant peaks, or decay of free oscillations. The attenuation of seismic waves through rocks can also be measured by ultrasonic pulse techniques in the laboratory. The development of bender elements incorporated into computer controlled cyclic triaxial cells, has enabled the arrival time of shear waves to be estimated to around ± 7 per cent. There are still problems in the stiffer soils and care needs to be taken to identify the true shear wave.

All methods involve uncertainties and these have been examined with special reference to the use of dynamic parameters in numerical modelling. The uncertainties arise from the measurement procedures themselves (pick of events, timing and distance errors), from a mismatch between the value of the parameter being derived and that which should properly be used (eg neglecting anisotropy, rate of strain), and the representatives of the value derived in what is usually inhomogeneous ground. It is salutary to note that in assigning rock or soil properties for soil structure interaction modelling, the US Nuclear Regulatory Commission (UNRC) requires that a range ± 50 per cent on the best estimate has to be explored.

Soil and rock stiffness

Although shear wave velocity depth profiles are in themselves used to characterise a site, eg in Eurocode EC8 part 5, engineers often require the small strain shear modulus (Go = density x V_s^2) and in numerical modelling of geotechnical problems, the small strain Youngs Modulus and Poisson's Ratio. The developing approach to geotechnical analyses for static as well as dynamic loadings requires these small strain properties (Atkinson, 2000).

5.4.2 Seismic surveying

Seismic refraction

The seismic refraction method involves recording the primary or compressional *P*-wave travelling both directly through surface layers and refracted along underlying layers of higher seismic velocity. Seismic sources range from the hammer and falling weight to detonators or explosives. Interpretation of the data provides layer thicknesses and seismic velocities, but it should be noted that where a low velocity layer is overlain by a high velocity layer, a misleading interpretation and incorrect depth determination may result. The method is best used to provide detailed information along a line where the geology is not too complex, or where the lithological or structural variation in the bedrock is of greater interest than variations in the overburden. For these situations the technique provides data efficiently, although it is relatively expensive if explosives have to be employed. The presence of significant ambient noise, such as that generated by a busy road, may inhibit the use of the method. A study of secondary or shear *S*- wave refraction data is carried out if information on the *in-situ* dynamic elastic properties of the bedrock is required. The method is widely used to determine depth to bedrock, particularly in site investigation for roads, dam sites and tunnels. It is also generally applicable to the assessment of rock mass rippability, based on the published tables of the Caterpillar Tractor Company (1988), Section 8.2.5. Calibration of seismic velocity data by laboratory tests on borehole core is recommended.

The major advance in seismic surveying has been in the area of signal enhancement, where digital methods using micro-processors have replaced the analogue recording techniques, used in the previous generation of seismic recorders. Enhancement by computer is based on the averaging of repeated measurements, and enables small signals to be accurately measured (See Chapter 6). The process effectively increases the signal-to-noise ratio because, the measurements are repeated a number of times, added together or stacked and then divided by the number of measurements and the signal-to-noise ratio is increased by $N^{0.5}$, where N is the number of repeated measurements. The advantage of the modern seismic recorder is that the seismic data can be entered directly into a PC, either in the field or the laboratory, so that rapid processing is possible. Signal enhancement extends the range of a geophone spread to around 100 m with a hammer source. A typical example of this process is shown in Figure 5.12, which shows the effect of signal averaging on the seismic pulse train detected by a three-component borehole geophone, with a borehole sparker as the seismic source. Significant noise reduction is achieved and the vertically polarised shear-wave is clearly visible.

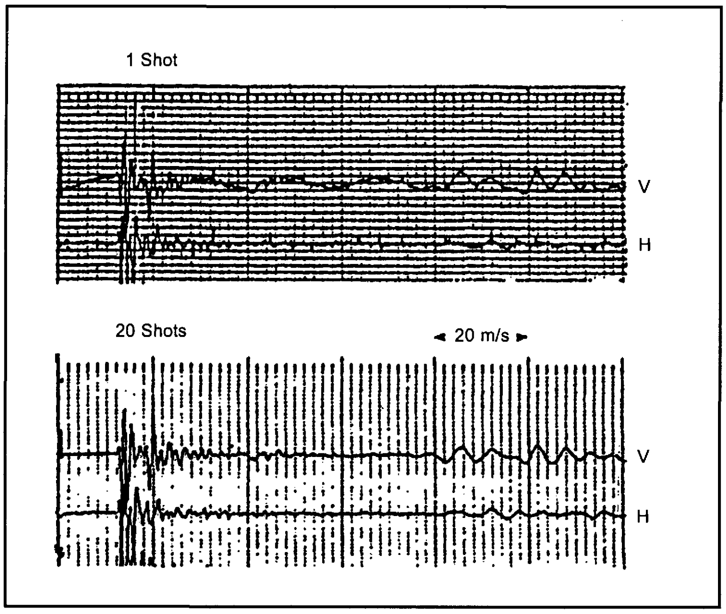


Figure 5.12 *Stacking of a seismic pulse train*

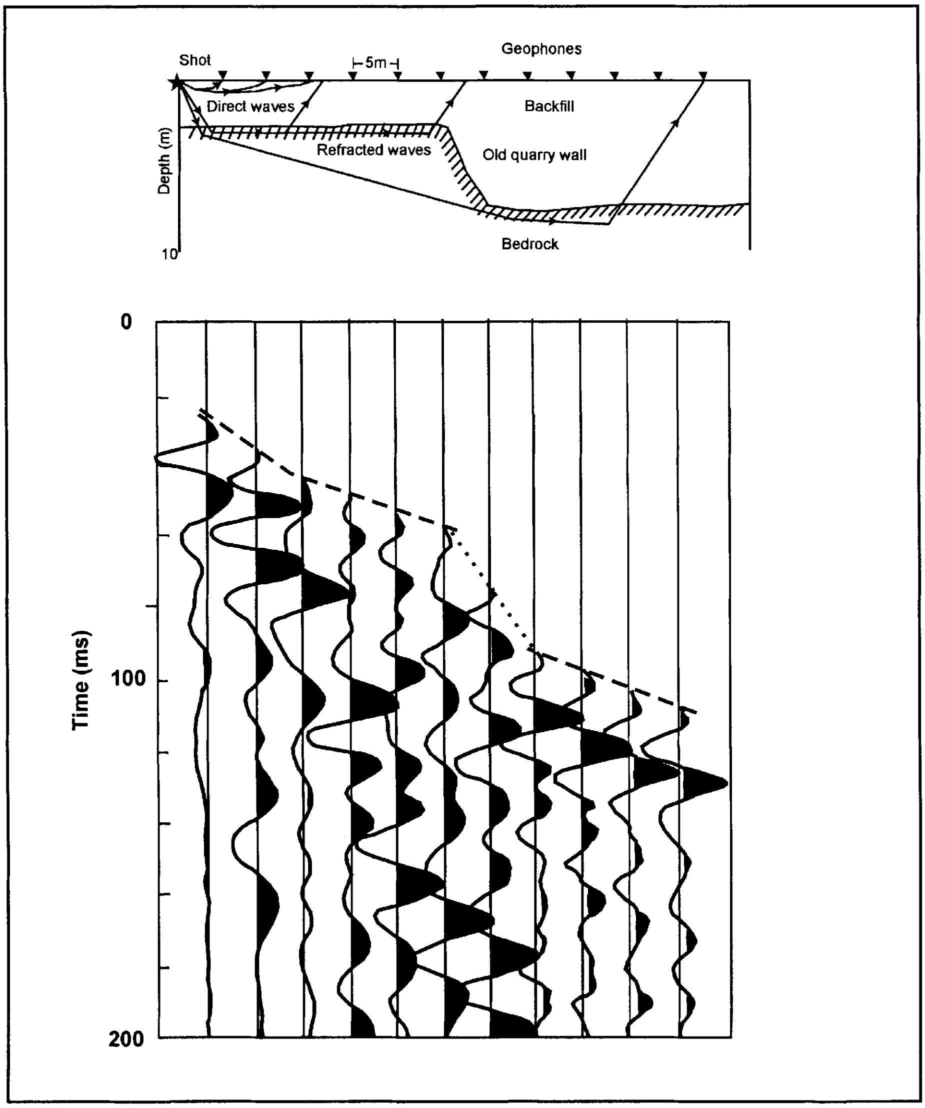


Figure 5.13 *Seismic section over a backfilled quarry (after Reynolds and McCann, 1992)*

An example of a typical seismic refraction survey is given in Figure 5.13, which shows the seismic record obtained over an in-filled quarry. The seismic signals arriving from the two distinct interfaces are clearly visible in the record.

Seismic reflection

Seismic reflection sections over the depth range between 10 m and 50 m have been obtained using standard 12- and 24-channel signal enhancement seismographs and hammer or similar seismic sources. Good reflections can be obtained, if the bedrock offers a marked contrast in acoustic impedance compared with the overlying superficial material. Resolution and, hence, the shallower limit to useful data is presently limited by dominant source frequencies of approximately 100 Hz. The ability of any seismic reflection method to resolve layering depends on the wavelength of the impinging wave. When the source generates high frequencies and consequently predominantly short wave lengths (eg 10 m for 100 Hz *P*-wave at 1000 m/s velocity), it constrains resolution of smaller layers or features, using the so-called "half wave-length rule" (Backus, 1962). Although penetration depth is an order of magnitude greater than can be easily obtained by the seismic refraction method using a hammer source, the technique is not in routine use. One of the main reasons for this is the difficulty in identifying low energy reflection arrivals in the part of the seismic record that often includes strong refraction and surface wave arrivals.

The seismic reflection method is commonly used for regional engineering studies on land, when information is required about the geological structures down to depths of 300 m. It should be noted that deeper reflection techniques, using surface vibrators and sophisticated correlation processing, have been used in conjunction with special engineering studies for deep radioactive waste repositories and for gas storage.

The use of a high frequency borehole sparker as a seismic source for a reflection survey is demonstrated in Figure 5.14, where the shallow reflection at 30 m from the Pre-Cambrian bedrock is clearly defined on the record. This would not be discernible if low frequency, surface seismic sources, such as the hammer, were used.

The use of digital filtering, together with high frequency geophones, has increased the resolution that can be achieved with shallow seismic reflection surveys. Although considerable success has been reported (Miller and Steeples, 1994) with the development of seismic reflection, it is not in common use in near-surface site investigation. Nevertheless reflection methods are widely used for major schemes such as dams and tunnels. The main reason for this is that the majority of seismic sources currently used for land-based surveys, have pulse widths that are too long to resolve the fine detail of the near-surface geological structure. Attempts to use higher frequency sources to improve the basic resolution have been inhibited by the lack of penetration of the seismic pulse, caused by attenuation of the seismic energy in the near-surface layers.

However, it is emphasised that progress is being made, and the seismic reflection method is in common use on land in more regional engineering studies, where the study of the geological structures down to depths of 300 m is required. In these deep seismic reflection studies, surface vibrators and sophisticated correlation processing have been used in conjunction with special engineering studies, for deep radioactive waste repositories, gas storage, and geothermal reservoirs. A typical example of a deep seismic reflection survey using Vibroseis is in Figure 2.2, which shows a strong seismic signal reflected from the base of the Oxford Clay. The depth to the reflecting interface can only be calculated from the measured travel time if the compressional wave velocities in the overlying strata are known.

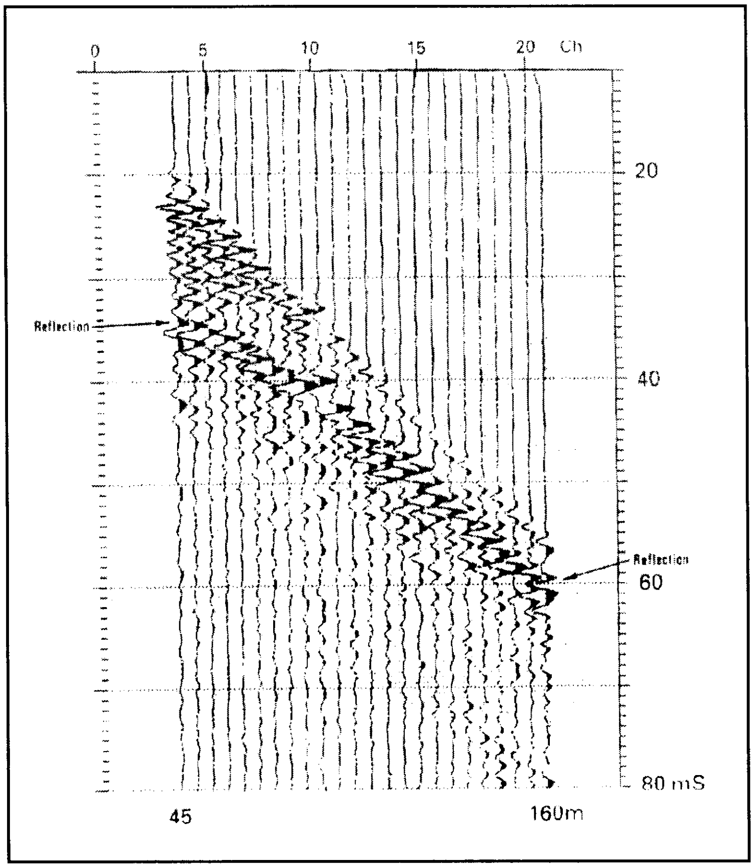


Figure 5.14 *Shallow seismic section reflection survey (after Baria* et al, *1989)*

5.4.3 Borehole seismic (sonic) methods

Borehole logging

Sonic log

In its most basic form, the sonic log is a simple seismic refraction survey run along the borehole wall, recording the time taken by *P*-waves from pulses, to travel a defined length of formation along the borehole wall, plotted against depth. In the oil industry, this is expressed as "microseconds per foot", but in civil engineering applications the more familiar units of "microseconds per metre" are used. The basic sonic log is used mainly to compute the formation porosity using the time-average equation of Wyllie *et al*, (1958). Acoustic imaging of a borehole wall also provides information on lithology and fine structure, eg cleavage, as well as mapping the wall profile. This can be useful in unravelling complicated geological structures.

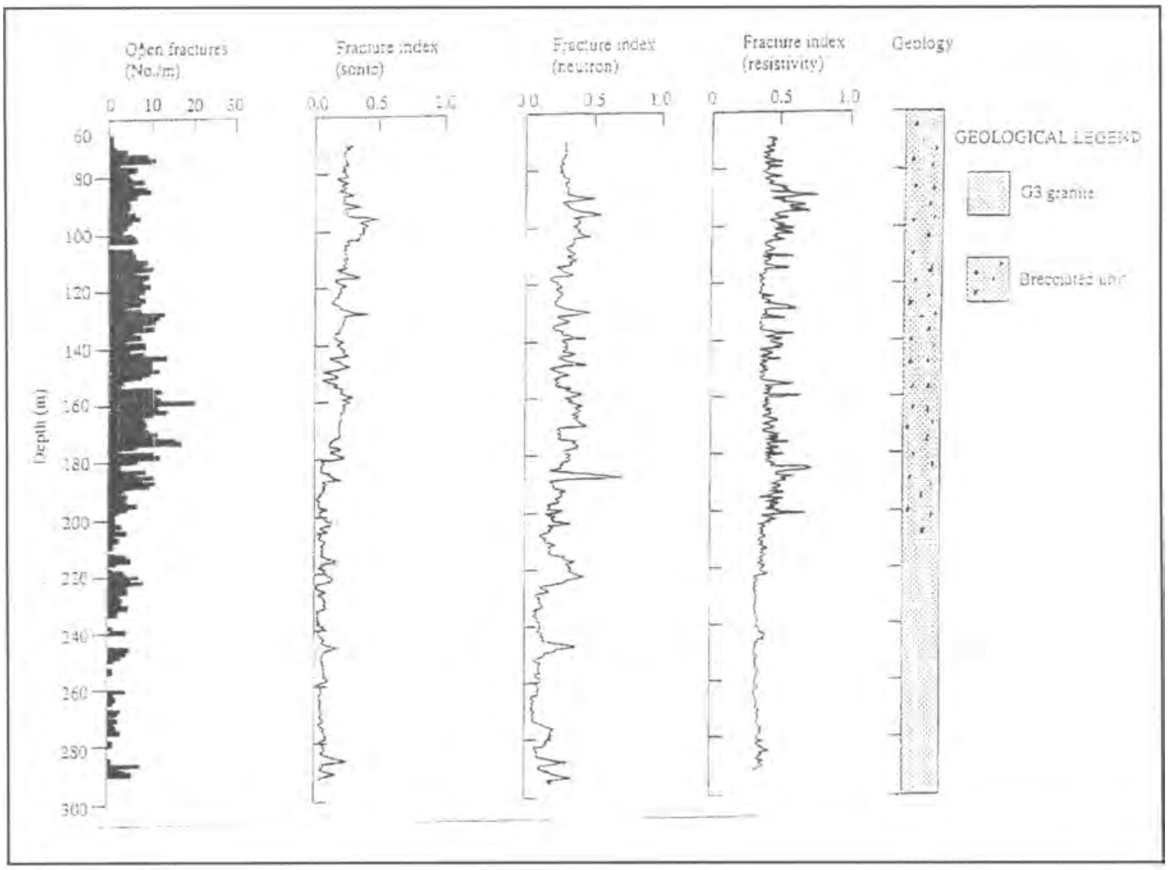


Figure 5.15 *Full-wave-train sonic log and rock fracturing (from McCann* et al, *1990)*

With the full-wave-train sonic log, it is often possible to measure the velocities of both the *P*- and *S*-waves. Using values of the formation density computed from the gamma-gamma log (See 5.6.2), it is possible to calculate the dynamic elastic properties of the rock mass from the *P*- and *S*-wave velocities. It is not always possible to identify the

S-wave as there is often no distinct break at the onset of the shear wave pulse, or the shear wave is highly attenuated. In the latter case this is extremely useful in showing up zones of highly fractured rock.

The presence of fractures in the rock mass will interfere with the transmission of elastic wave energy along the wall of the borehole. In highly fractured rock, both the velocity of propagation and the amplitude of a compressional wave are considerably reduced and similar characteristics have been noted for shear waves. A typical example of the use of the full-wave-train sonic log to assess the degree of fracturing in the rock mass is shown in Figure 5.15.

Televiewer

The Acoustic Borehole Televiewer produces an image of the borehole wall based upon either the measured amplitude or transit time of a reflected acoustic pulse. The televiewer pulses ultrasonic energy from a piezoelectric transducer to the borehole wall via the fluid in the borehole, where some of the energy is reflected and detected by the transducer (now acting as a receiver). The transducer is rotated in the borehole at 3 rev/s and is orientated relative to the earth's magnetic field by a downhole magnetometer within the sonde. The amplitude of the reflected signal is proportional to the reflected energy, which is a function of the acoustic impedance of the borehole wall. The raw amplitude and transit time values are processed using the digital techniques applied to the electrical data and a flattened picture of the borehole wall, with fractures appearing as a sine wave is obtained.

Cross-hole seismic measurements

The need for information on the ground mass outside site investigation boreholes has resulted in a number of geophysical methods that operate between adjacent boreholes. The oldest of these methods is the cross-hole seismic technique, which provides a scan of the variation of the velocity of propagation and attenuation, of both compressional and shear-waves with depth. Cross-hole measurements with different sources can provide profiles of P, V_H and V_S. Typical examples of crosshole data from a normally consolidated sand site and an overconsolidated clay site are shown in Figure 5.16 from Butcher and Powell (1997a), compared with Rayleigh wave velocities. An advance in this method has been the development of seismic tomography, which can provide an image of the rock mass in terms of a seismic parameter, such as compressional wave velocity. This image can be related to the presence of geological discontinuities, such as fault and fracture zones, cavities, or dykes.

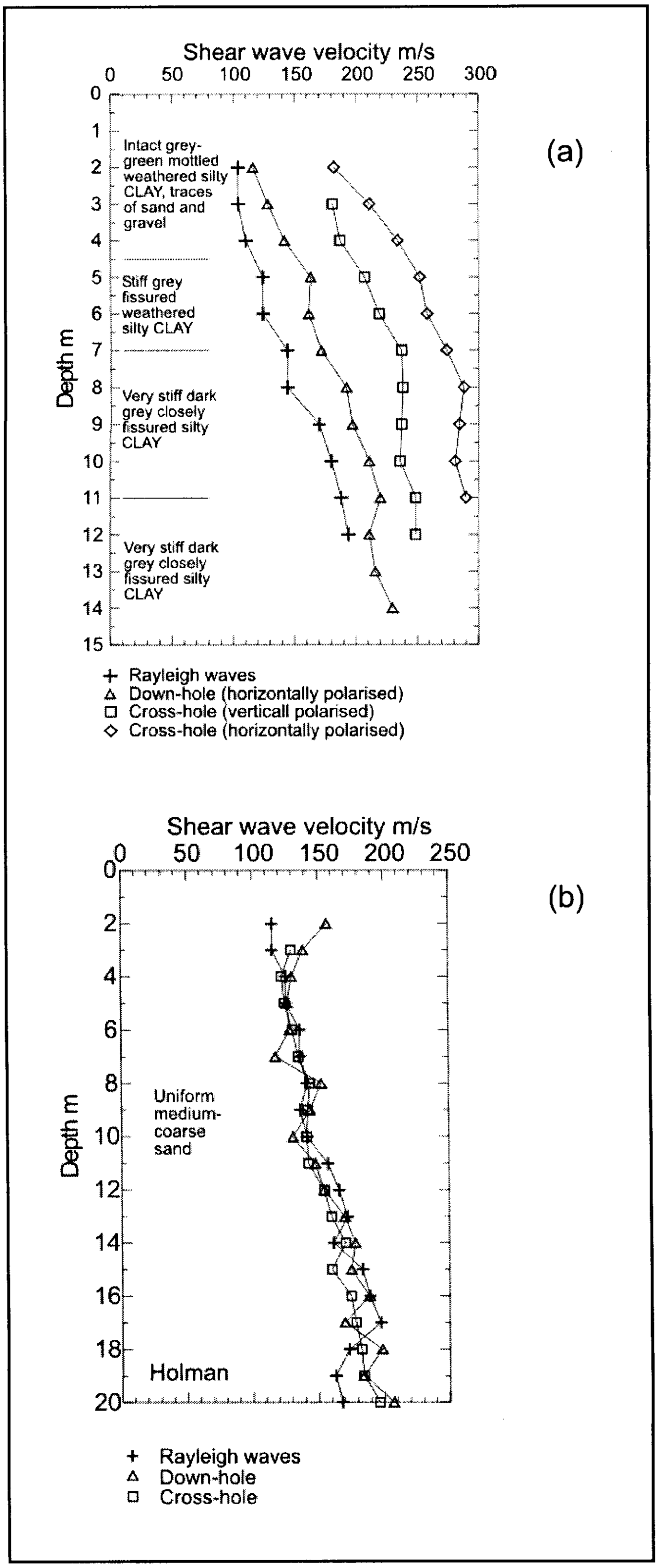


Figure 5.16 *Shear wave versus depth profile for a) heavily overconsolidated clay, b) uniform, medium dense sand (after Butcher and Powell, 1997a)*

Further research into the development of the cross-hole electrical and radar techniques is in progress, and again increased use of both methods is anticipated in the future.

Vertical seismic profiling

This technique combines the down-hole, refraction and reflection methods. For VSP the array of seismic detectors is deployed in a borehole and shots are fired from a seismic source located on the ground surface. Similar results to those obtained in standard seismic refraction and reflection surveys are observed, as each detector will record both the direct seismic pulse as it propagates downwards and later pulses reflected from interfaces within the rock mass. The basic principles of the VSP method are illustrated in Figure 5.17. By moving the seismic source away from the top of the borehole, or moving the detector array within the borehole, it is possible to determine the source of each pulse train observed at an individual detector and produce a geological model that will fit the recorded data. The VSP method can also be operated with the seismic source in the borehole and the detecting array on the ground. A shear wave source can also be used and the dynamic elastic moduli can be derived from the compressional and shear wave velocity data.

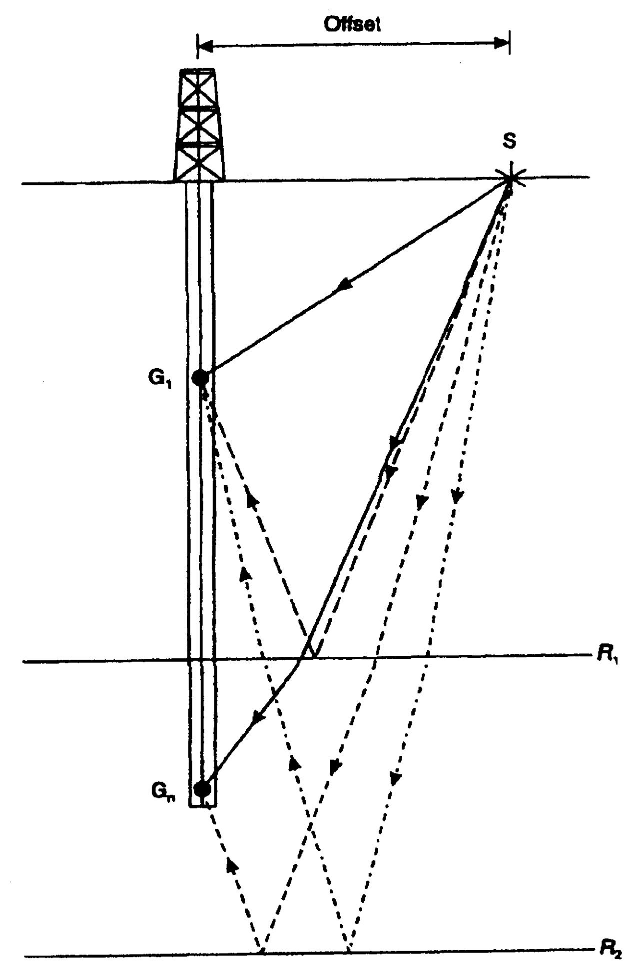


Figure 5.17 *Schematic diagram showing the principle of vertical seismic profiling (VSP) (after Reynolds, 1997)*

5.4.4 Marine seismic surveying

Echo sounding

A continuous water depth profile along the track of a survey vessel is obtained by using an instrument, that measures the time taken for a short pulse of high frequency sound to travel from a transducer attached to the survey vessel down to the sea-floor and back again. Such profiles are combined to produce a bathymetric chart. Additional control may be required to ascertain whether the sounding is reproducing reflections from soft surface sediments, or higher density material underneath. Compensation may be required to correct the vertical motion of the survey vessel. Swathe systems where multiple echo-sounders collect depth data across a swathe (up to 6 times the water depth) are increasingly used. Again, proper interpretation will involve reduction to an appropriate datum level, applying tidal corrections to the data obtained (See 8.9).

Side-scan sonar

This is an underwater acoustic technique (analogous to oblique aerial photography) used for imaging the sea floor. It is based on the back-scattered reflection of high frequency pulses of sound from the seabed, and provides a quantitative guide to the position and shape of seabed features and a qualitative guide to the type of seabed material. The system is particularly useful in surveys for rock outcrops, pipelines, sand waves, trenches and seabed obstructions, such as wrecks.

Proper interpretation will involve reduction to an appropriate datum level, applying tidal corrections to the data obtained.

Seafloor mapping systems are available, which apply digital scale corrections to produce a true isometric display of the seabed topography. Records from adjacent lines can be combined to produce a composite mosaic of the survey area.

Continuous seismic reflection profiling

The use of continuous seismic reflection profiling (see Figure 5.18) should always be considered as an aid to exploratory borings in major offshore site investigations. An instrumental extension of the echo-sounding principle is used to provide information on sub-seabed acoustic reflectors, which usually correspond to lithological and geological horizons. The instrumentation required, especially the acoustic source type, depends on the local geological conditions. While the choice should be left to a geophysics adviser of suitable experience, a guide is as follows. The higher frequency sources, such as the "pinger" and "high resolution boomer" are generally suitable for resolving near-surface layering, whereas the "sparker" or "air-gun" is more suited for coarser and thicker overburden, and for the acquisition of data from deeper levels beyond the penetration of boomers.

Signal processing can enhance the resolution, penetration, and signal-to-noise ratio of the resultant record. Important techniques are "swell filtering" to compensate for short period source-detector motion, "time-variant gain correction" and "time-variant frequency filtering". The results may visually reproduce geological features, but quantitative data on depths to interfaces can only be determined if characteristic velocities of the sea-bed materials are known. Close spacing of the seismic profiling survey lines, allows 3-D images of the geological structure to be created. Two limitations of the technique are:

1. It usually cannot delineate the boundary between two dissimilar materials that have similar geophysical characteristics, eg a very coarse high density, glacial till and a heavily weathered and fractured rock.
2. In shallow water particularly in areas of "acoustically hard" seabed, near-surface reflectors may be obscured by multiple reflections originating from the seabed itself.

Single and multi-channel digital recording systems are available, which allow multiple suppression, filtering, and other signal enhancement operations to be carried out on the recorded data.

For accurate interpretation and reduction to an appropriate datum level, it is necessary to apply tidal corrections to the data obtained, particularly in the near-shore environment. Standard tide tables for the area of interest are often used, but in some cases a tide gauge may be installed and continuously monitored.

In deep water, seismic surveys operated from the sea surface usually lack the resolution required to delineate the lithological variation in the near-surface sediments, required for a civil engineering site investigation. This has resulted in the development of deep-tow seismic instruments, which are deployed close to the sea-floor to generate not only high resolution seismic sections, but also detailed sonar records of the sea-floor.

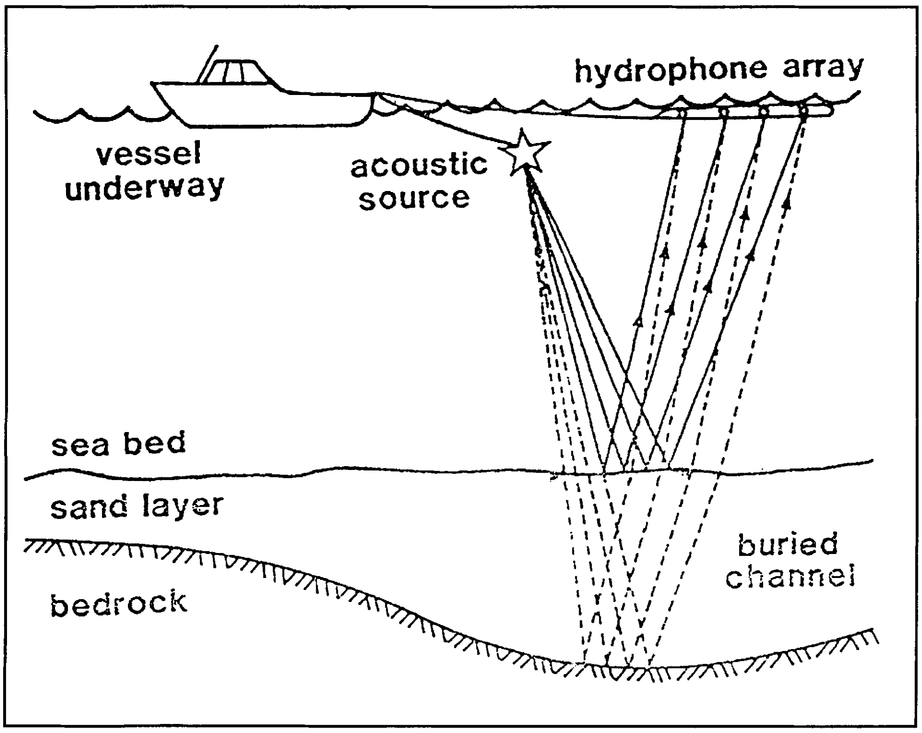


Figure 5.18 *Continuous seismic reflection profiling: operating principle (from McCann and Forde (in press))*

5.4.5 Other seismic methods

Surface waves

Surface or Rayleigh waves are distortional stress waves that propagate near to the boundary of an elastic half space, in this case the ground surface. The propagation velocity of surface waves is controlled by the stiffness of the ground within one half and one third wavelength of the surface and so measurements therefore need to determine their wavelength as well as their velocity.

Measurements of surface waves can be made of either transient or continuous waves. Transient waves are produced either by a vertical impact or by a working construction plant. The transient wave will comprise of a range of frequencies that can be processed by spectral analysis to determine the dispersion curve (variation of phase velocity with frequency) from which the wavelength can be calculated. This technique is called the Spectral Analysis of Surface Waves (SASW).

Continuous surface waves are produced by a vertically oscillating vibrator, placed on the ground surface. In this case the dispersion curve is produced by varying the frequency of the vibrator and measuring the phase change of the wave as it propagates away from the source. The phase change can be used to calculate the phase velocity and therefore the wavelength. This technique is called the Continuous Surface Wave (CSW) method.

The effective depth of travel of the Surface wave is a function of the wavelength and depends upon the variation of stiffness with depth. Gezatas (1982) recommends the use of one third wavelength where the stiffness increases with depth, but one half where the stiffness remains constant with depth. This is the simplest approach that can give data on site at the time of making the measurements, but gives an approximate depth that would need to be correlated to some other information such as a borehole log. Other methods start with a synthetic dispersion (velocity-frequency) curve and use an algorithm (based on Haskell, 1953) to iteratively adjust the curve until it matches the field data.

Surface waves travel between 5 per cent and 9 per cent slower than the shear wave, as a function of the Poissons ratio (v). In most cases 5 per cent is used. Details of the behaviour and use of surface waves have been reported by Matthews *et al*, (1996)

Microseismics

Large installations, eg dams and radioactive waste disposal sites, require the installation of networks of seismographs, designed to pick up small seismic events (0 to 2.0 ML). These installations monitor potentially threatening faults and the effects of induced seismicity, related to reservoir operations. In the extractive industry, such microseismic monitoring is a key element in the monitoring and control of rock bursts, and has been used to monitor both evaporite solution cavities and the stability of large and potentially threatening cavities. The data from such installations can be used to estimate the stress state at depth. In areas where strong-motion seismic data are not available, microseismic data can be used for seismic hazard assessment. Microseismic activity is also used in the monitoring of landslides. Sea-bottom seismic sensors are placed on the sea floor to monitor natural seismic activity from earthquakes and microseismic signals associated with pumping activities from oil platforms.

5.4.6 Sonic and ultrasonic NDT methods

Non-destructive sonic and ultrasonic testing methods are non-invasive and have been used for the past thirty years in the assessment of civil engineering structures and materials. The sonic method refers to the transmission and reflection of mechanical stress waves, through a medium at sonic and ultrasonic frequencies. Seismic waves, which are also generated by an impact source, are commonly referred to in non-destructive testing applications and propagate at frequencies in the range of 100 Hz to 1 kHz. The terms “sonic” and “seismic” are often interchanged in practice, as both refer to the propagation of compressional waves in a medium.

The five most commonly used sonic methods are:

1. sonic transmission method
2. sonic/seismic tomography
3. sonic/seismic reflection method
4. ultrasonic reflection method
5. sonic resonance method.

Sonic transmission method

Direct transmission involves the passing of a compressional wave, at frequencies between 1 and 10 kHz, through the thickness of the wall (or the structure) under investigation. Transmission of the wave is initiated on one side of the structure by the impact of the force hammer, and reception on the opposite side is performed by an accelerometer, positioned directly opposite the force hammer. The resulting wave velocity is an average of the local velocity along the path and it is not possible to establish the position and the extent of any possible inhomogeneity. The velocity magnitudes may be plotted in a contour map format, with grid points as X and Y co-ordinates and the pulse velocity as the Z co-ordinate. This format allows a simple evaluation of the relative condition of the masonry or concrete walls of the structure, or an evaluation of the internal fabric of a structure, such as a masonry arch bridge.

It is generally recognised that the direct transmission arrangement is a simple technique to apply in the non-destructive testing of structures, because it provides a defined path length through the structure. Furthermore, as the arrival time of the first wave is of primary concern, no attempt to distinguish complex wave frequencies and reflections is required for the analysis. This method has been successfully used to evaluate material uniformity, detect the presence of voids, estimate the depth of surface cracks, and calculate an average compressive strength for the structure or the material. The detection of flaws is possible because sonic waves cannot transmit across an air gap, eg a crack, void or delamination at the interface between brick or stone and mortar. A propagating wave must find a path around the void, resulting in attenuation and an increase in the transit time of the signal.

Sonic/seismic tomography

Sonic tomography represents an improvement in the sonic transmission test method because tests are performed not only in the direct mode, but also along paths, which are not perpendicular to the wall surfaces. The wall of the structure, or the masonry section, is thus crossed by a dense net of raypaths, each of which relates to a specific travel time between the sonic source and receiver through the structure. These values of travel time can be used to compute a three-dimensional reconstruction of the velocity distribution, across the structure or selected cross-section, so that local variations in velocity can be identified and correlated with zones of weakness, or flaws in the internal fabric of the structure.

It is usual to assume a linear structural response in the application of the tomographic method. This is because the response is measured with transducers, which are usually mounted well away from the location of the impact, where non-linear behaviour may arise. Any variation from the expected travel time is therefore attributed to inhomogeneity in the structure or damage. In order to obtain good statistical accuracy, it is necessary to maximise the amount of experimental data included in any calculation used, by ensuring that all areas of the proposed tomographic section have adequate raypath coverage. Several inversion algorithms are commercially available for tomographic reconstruction.

Acquired data usually exhibit velocity scatter, resulting from variations in the strength and nature of the hammer blow generating the input signal, the interpretation of acquired waveforms by the operator, and coupling of the receiving transducer to the masonry or concrete surface. Data scatter has the effect of increasing the residual of tomographic velocity reconstruction and may lead to identification of false anomalies. The accuracy of the velocity reconstruction can be improved by:

- better understanding of the input signals
- a carefully planned choice of position and number of the reading stations
- simple data smoothing prior to analysis.

Sonic/seismic reflection method

In the sonic reflection method, both the initiation and reception of the sonic wave are performed on the same face of the masonry, as in the case of indirect transmission. However, the stress wave recorded is the direct stress wave reflected from any internal flaw, or from the rear face of the structure under investigation. The velocity calculated from the rear wall or face of a structure is a measure of the local velocities along the path.

In principle, the properties/defects that reflection methods may be used to search for in retaining walls are:

- internal dimensions and shape
- type and properties of fill
- voiding within the fill material
- cracks and voids within the internal fabric of the structure.

Seismic waves that are also generated by an impact source are commonly referred to in non-destructive testing applications, and propagate at frequencies in the range 100 Hz to 1k Hz. However, the terms sonic and seismic are often interchanged in practice, since both refer to the propagation of compressional waves in a medium. Seismic reflection techniques may be employed from the road surface, arch barrel or spandrel walls of a masonry arch bridge, the front of a retaining wall, or a harbour dock wall. It is not a method currently recommended however, since the resolution achievable with the low frequency energy is poor and it is often difficult to distinguish reflections from surface waves and refracted arrivals.

The impact echo system

The most recent development of the sonic/seismic reflection method is known as the impact echo test method, which was developed originally to measure concrete thickness and integrity from one surface. The method is performed on a point-by-point basis by using a small, instrumented impulse hammer to hit the surface of a structure at a given location and record the reflected energy with an accelerometer, mounted adjacent to the impact location (Figure 5.19(a)). Since reflected signals are more easily identified in the frequency domain, the received energy recorded in the time domain is passed to a signal analyser for frequency domain analysis using a fourier transform algorithm. A transfer or frequency response function (FRF) is then calculated for the impulse hammer/accelerometer system, and reflections or echoes of the compressional wave energy are indicated by pronounced frequency peaks in the transfer function or frequency spectrum record (Figure 5.19(b)). These peaks correspond to the thickness or flaw depth resonant frequencies and knowing the compressional wave velocity in concrete or any other construction material, the depth to the corresponding flaw can be calculated. The depth of the reflector will correspond to the slab or wall thickness if the concrete used in construction is sound. The original concept of FRF testing of civil engineering structures dates back to the testing of concrete piles (Davis and Dunn, 1974), while the modern adaptation of the method was undertaken at the National Institute for Standards and Technology, USA and Cornell University.

Impact echo testing of bridges has largely been focused on identifying voids in ducts, in post-tensioned concrete bridges. Experimental work in this area has indicated some ambiguity in the results obtained and this is attributed to the following effects:

- three-dimensional dispersion of the impact echo wave through the concrete as a result of the presence of aggregate and other inhomogeneities
- possible reduction in frequency of the impact echo signal, due to crumbling of the concrete surface, resulting in a longer contact time and hence a lower frequency
- possible lack of sensitivity of the accelerometer.

Ultrasonic reflection method

Ultrasonic waves, which are generated by a piezoelectric transducer at frequencies above 20 kHz, propagate with a wavelength around 50 to 100 mm in masonry. This form of testing is used successfully at ultrasonic frequencies, for the detection of flaws in metal castings and was the first NDT developed for the testing of concrete. However, it is much less practical in concrete and masonry, because they have much higher attenuation characteristics, requiring lower frequency signals to obtain a reasonable penetration. In addition, the numerous boundaries in these materials result in scattering of both incident and reflected waves. Despite this, ultrasonic reflection has been successfully used for identifying and locating specific flaws in concrete and is also applicable to the investigation of small defects within masonry walls.

At present the method is not commonly used for these purposes, because of a number of technical difficulties. In the case of ultrasonic signals, the main factors to be overcome are the need for good coupling of the transducer to the surface, which is often rough, and the scattering of the wave due to material heterogeneity. The need for effective coupling requires the use of a coupling agent, such as grease or petroleum jelly, so that the transmitter and receiver will temporarily adhere to the surface. This makes the process of moving the points of measurement quite slow and it is often difficult to achieve adequate coupling on uneven surfaces. Scattering of the signal limits the propagation through the material and produces a complicated series of return signals, making it difficult to identify defects amongst the noise. In addition, surface waves which travel more slowly than the compression waves, may arrive at the receiver within the same time interval and confuse interpretation. Further developments of the ultrasonic technique, for example improvements in signal generation, detection and data processing, are underway and may lead to a practical tool if the problems mentioned above are overcome.

Sonic resonance method

A simple variation of the Impact Echo Method (described above) has been used in the UK for many years to detect defects or cavities behind the linings of tunnels, or areas of rendered wall where the rendering has separated from the brick or stonework. In this case, the wall or lining is tapped with a lightweight hammer and the ringing or echo associated with a hidden cavity or defect, produces a significant change in frequency as the impulse hammer is operated in the defective area. The method is quick because the human ear is extremely sensitive to the change in the resonant frequency, but is subjective as a hollow sound can imply near-surface defects as well as ring separation at depth.

Acoustic emission

Acoustic emission is induced when a stress is applied to a structure. The resultant acoustic signals that are generated by internal failure in the fabric of the structure are of a transient nature and similar in characteristic to the microseismic signals discussed above in Section 5.4.4. Acoustic emission has been detected in structures for many years, but its use in monitoring the operational performance of a structure has only become practical over the past decade. The advent of small high performance computers capable of recording and interpreting large sets of continuously recorded data, from accelerometer arrays deployed on the structure, has enabled the engineer to monitor acoustic emission on a continuous basis. From this data it is possible to detect internal failures within the fabric of a structure and locate their position for remediation in the future. The method can also be used in a fail-safe manner, in the same way that rock bursts are recorded in mining excavation, since the detection of a significant level of acoustic emission activity may well be associated with imminent failure of a structure.

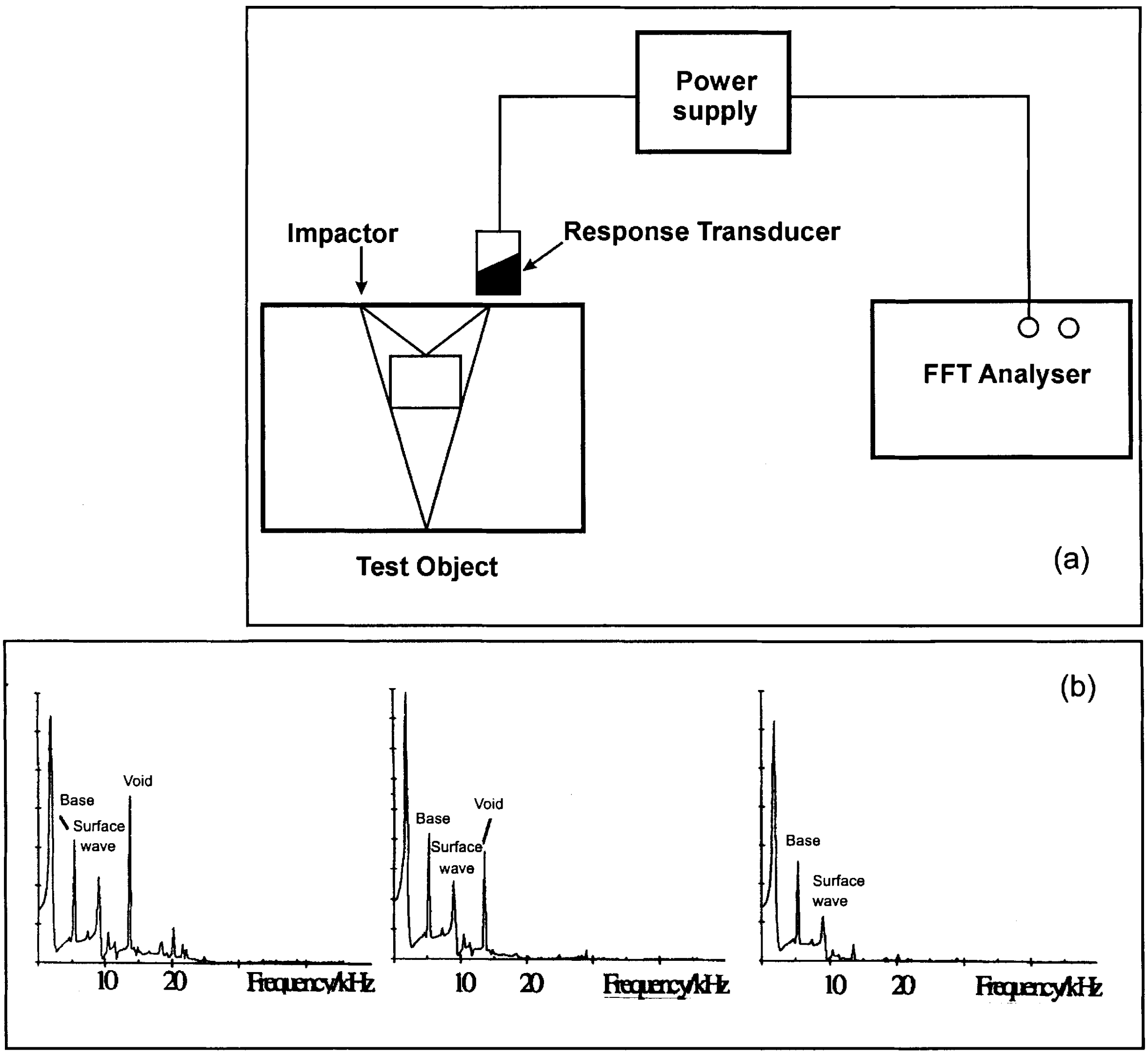


Figure 5.19 *Impact echo test showing (a) Basic set-up of instrumentation and (b) Frequency spectrum obtained after impact with hammer on test wall*

5.5 ELECTROMAGNETIC METHODS

The electromagnetic method is based on the effect of ground conductivity, on the transmission of electromagnetic energy generated by either natural or man-made sources. As with vertical electrical sounding described in Section 5.1.1, the objective of the method is to determine variations in electrical conductivity with depth, usually assuming horizontal layering. Soundings can be made at a constant frequency by varying the spacing between source and receiver, while conductivity mapping can be carried out with a fixed spacing between the two coils. Measurements can also be made at a number of frequencies (referred to as frequency-domain sounding) or at several time intervals after a transient pulse (referred to as time-domain sounding). The conductivity of the ground is the inverse of its electrical resistivity value (see Figure 5.2) and a range of conductivity values is given in Table 5.2. The operating principle of electromagnetic surveying is shown in Figure 5.20.

Table 5.2 *Electromagnetic properties of typical rocks at 100 MHz (from Darracott and Lake, 1982)*

Material	εr	σ (mS/m)	Material	εr	σ (mS/m)
Air	1	0	Dry clay	3	1–10
Metal (iron)	1	10^8	Saturated clay*	15	10^2–10^3
Fresh water	81	1	Rock	4–10	
Seawater	81	4×10^3	Dry Granite	5	10^{-5}
Dry sand	3	10^{-4}–1	Wet granite	7	1
Saturated sand*	25	10^{-1}–10	Limestone	4–8	0.5–2
Soil (dry)	2–6		Wet sandstone	6	
Soil (wet)	5–15		Dry concrete	6	1
Clays	5–40	2–1000	Saturated concrete	12	10^8

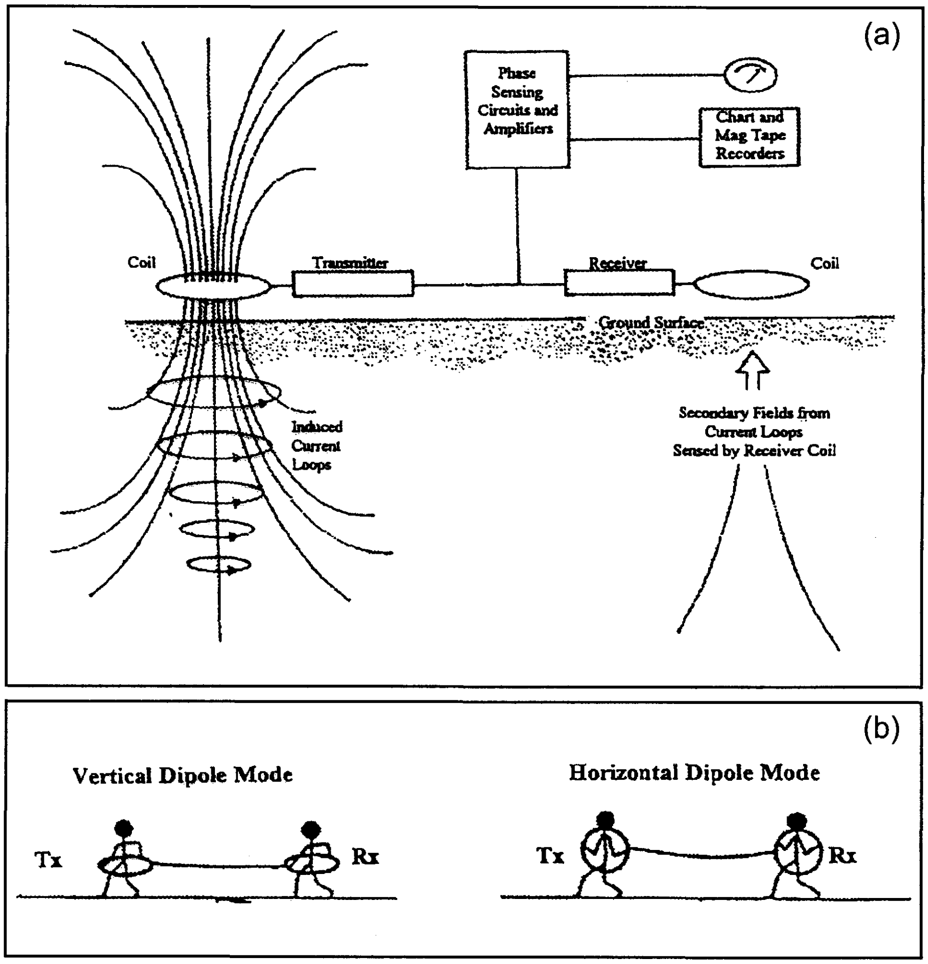


Figure 5.20 *Electromagnetic surveying, (a) operating principle, (b) dipole modes*

5.5.1 Electromagnetic Surveying

Ground electrical conductivity method

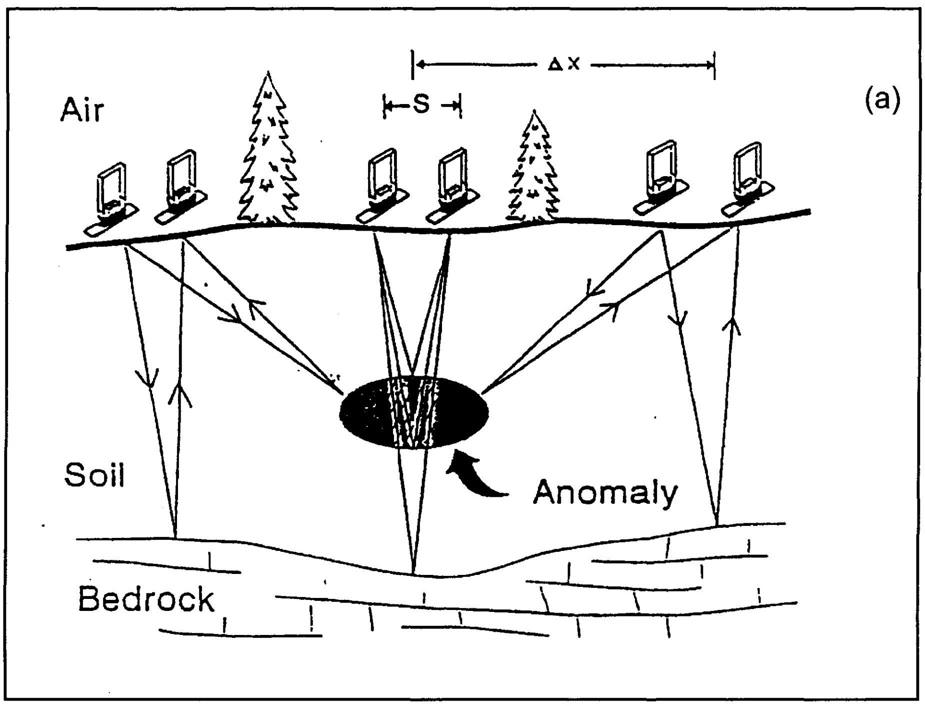
In this method a transmitter coil is energised with an alternating current and is placed on, or above the ground surface. The time-varying electromagnetic field in the transmitter coil induces very small currents in the earth. These currents generate a secondary magnetic field, which is sensed together with the primary field by the receiver coil. The intercoil spacing and operating frequency are chosen so that the ratio of the secondary to primary magnetic field is linearly proportional to the apparent ground conductivity. This ratio is measured and a direct reading of apparent ground conductivity is obtained. Using a fixed separation of 4 m between the transmitter and receiver coils, the depth of penetration is limited to less than 6 m, but the survey can be carried out in a rapid and economic manner by a single operator. Greater penetration to depths down to 30 m is achieved by moving the two coils apart to a maximum distance of 40 m, or by reorientating the coils.

It is important to realise that a ground conductivity survey does not supply the quantitative information on earth layering that can be obtained by resistivity sounding or seismic refraction surveys. However, as the technique is so cost-effective it should be used for site investigation mapping, for the design of drilling and trial pit programmes, or for filling gaps between boreholes or resistivity soundings. The constant separation equipment is particularly effective in the location of cavities or buried mineshafts, when used in conjunction with a magnetic survey. The measurements compare closely with results obtained from conventional resistivity profiling. Ground conductivity surveys are preferable to resistivity profiling if the same depth of investigation is required.

Ground penetrating radar (GPR) method

This method has been introduced to site investigation in the UK over the past twenty years. The system consists of a radar antenna transmitting electromagnetic energy in pulse form at frequencies between 25 MHz and 1 GHz. Its basic principle of operation is shown in Figure 5.21 (a). The pulses are partially reflected by the subsurface geological structures, then picked up by a receiving antenna and plotted as a continuous two-way travel time record, which is displayed as a pseudo-geological record section (Figure 5.21 (b)). The contrast in dielectric constant between the soil and the bedrock in Figure 5.21 (a) determines the proportion of the signal reflected from and transmitted into the bedrock. A range of the typical values of dielectric constant is given in Table 5.2. The vertical depth scale of this section can be calibrated from the measured two-way travel times of the reflected events, either by use of the appropriate velocity values of electromagnetic energy through the lithological units identified, or by direct correlation with borehole logs.

The depth of penetration achieved by the radar pulse is a function of both its frequency and the electrical conductivity of the ground. A range of typical values of electrical conductivity is given in Table 5.2. For UK soils, where clay materials tend to predominate in the near surface, the maximum depth of penetration is likely to be between 1 and 4 m, but useful penetration to greater depths can sometimes be achieved in more resistive geological environments.



continued on next page...

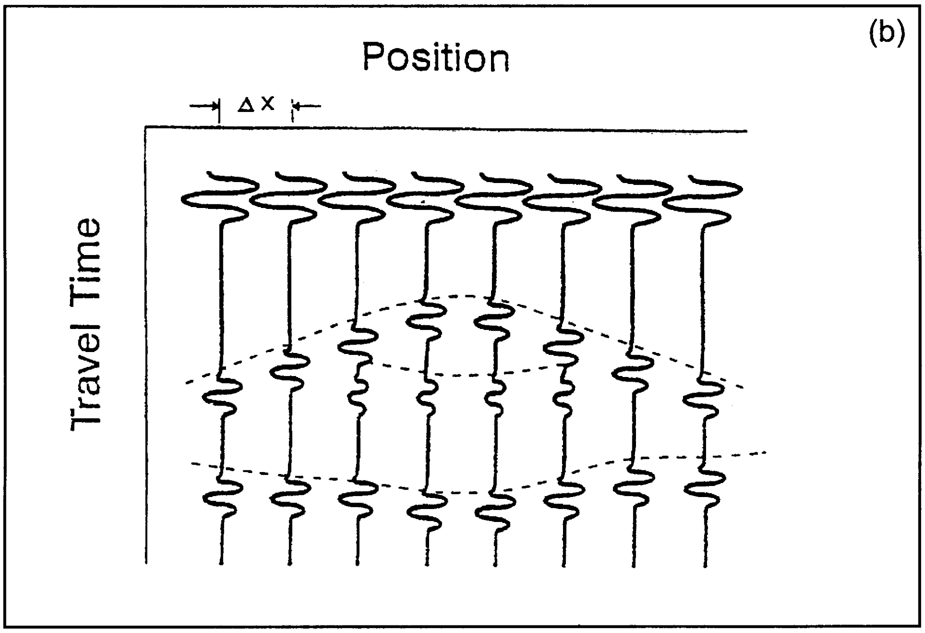


Figure 5.21 *Ground penetrating radar, (a) operating principle and (b) two-way travel time record (after Annan, 1992)*

A typical example of a modern ground penetrating radar survey is shown in Figure 5.22. The Pulse Echo IV system has been used with a 50 MHz antenna, to determine whether a known coal seam in the subsurface has been worked in the past. Although both the surface topography and mining records give no indication of any past mining activity, the radar section indicates the presence of a major disturbance in the near surface geological structure, which is associated with an old shaft leading down to the coal seam. The subsurface disturbance determined by the GPR survey defines the hazardous ground above the entry and localises the site of imminent collapse.

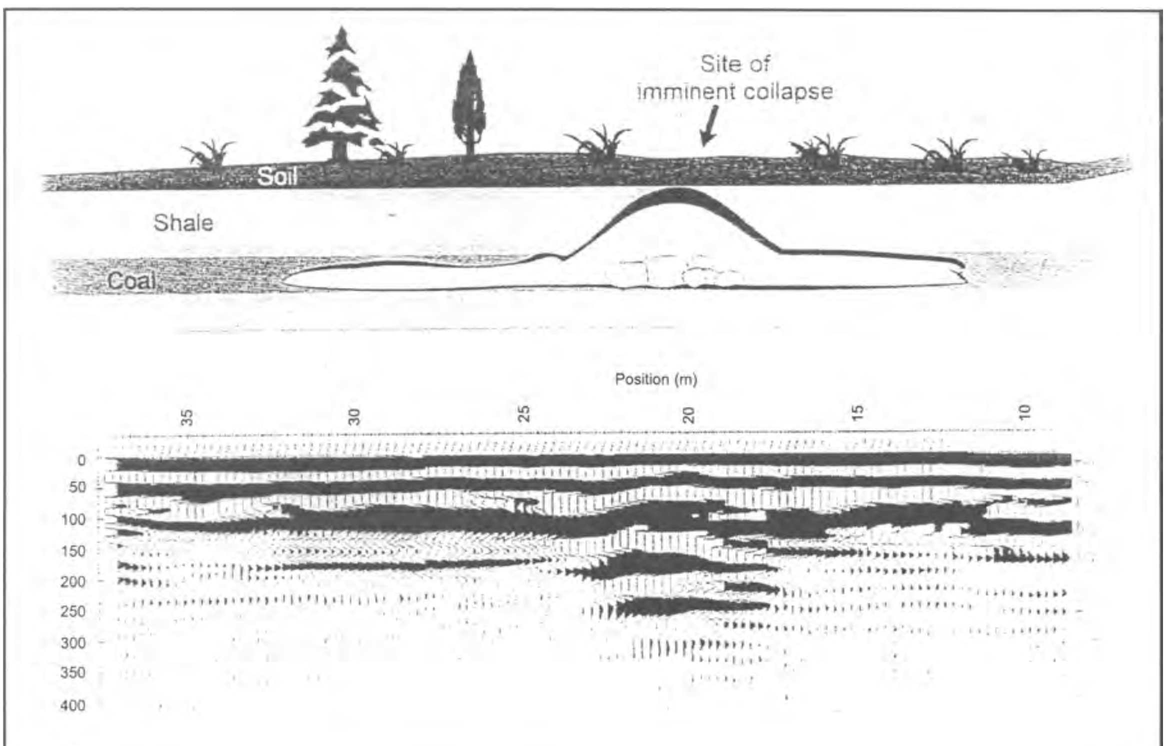


Figure 5.22 *Typical ground penetrating radar section over a suspected mineshaft with a 50 MHz antenna (Courtesy of STS Ltd)*

In the freshwater environment, which includes rivers, canals, lakes, and reservoirs, increasing use is being made of ground penetrating radar systems in the study of the sub-bottom geological structure. GPR is particularly effective in very shallow water and has the added advantage that the antenna can also be deployed on the adjacent land. One important application is the evaluation of scour processes at bridge piers and abutments.

Transient electromagnetic (TEM) method

Electromagnetic energy can be applied to the ground using transient current pulses instead of the continuous waves mentioned above. The collapse of a steady state primary magnetic field will induce eddy currents to flow in a conductive earth, and these will give rise to a transient secondary magnetic field, which may be detected in a receiver coil as a time-dependent decaying voltage. The characteristics of this transient decay can be related to the conductivity and geometry of the subsurface geology. Typical TEM systems provide rapid geo-electric depth scans, from a few metres down to several hundred metres, and therefore present an attractive alternative to electrical resistivity sounding. TEM is a well-established technique for mineral exploration and is increasingly being applied to hydrogeological mapping (especially saline intrusion problems) and to shallow engineering site investigation studies.

Figure 5.23 shows a typical example of a geological model of the margin of a tunnel valley in Suffolk, derived from the interpretation of individual TEM soundings. The model is derived from a series of geo-electric depth scans that have been interpreted individually and then linked together to produce the geological section.

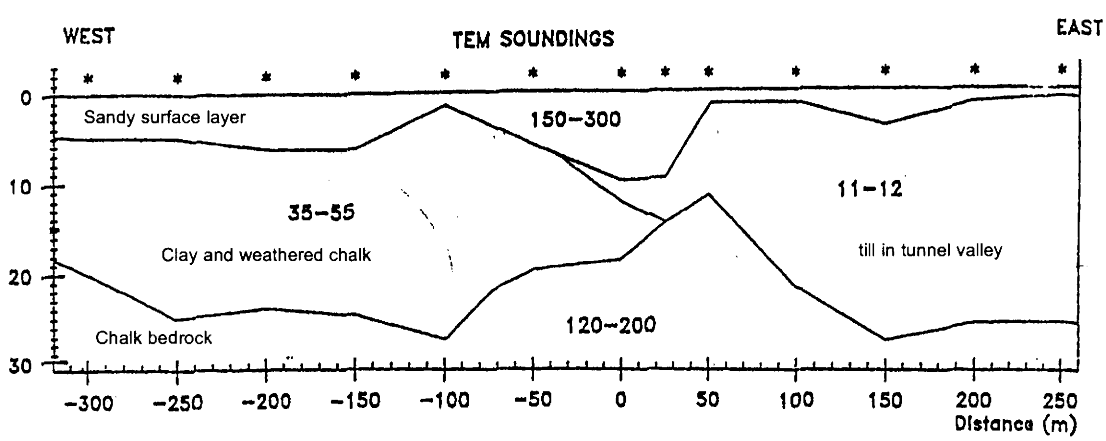


Figure 5.23 *Geological model of the margin of a tunnel valley in Suffolk derived from TEM sounding resistivities shown in ohm-metres (Courtesy British Geological Survey)*

Very low frequency (VLF) method

Electromagnetic waves transmitted from distant, very low frequency (VLF) radio stations (10 kHz to 30 kHz) such as in Rugby in the UK, are used in place of a local receiver. As the VLF waves are propagated some energy penetrates into the ground surface since the Earth is not a perfect conductor. In a conductive ground the VLF primary magnetic field induces eddy currents, which in turn produce a secondary magnetic field with the same frequency as the primary field, but usually with a different phase. With the VLF receiver aligned with the distant transmitter, a comparison is made between the vertical and horizontal magnetic fields either directly or by measuring the phase or tilt angle. The VLF equipment can be operated on the ground and from the air.

The method has been used in mineral exploration for the location of mineralised fault zones. It may have some applications in cavity and mineshaft location, where fairly low resistivity material overlies a resistive bedrock. The location of fluid-filled fault zones in groundwater studies, is another area where this method has an application. However, more recent studies (Fitzgerald *et al*, 1987) have shown that the method is also applicable to the location of high conductivity zones in a contaminated landfill site, associated with the presence of leachate.

Magnetotelluric (MT) method

Time-varying electromagnetic fields above the Earth's surface induce electrical currents in the subsurface. The induced electric field decays with depth according to a skin-depth rule, which depends on the frequency. The largest fields are natural and occur at low frequencies (< 1 Hz). They are the result of solar particles (eg flares) interacting with plasma in the Earth's near-space environment. The currents extend many kilometres into the subsurface. At higher frequencies there are natural fields due to thunderstorms (atmospherics), which induce current systems in the shallow subsurface. By using sensitive sensors to measure the time variations of the electric (E) and magnetic fields (B) at the surface, the impedance (E/B) obtained provides a measure of the subsurface resistivity structure for geological interpretation. High frequency measurements have potential for both engineering and hydrogeological investigations.

5.5.2 Borehole electromagnetic methods

Induction log

The induction log is an electromagnetic device, which measures the electrical conductivity of the surrounding rock mass within a distance range from 0.2 m to 1 m from the borehole axis. Its mode of operation is similar to that of the ground conductivity meter described in Section 5.5.

The principal advantage of the induction log is that the conductivity of the rock mass can be measured, in dry sections of the borehole above the water table and in boreholes that have been cased with insulating PVC or Teflon tubing. The induction log is used to provide lithological information, to locate zones of significant groundwater contamination. It is also used in uncased boreholes to optimise the positioning of well screen and in existing boreholes to confirm that the screening is correctly placed. The log can also be deployed for monitoring contamination levels outside cased boreholes to indicate changes in plume composition with time.

5.5.3 Airborne electromagnetic methods

The basic principle of this method is similar to that described for the ground conductivity survey in Section 5.5 above. The transmitter and receiver coils are separated by a distance of between 5 m and 8 m and are deployed in an "aerodynamic bird", which is towed on a 30 m cable suspended from the aircraft or helicopter. A parallel grid of lines is flown at separations between 30 and 50 m, depending on the anticipated size of the electromagnetic source. The recorded data are displayed in the form of a contour map of apparent resistivity, while the shape and depth of a specific conductor can be modelled with appropriate software.

Airborne electromagnetic surveys are normally carried out as part of major programmes for mineral exploration. Some success has also been achieved with the method in large-scale groundwater studies, but in general its high cost mitigates against its use in environmental applications. In contaminated ground areas and hazardous waste sites it may be economically viable, but should be combined with aeromagnetic and airborne radiometric surveys.

5.5.4 NDT electromagnetic methods

Impulse radar

Impulse radar uses the same instrumentation as that described in Section 5.5 for ground penetrating radar, but usually deploys higher frequency antenna (above 1 GHz) to obtain the resolution required, over the shorter distances involved in the testing of a structure. In some instances, such as the evaluation of the internal structure of a masonry arch bridge or a harbour dock wall, greater penetration of the electromagnetic energy will be required and lower frequency antenna in the range 100 to 500 MHz will be used. The range of potential uses for impulse radar in the non-destructive testing of civil engineering structures is so wide, that it is likely that the method will undergo significant development in this area over the next few years. For example, the Concrete Society (Anon, 1997) has published a technical report giving guidance on the radar testing of concrete structures, while the Highways Agency has commissioned a study of the use of radar in the evaluation of masonry arch bridges.

Conductivity meter

The electromagnetic conductivity of a masonry structure is a function of the degree of the water saturation of the materials within it and their electrical properties. Electromagnetic fields are propagated into the structure and variations are monitored and recorded. These provide geometrical and electrical information on the materials investigated and their degree of saturation. The simple equipment in current use is non-contacting. No surface mounted devices are required and it can be deployed rapidly.

Water ingress and moisture movement into structures is important in terms of structural durability. For example, if the road surface of a brick masonry-arch bridge allows water entry, the soil-fill above the arch barrel may become saturated. This can result in degradation of the mortar between the bricks, giving rise to premature failure. Another example of water inclusion in masonry structures is due to the moisture capillary rise from the building foundations. The architect or engineer may want to know the actual height of water rise in the inside of the wall – this height is generally greater than that observed on the external wall surface.

In the majority of the cases, salt content is associated with water content in the structure. This phenomenon can cause damage to the structure and the rapid decay of a masonry wall, which is a cause for concern. A non-invasive method of determining moisture movement behind or inside the masonry walls is of significant engineering value.

Conductivity measurements can be used to assess:

- moisture content in the masonry
- salt content in the masonry associated with moisture content
- height of moisture capillary rise
- thickness of the masonry wall
- multi-wythe nature of the masonry wall
- composite construction of the masonry structure

- presence of voids or inhomogeneities in the wall
- presence of metal reinforcements, pipes, drains, etc in the wall.

Figure 5.24 shows the results from a conductivity survey on the wingwall of a 100-year-old masonry arch bridge. The pink shaded area represents an area of high conductivity, which is possibly related to the ingress of de-icing salt and rainwater.

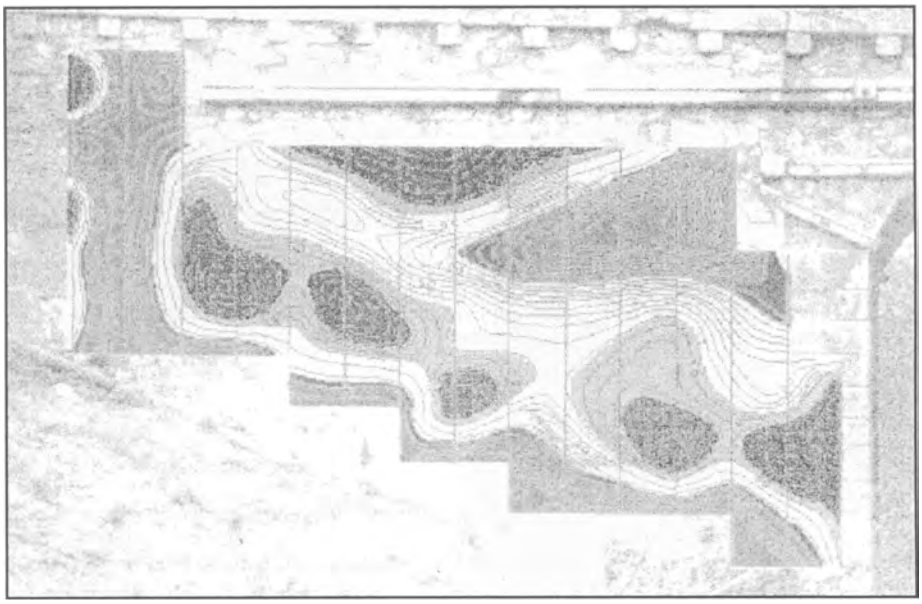


Figure 5.24 *Conductivity survey on the wingwall of a masonry bridge (from McCann and Forde (in press))* (for colour version see page 251)

Covermeter

Electromagnetic methods are commonly used to determine the location and thickness of concrete overlying the reinforcement rods, embedded in the concrete. The commercially used "covermeter" is based on the principle, that the presence of the steel rod within the concrete affects the field of an electromagnet.

The covermeter consists of two coils positioned on an iron-cored inductor. When an alternating current is passed through one of the cores, a current is induced in the other, which is then amplified and measured. The influence of steel on the induced current has a non-linear relationship with the thickness of the concrete and is also influenced by the diameter of the rod. Modern covermeters however, are designed and calibrated to accommodate these effects and with careful application excellent results can be achieved. If the concrete has been penetrated by saline water, the increased electrical conductivity of the concrete above the reinforcing rods, could affect the accuracy of the results measured on the covermeter.

5.6 RADIOMETRIC METHODS

5.6.1 Radiometric surveying

The principal form of radioactivity detected in rocks and sediments arises from the emission of gamma-rays, which are monitored using gamma-ray scintillometers or spectrometers. These instruments were originally developed for the location of uranium deposits, but are now also widely used in geological mapping and mineral exploration. Hand-held spot measurements are usually made. For surveys of extensive contamination, say for uranium mine tailings, low-level air-borne (helicopter) surveys would be made. The principal long-lived radioactive isotopes found in nature are potassium 40, thorium 232, uranium 235, and uranium 238.

In the marine field a towed sea-floor gamma ray spectrometer has been constructed to measure the natural gamma ray levels on the sea-floor. It has been used in mineral exploration and for monitoring contamination of the sea-floor by radioactive waste products.

5.6.2 Borehole radiometric methods

Natural gamma

This log uses a scintillometer to measure the natural radioactivity of a formation caused by the presence of potassium, uranium and thorium isotopes. As these isotopes occur mainly in clay minerals, it is possible to differentiate clays from sandstones and limestones, which have low natural radioactivity. The log is very useful for lithological and stratigraphical correlation. It is also useful for correlation in Coal Measures and in recognising coal seams, which have been extracted. The log also can be used for the identification of zones containing radioactive minerals, such as potash (K_2O) or uranium-rich ores.

A typical sequence of gamma ray logs from a site investigation borehole programme is shown in Figure 5.25. The Fuller's Earth beds are clearly shown dipping to the south on the logs for the borehole sequence G, A, B, H; boreholes E and F are to the north of a minor fault and show there is some bifurcation of the Fuller's Earth beds.

Gamma-gamma

This log measures the intensity of gamma radiation from a radioactive source, such as cobalt 60 or caesium 127 in the sonde, after it is back-scattered and attenuated within the borehole and the surrounding rock mass. Provided the necessary calibrations are applied to the sonde, the recorded count rate is directly inversely proportional to the formation density. The effects of variation in the borehole diameter are offset by forcing the sonde against the wall of the borehole with an excentering arm. Bulk density can be measured to an accuracy of $\pm$ 0.05 Mg/m^3. This may be improved by careful calibration of the source detectors and instrumentation, and with care in the preparation of the borehole.

The main use of the gamma-gamma log in the oil industry is the determination of formation porosity, while in engineering investigations it is the formation density that is usually derived. The gamma-gamma log is not diagnostic of lithology but, used in combination with other logs such as the neutron log, can provide accurate lithological information.

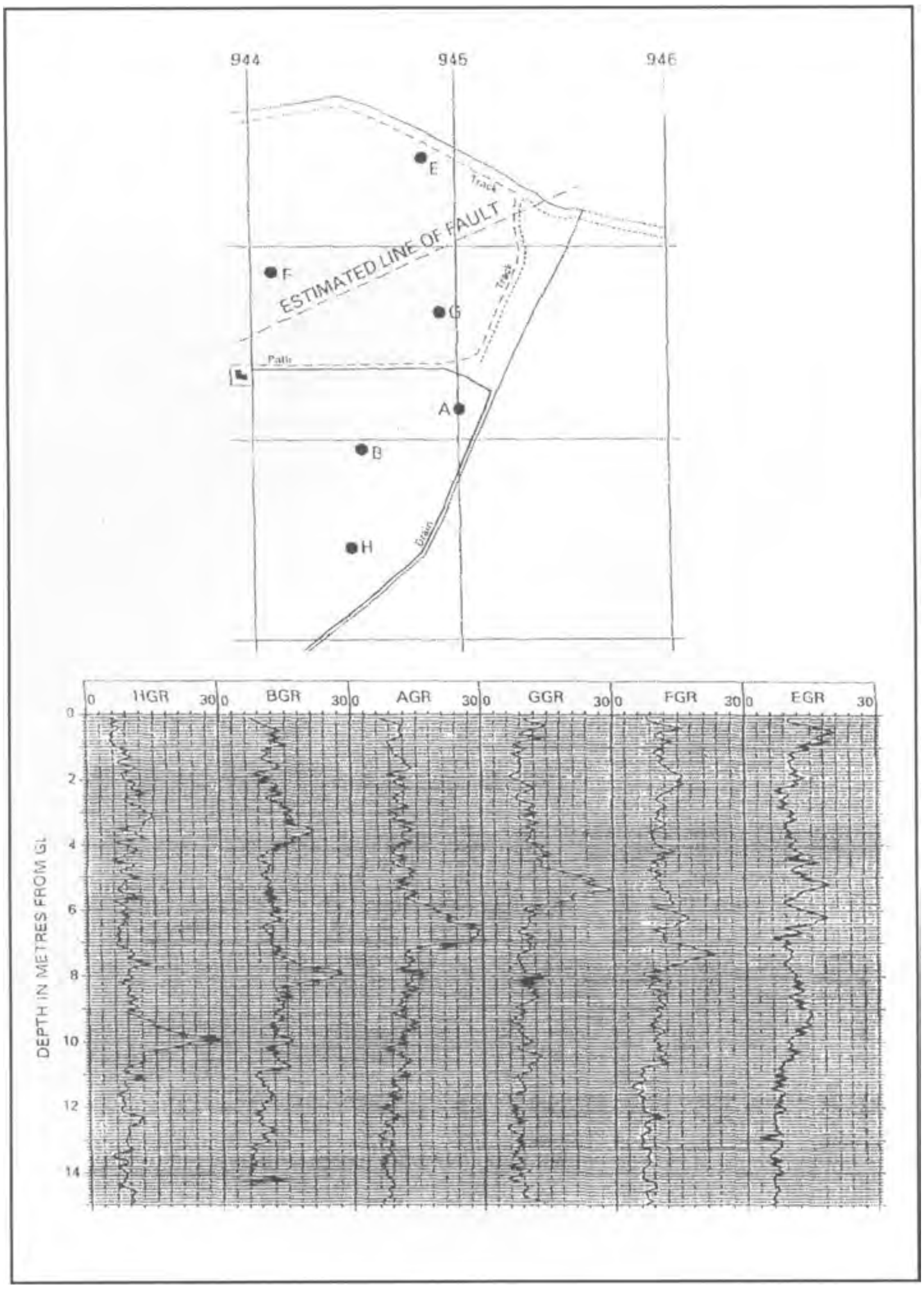


Figure 5.25 *Correlation of natural gamma logs in a typical site investigation involving closely spaced boreholes (from Cripps and McCann, 2000)*

Neutron

The neutron log bombards the formation with high-energy neutrons. These lose energy through elastic collision with various atoms, of which hydrogen causes the greatest energy loss. A detector in the sonde records the number of returned neutrons, which is inversely proportional to the hydrogen content of the formation. As most hydrogen is contained in the water held in the pores of the rock, the log gives a good measure of its porosity. The neutron sonde responds to the total water content of the formation, and as this would include absorbed water associated with clay minerals, the porosity measured on a shale for example, will be greater than the effective porosity of the formation. The log is usually very subdued in low porosity crystalline rocks, but the presence of a fracture zone will artificially increase the effective porosity to reduce the neutron count.

5.6.3 NDT Radiometric methods

Very short wavelength electromagnetic radiation (X-rays, gamma-rays or neutron rays) will penetrate through solid media, but will be partially absorbed by the medium. The amount of absorption that occurs will depend upon the density and thickness of the material, which the radiation is passing through, and also the characteristics of the radiation. The radiation that passes through the material can be detected and recorded on either film or sensitised paper, viewed on a fluorescent screen (such as a television screen) or detected and monitored by electronic sensing equipment. In the strictest scientific terms, radiography implies a process in which an image is produced on a film. When a permanent image is produced on radiation sensitive paper, the process is known as paper radiography.

Radiography is capable of detecting any feature in a component or structure, provided that there are sufficient differences in thickness or density within the test piece. Large differences are more readily detected than small differences. The main types of defect, which can be distinguished, are porosity and other voids and inclusions where the density of the inclusion differs from that of the basic material. Generally speaking, the best results would be obtained when the defect has an appreciable thickness in a direction parallel to the radiation beam. Planar defects such as cracks are not always detectable and the ability to locate a crack will depend upon its orientation to the beam. The sensitivity possible in radiography depends on many factors, but generally if a feature causes a change in absorption of 2 per cent or more compared to the surrounding material, then it will be detectable.

Radiographic techniques are often used for checking welds and castings and in many instances radiography is specified for the inspection of components, as discussed above.

X-ray systems

X-rays require an instrumentation system employing an electrically powered linear accelerator to generate X-rays. As will be appreciated from the medical use of X-rays, significant health and safety precautions have to be taken by personnel in the vicinity of an X-ray and suitable protective clothing must be worn. These precautions are for low-powered X-rays, which are adequate for checking fractures or bone structure, shapes (such as the spine), where only low doses of radiation are necessary. However, in electrically "lossy" materials such as concrete, significantly higher doses of X-ray are required to be effective, which means that safety becomes paramount. Higher dosages of X-ray can be used where the component can be put into a sealed container (as occurs when X-raying baggage at an airport), but when working on a construction site this is a totally different application. A specialist, and potentially cost-effective, application of radiography includes checking for voiding in post-tensioned bridge structures. The instrumentation system used in this instance is the "Scorpion System", but the very high dosage of X-rays means that an exclusion zone, of up to a thousand metres, may need to be cleared of human beings and cattle. However, the plus side is that the Scorpion System, with high powered X-ray, gives an instant view of the inside of a post-tensioned bridge duct on a television monitor, which is then video recorded for future analysis.

Gamma-ray systems

Gamma-rays use a nuclear source and require the nuclear probe to be brought into contact, or into a hole drilled in the structure. This technique is potentially less dangerous than X-rays provided that the nuclear source is carefully controlled. The gamma-ray procedure emits far less power than the X-ray system however, and the images tend to be weaker and require longer "stacking" time. Thus, a survey that might take thirty minutes using a high powered X-ray, would take several hours using a gamma-ray procedure.

In terms of safety, if something goes wrong the X-ray, being an electrically generated system, can be switched off. The gamma-ray system, in contrast, cannot be switched off because it is a nuclear source. Gamma-ray sources cannot be carried in a conventional vehicle, because they require the special facilities of a lined and protected box and the necessary warning signs. The vehicle cannot be randomly parked, for example in service stations on motorways. Special licences have to be obtained for the carriage and use of gamma-ray sources. There are also limitations concerned with the health of workers exposed to gamma-rays, particularly those who are vulnerable because of health problems or pregnancy.

Neutron radiography

Neutron radiography is an established non-destructive testing technique, for identifying internal details, materials and assembly. A neutron flux, which passes through an object, is differentially attenuated by the various materials present. This differential can be recorded on film, as the flux emanates from the specimen, revealing details of the composition of the object. This is similar in many respects to X-ray radiography, in which X-rays constitute the radiation flux. Neutron radiography has recently been used to study internal cracking patterns in concrete, by causing the cracks to absorb a contrast agent, which readily attenuates neutrons.

Neutron radiography has a place in laboratory testing, but cannot easily be used on large-scale structures, such as bridges. Some of the emerging technologies may be more appropriate for non-destructive testing of concrete, than some of these "more dangerous" techniques. Radar techniques (which are still at a development stage) can be more effective for investigating moisture and voiding in concrete and the positions of reinforcement bars. On the other hand, radar cannot penetrate metals.

5.7 THERMAL METHODS

5.7.1 Infra-red thermography

Infra-red thermography is a process in which heat at any temperature can be converted into a thermal image, using specialised scanning cameras. Buildings or structures with defects, such as debonding render and mosaic or delaminating concrete, emit differing amounts of infra-red radiation. If a concrete surface with an even colour and texture is viewed with an infra-red camera it will appear quite uniform when the concrete is free of defects. However, if there are any cracks or delaminations within the concrete, the surface will heat up faster (under solar irradiation) in these areas and hot spots will be observed in the thermal record. These areas can then be examined more closely and marked on the structure for identification and future investigation. This method has proved to be most effective as a reconnaissance tool, for the rapid assessment of large buildings, particularly high-rise apartment blocks.

Infra-red thermography is being used increasingly in the aerial survey of landfill sites, as a result of advances in the development of portable, high-sensitivity thermal imagers. By combining this equipment with the mobility of a helicopter, it is possible to assess a number of landfill sites, to detect the leakage of methane gas and leachates escaping from the sites economically. The method produces an image of temperature variations over the ground surface. Ground investigations are essential to calibrate any temperature anomalies against the presence of methane leaks or the movement of leachates. The method should not be confused with infra-red photography, which is used widely in surface vegetation studies.

5.7.2 Thermal conductivity

Knowledge of thermal conductivity is essential, for the estimation of heat flow, in the increasingly important fields of geothermal studies and disposal of radioactive wastes. It is also needed for design of buried pipelines and storage facilities for hot or cold fluids.

There are a number of theoretical models, which can be used to predict the conductivity of sedimentary rock. In the absence of anisotropy, the geometric mean model is satisfactory:

$$k = k_w^{w}\, k_s(1^{-w})$$

Where k_s is the thermal conductivity of the matrix, k_w is the thermal conductivity of water (0.6 W/mK) and w is water content as a decimal.

Field measurements

The measurement of thermal conductivity *in situ* is limited to soft materials, eg sea or lake bed sediments or surface soils, into which a probe can be inserted. Thermal conductivities are usually measured during heat-flow tests. A probe is inserted into the sample, and after the temperature gradient has been measured, it is heated by a line heat source and the thermal conductivity determined between temperature sensors.

A needle probe technique has also been used. Needle temperatures are measured in a Wheatstone bridge thermometer. With a current of 150 mA the heating unit provides an output of 10 W/m. Needle probe temperatures are measured at intervals of 10 s with an accuracy of $\pm 3 \times 10^{-5}$ °K. Von Herzen and Maxwell (1959) describe how to calculate thermal conductivities by applying a linear least-squares fit to the linear part of the temperature-log time curve. Other methods use the exact integral solution of the transient cylindrical probe problem.

Laboratory methods

Thermal conductivities of rock are determined in the laboratory, by either needle probe methods or the classical divided-bar technique. These methods are well described in material science texts. The divided bar method needs calibrated quartz standard discs of varying thickness and a very high quality finish on the ends of the rock cylinder. Sass *et al*, (1971) describe the estimation of thermal conductivity using rock fragments.

Measurement on argillites in the laboratory is described by Midttomme *et al*, (1997) using a divided bar method. Laboratory measurement of the thermal conductivity of soils is sometimes required for the design of ground freezing, and to do this under cryogenic conditions is extremely difficult. Techniques, which do not provide confining pressures, give misleading values as a result of shrinkage and microcracking. In clay soils, porewater may migrate to microfissures.

5.8 MEASUREMENT OF GEOPHYSICAL PROPERTIES OF SOILS AND ROCKS

Many of the geotechnical properties of rocks and engineering soils can be determined indirectly from geophysical measurements. Bulk density, porosity and permeability are examples of physical properties that can be obtained in this way. The most important geophysical properties, in this respect, are electrical resistivity and seismic wave velocity, as they can be used directly in engineering studies. Some derived properties need to be modified, usually according to semi-empirical constitutive relationships. For example, the modification of elastic moduli, determined by elastic wave propagation methods to take account of larger strains, varied strain rates, different mean effective stress and duration. Other geophysical measurements can be translated by empiricism into useful engineering indices (eg rippability from seismic velocity, corrosivity from soil resistivity), as discussed in Section 8.

The emphasis in this section is upon field geophysical measurements, but laboratory tests are also necessary. These are carried out on samples of rocks, engineering soils and groundwater, mainly to assist in the interpretation of geophysical results obtained in the field. For example, magnetic susceptibility and remanence values from rock and soil samples enable a quantitative interpretation of magnetic anomalies, obtained from traversing over dolerite dykes. Laboratory measurements of compressional and shear wave velocities can be used to calculate the dynamic elastic moduli of rock samples, for comparison with *in-situ* values. Measurements in the laboratory could also be used to determine the sensitivity of geophysical, and corresponding geotechnical properties, to possible temporal changes in ground conditions, such as moisture content, temperature and pressure.

The increasing use of electromagnetic methods, including GPR, has drawn attention to the fundamental physical properties to which they respond, and the possibility that useful information about engineering/environmental characteristics of the ground may be related to such properties (Mahrer, 1995). It has been reasoned that these properties, reflecting the fundamental micro properties of soils, may be linked to geotechnical properties, including soil compressibility and consolidation. Dielectric permittivity at low EM frequencies has received particular attention (Klein *et al*, 1997).

Laboratory and field test results are of little value, unless standard test procedures are followed and the samples are fully described. Where standard procedures and equipment are not available, a full description of the equipment and methods used is essential. Many laboratory tests are described in standards and codes of practice. It preferable for all testing to be carried out within QA/QC procedures (See 3.3.5). Sample disturbance and changes in moisture content have to be minimised and, where comparison is made with geophysical properties, an adequate number of representative samples should be obtained. Special test procedures may have to be devised and carried out, not primarily for comparison with geophysical properties, but to explore the sensitivity of those properties to conditions, which might vary with time or engineering activities. Examples could be the effects of a change in pore fluid chemistry in a soil or rock, or the effects of a change of effective stress path on shear wave velocity. In the last decade there have been significant advances in the testing of soils and rocks, such that samples are tested at small strains, approaching the order of those imposed by seismic field-testing methods.

With the improvements in imaging the ground in two and three dimensions using seismic, electric and radar methods, the ground may be "characterised" in terms of the distribution of a geophysical or derived physical property. This may lead to particular engineering design choices. For example, the selection of a design seismic action may depend on the kind of profile of shear wave velocity with depth at the site (EC8 Part 1).

Within the last decade, geophysical properties, which define the degree and extent of ground contamination, have become of increasing interest to environmental engineers (see Chapter 9). Many of these parameters are related to electrochemistry and are revealed in a new generation of electromagnetic techniques, such as ground penetrating radar (GPR) and time domain electromagnetic systems (TDEM). Familiar parameters, such as magnetic susceptibility, are used in assessing ground contamination either directly or by association with other contaminants.

Geological Society, London, Engineering Geology Special Publications

Data acquisition, processing and presentation

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 111-126
doi:10.1144/GSL.ENG.2002.019.01.06

6 Data acquisition, processing and presentation

Geophysics involves the measurement of signals, which are subsequently processed and analysed prior to interpretation and presentation, in terms of a "geophysical" ground-model. Typically, a geophysical method concerns measurements that are in turn controlled by a "geophysical" mass property. For example, if the travel time of seismic waves were the measurement, the controlling ground property would be seismic velocity. Generally, geophysical mass properties are controlled by lithology and rock mass condition. It is important to select geophysical methods that give the greatest response to the variability of geophysical mass properties, of relevance to the civil engineering problem in hand.

Forward modelling

In the past, an estimate of the "likely" property distribution, typically a simple "layer-cake" ground-model, would be used to generate a synthetic dataset that would be compared to the measurement dataset acquired in the field. This property distribution would then be varied manually, until the synthetic and field measurement datasets agreed. This "forward modelling" approach, which can be laborious, requires knowledge of the number of layers present at a site and may be tractable for simple geology only (eg 1-D) (See Chapter 4).

Inverse modelling

Forward modelling has been largely superseded by automatic numerical inversion processing, that "inverts" measurements directly into a spatial property distribution (1-D, 2-D and 3-D) without manual intervention. Inversion is at the heart of modern geophysical data processing and interpretation. It is a significant advance on forward modelling methods, because it enables the spatial distribution of geophysical properties to be displayed "tomographically" as images (eg cross-sections) that can be readily incorporated into the current ground model.

An example of these different approaches to a typical problem, would be estimating the depth to the watertable. Assuming a horizontally layered earth and using a 1-D forward model, the field dataset that is acquired comprises measurements over a gradually increasing depth of investigation. However, using modern resistivity inversion, lateral as well as vertical variability can be investigated and the watertable might be "seen" in a tomographic, cross-sectional, resistivity image, as an interface across which electrical resistivity drops dramatically.

6.1 ACQUISITION AND MEASUREMENTS

Measurements made with geophysical instruments are increasingly being used as input to automatic inversion processes, which predict ground properties directly. For example, resistivity-sounding data (apparent resistivities) are routinely inverted, generating uniform layer models, each layer having a constant resistivity (Gupta *et al*, 1997). In the past, geophysical data have often been displayed as processed measurements in map or sectional form, without error information, even though noise in geophysical measurements was known to limit both the resolution and depth of investigation. For inversion schemes on the other hand, the errors are used to weight each measurement in the inversion process. Thus in modern geophysical surveys, while errors are used during inversion processing, their effect on the tomographic output is not always self-evident.

6.1.1 Improving the quality of measurement signals

A convenient way to describe signal quality is by the signal-to-noise ratio, as used in electrical and electronic engineering. Noisy environments have low signal-to-noise ratios and reduce the maximum depth of effective investigation of the measurements. Signal-to-noise ratios control the depth of investigation of electrical resistivity investigations, for example (see Figure 6.1). Note that values of the standard deviation of a signal can mislead, because the same value could apply to signals with substantially different signal-to-noise ratios. For example, small apparently "noisy" signals can have standard deviations similar to those of larger apparently "noise-free" signals.

The most effective way to improve signal-to-noise ratio is to remove or reduce the noise, eg use water electrodes to improve ground contact in a resistivity survey, cover geophones with soil or sandbags in windy conditions. Careful electrical screening and mechanical isolation may reduce external noise levels during geo-electric and seismic surveys, respectively. If the source of the noise is known, steps should be taken to minimise the noise for the duration of the survey. This is particularly important for resistivity surveys that can be highly susceptible to electrically powered machinery. Noise due to wind and rain can be a problem during shallow seismic surveys, if they are not anticipated by measures such as burial. Environmental noise tests are advised before and after surveys with periodic calibration at a known test site.

The next most effective way of improving the signal-to-noise ratio is by increasing the power of the geophysical source, eg the magnitude of the current passed or the energy of a seismic impact. Larger signal-to-noise ratios could be generated by changing the survey design, eg by increasing the dipole spacing during a resistivity survey or by using active geophones. While being lower in instrumental noise, signals from active geophones can be "contaminated" by environmental noise that has remained constant in relative terms. Examples of this effect would be electromagnetic noise during a resistivity survey increasing linearly with the spacing of the potential dipole, and wind noise during a seismic survey that is amplified, together with displacements, due to the transmission of seismic energy from the source.

Signal-to-noise ratios can be increased by averaging repetitive signals. In Figure 6.2, which is a seismic survey using a borehole sparker source and a surface geophone, the wind and non-coherent EM noise has been successfully removed. After averaging 100 shots, the travel time or "time of flight" of the seismic pulse can be assessed with far greater confidence than using one shot.

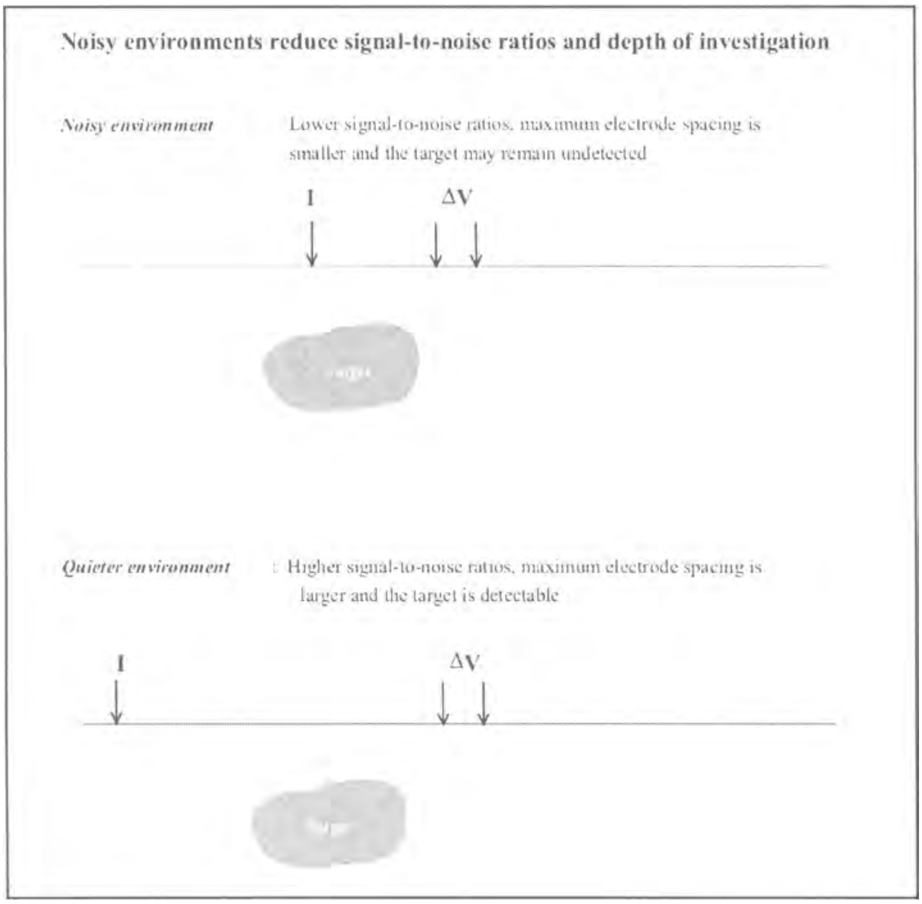


Figure 6.1 *Noisy environments reduce signal-to-noise ratios and depth of investigation*

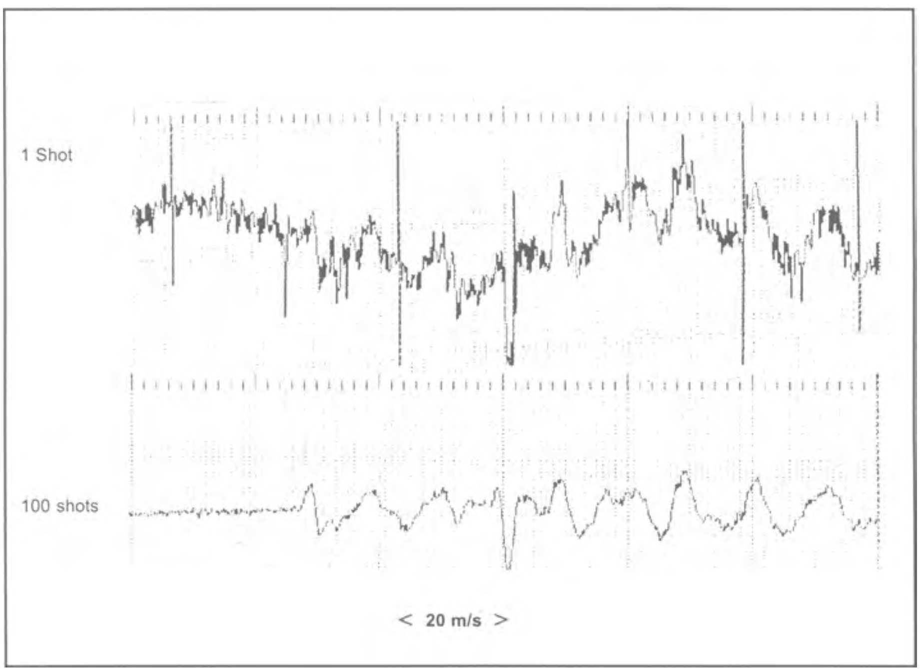


Figure 6.2 *Signal quality improved by averaging repetitive signals*

Geological "noise" is pervasive and is normally associated with features that cannot be accommodated by the survey and its interpretation. Geophysical surveys by their nature and scale are relatively broad brush in their characterisation of the ground. Therefore geological models, derived from such surveys, entail approximations. Until recently, heterogeneity associated with 3-D geological structure has necessitated relatively large approximations. In Figure 6.3, heterogeneities smaller than the spatial resolution of a technique can still make a substantial contribution to the measurements, constituting a source of unwanted signal in addition to instrumental noise. Here the measurement ((V) will change substantially if the electrodes are moved away from the near-surface heterogeneity. The role of geological heterogeneity is increasingly being researched using high-resolution 2-D and 3-D surveys, which show promise in gradually characterising the subsurface, at a resolution that will substantially reduce "geological noise" in heterogeneous environments (McMechan *et al*, 1997; Turberg *et al*, 1994).

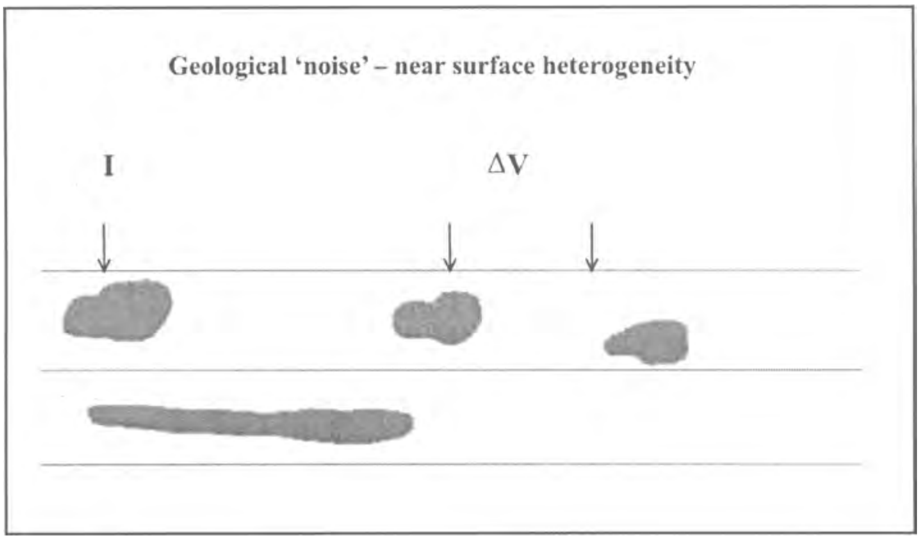


Figure 6.3 *Geological "noise" from near-surface heterogeneity*

Geological variability can be removed by taking differences between successive surveys, when a parameter of interest has changed, eg water content. Figure 6.4 shows the monitoring of fluid movement in a simulated aquifer using resistivity measurements. The upper pane shows the background (sand-filled trench in clay); the lower panels show time-lapse monitoring where conductive water has travelled from left to right.

If temporal changes in a parameter are required, the effects of geological structure and heterogeneity can be largely eliminated, and subtle changes enhanced, by normalising the results to the background dataset as shown in Figure 6.4 (eg see Jackson *et al*, 1992; Steeples and Nyqyist, 1995).

Signal enhancement is now commonplace in geophysical instruments. Computers interfaced to self-recording digital systems have enabled orders of magnitude more data to be collected compared with a decade ago. Automatic positioning systems are increasing this trend still further, making reconnaissance mapping very attractive.

Previously, enhancement had been limited to analogue filtering and the design of the survey, eg geophone clusters to reduce surface waves in seismic reflection surveys, or an increased potential dipole separation to increase the measured voltage. Analogue filtering of seismic events is often undesirable however, because it introduces small phase shifts in the waveforms, and increasing the separation of the electrodes reduces the resolution of resistivity surveys. Computer techniques can overcome both these problems. Digital filtering does not introduce phase shifts. Averaging repeated measurements increases small signals compared to the background noise. Common depth point (CDP) stacking has been successfully applied to shallow seismic reflection as shown in Figure 6.5. CDP processing of seismic reflection data, developed for oil exploration, combines arrivals reflected from the same point. It has been applied successfully to the shallow subsurface. In the absence of highly attenuating surface layers (eg dry materials), the seismograms depict geological structure directly (Miller *et al*, 1995).

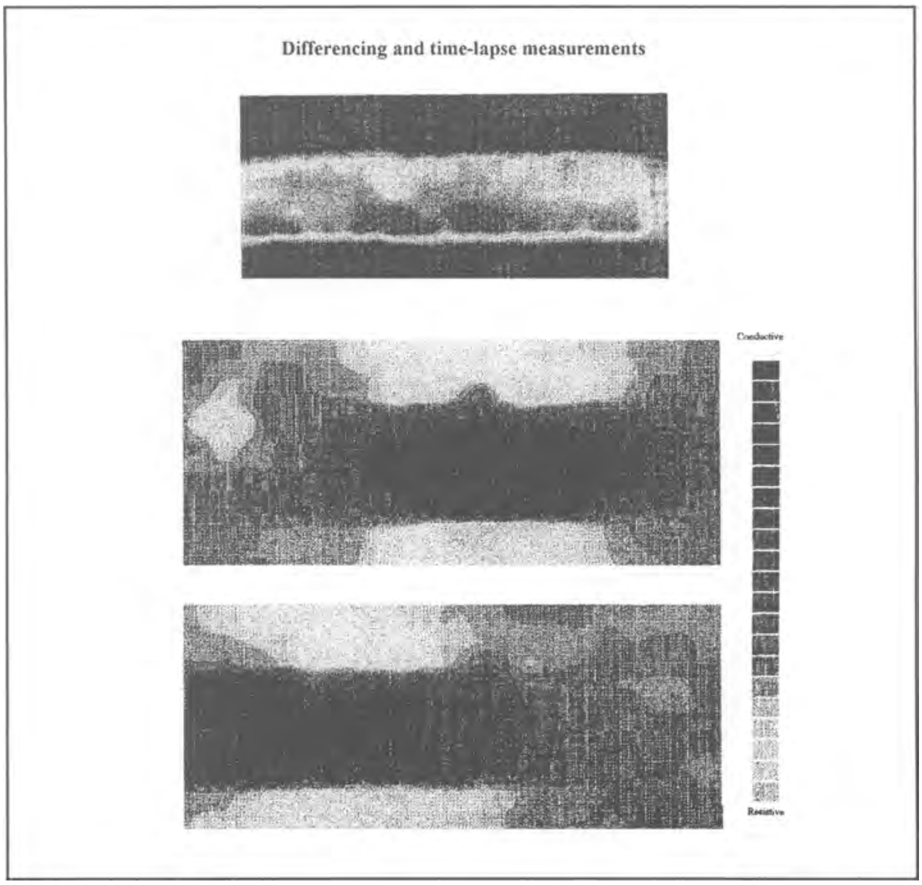


Figure 6.4 *Differencing and time-lapse measurements to remove geological variability*

Signal averaging is included in many geophysical instruments. Averaging increases the signal-to-noise ratio by the square root of the number of measurements. Although the magnitude and distribution of current, flowing during geo-electric measurements, can be repeated exactly, repeatable seismic sources may not be available. In contrast to explosives, which disturb the ground, and manual hammer impulses, being unsuitable for large numbers of blows, the borehole "sparker" source is an exception (Rechtien *et al*, 1993; Jackson and McCann, 1997), as it is automatic and repeatable without disturbing the borehole.

Improved signal-to-noise ratios allow the use of greater electrode separations (ie the measurement of smaller voltages) in resistivity soundings and longer geophone arrays in seismic refraction surveys, enabling deeper horizons to be investigated. In favourable conditions a maximum current depth base of perhaps 400 m in resistivity soundings and a maximum geophone spacing of 100 m, for a seismic refraction survey using a hammer source, is to be expected. If greater depths of investigation are required, more powerful energy sources should be considered, eg at least 200 m for resistivity soundings and explosives ,or specialised devices for seismic refraction surveys.

There is a need for careful consideration of equipment performance at the design stage of a survey, when geological input is essential to guide the assessment of the resolution and depth of investigation required.

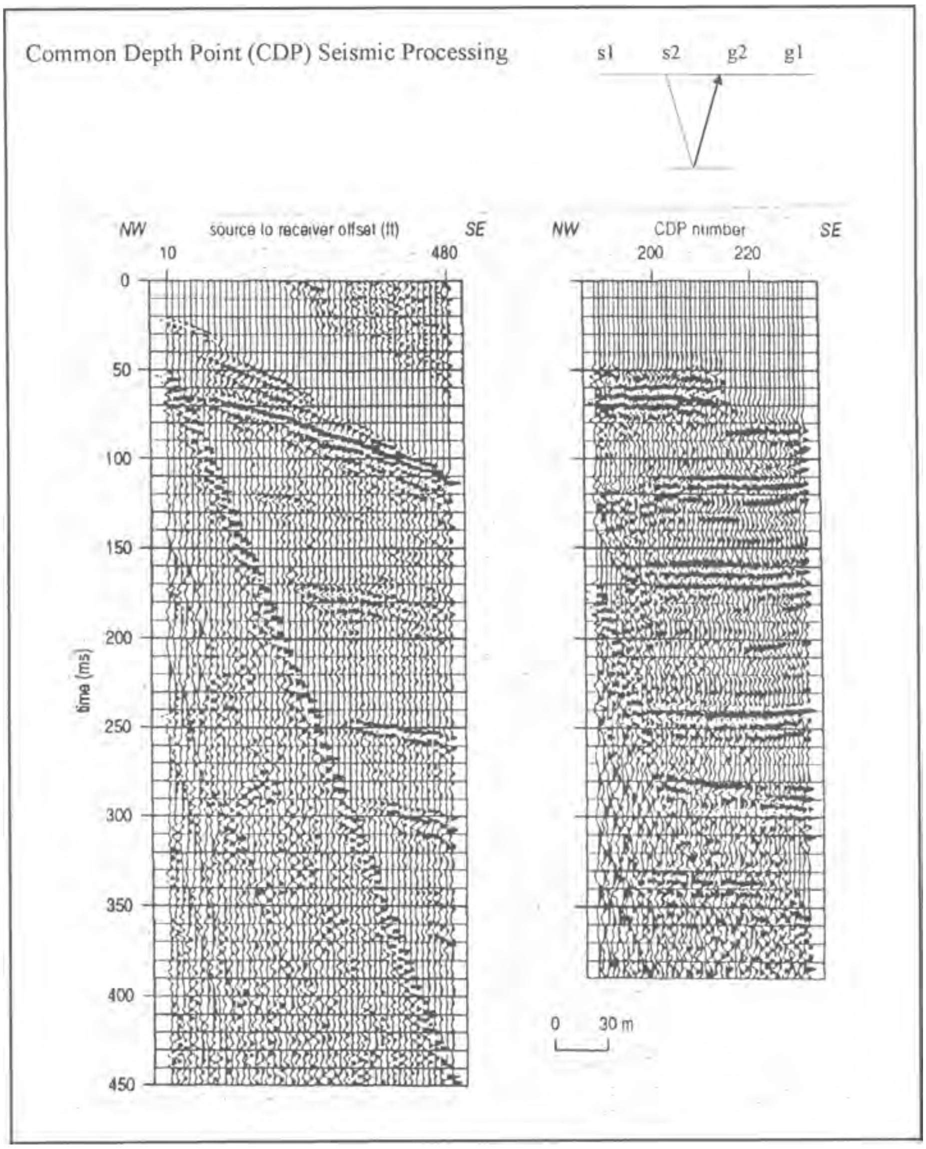


Figure 6.5 *Common depth point (CDP) seismic processing (after Miller* et al, *1995)*

6.1.2 The significance of errors

Acquisition technology has developed to an extent where analogue signals are routinely digitised at 16 bit, inferring a dynamic range of 1 to 65 000. This resolution is in excess of that required to characterise the subsurface, given the uncertainties in the measurements and the geological heterogeneity that cannot be incorporated into associated modelling and inversions. While shallow marine seismic reflection surveys typically use 16-bit resolution for analogue-to-digital conversion, the maximum noise levels for use of this dynamic range are far lower than typically experienced on land. Operational noise on land is often high for cross-borehole seismic surveys. This is because typically, sites are still under construction, resulting in low signal-to-noise ratios, which can be adequately recorded using lower acquisition resolution (eg 12 bit), given the averaging process has a far higher resolution.

Inverting multitudes of measurements into geophysical properties is now becoming the method of choice and requires knowledge of the error associated with each measurement. As mentioned above, these errors are used to weight each measurement and are thus an essential component of the acquisition method. The "quality" of the fit achieved during inversion is described using chi-squared statistics, also requiring knowledge of the errors and their distribution

In addition to guiding the inversion, errors in measurements become more significant as the depths of investigation increase, because greater changes in inverted properties are required to reduce the differences between the field measurements and the synthetic ones, calculated using the current values of the inverted properties. The root mean square (RMS) misfit quantifies the match between the field and synthetic measurement sets, as described in Box 6.1. When the errors have been confidently identified, a RMS misfit close to unity should be used to terminate processing; smaller values indicate the inverted properties may have a changed substantially in response to noise. If a RMS misfit is not quoted, it is difficult to assess the impact of errors, and "percentage fits" may be misleading.

6.2 PROCESSING AND INVERSION TECHNIQUES

The personal computer (PC) has now reached a stage of development where it pervades all stages of geophysical investigations. It can be argued that this technology has enabled geophysics to advance to the stage where non-invasive site investigation is technically feasible. Interfacing self-recording digital geophysical instruments to powerful portable PCs is routine.

Box 6.1 *Statistics used in geophysical inversion*

$(RMS)_{\text{misfit}} = \sqrt{(x^2/N)}$

$x = (\Sigma(M_{\text{field}} - M_{\text{synthetic}})^2/\ \sigma^2$

M_{field} = field measurements

$M_{\text{synthetic}}$ = measurements calculated from inverted property values

σ = standard deviation of field measurements

N = number of measurements.

Geophysics has always required computing power to process and model measurements, and for the first time computing power is both powerful and cheap enough to be used routinely. Methods are becoming standardised, the use of preliminary interpretations on site is becoming the norm, and data processing is keeping pace with data acquisition.

This situation has been facilitated by standardisation in the PC market where large production volumes enable the newest, high-performance technology to be sold cheaply and the development of universal software and data formats.

6.2.1 Geophysical processing techniques

Common depth point (CDP) stacking of seismic reflection data is an example of complex data processing that has become routine, as shown in Figure 6.5. CDP stacking concerns the combination of all seismic rays that have been reflected from the same point, each ray propagating at a different angle to the vertical and using different sources and detectors. The example shown in Figure 6.5, illustrates both the suppression of direct arrivals and the enhancement of reflections.

6.2.2 Inversion of measurements

Using a mathematical process to estimate the distribution of physical properties in the subsurface, directly from a dataset of geophysical measurements, is known as inversion. It is revolutionising the interpretation and display of geophysical surveys, displaying sectional geological structure in ways that are having a similar impact to that of seismic reflection profiling in the 1970s.

Typically, inverting geophysical measurements requires:

- a set of measurements and their errors
- starting values of the unknown geophysical property "pixels" (eg 2-D resistivity cross-section)
- a means of calculating "synthetic" measurements
- a constraint on the property "pixel" distribution and the rate of change of each synthetic measurement, with respect to each property "pixel".

Figure 6.6 is a simplified explanation of geophysical inversion. The geophysical field surveys acquire measurement datasets, which are "inverted" into estimates of the spatial distributions of geophysical properties, such as resistivity and *P*-wave velocity.

The inversion process selects a property distribution that minimises the difference between the real and synthetic measurements subject to a constraint, which stabilises the process.

A common approach has been to use the idea of Occam's razor, to justify constraining the roughness of the inverted parameter distribution, during the inversion procedure. Occam's razor can be expressed as: "the simplest theory to fit the facts **well** should be preferred" (Garrett, 1991). More formally, this approach is referred to as "smoothness constrained inversion" and has been applied successfully to both seismic and resistivity tomography / inversion (Pratt and Chapman,;1992, Sasaki, 1992). Simultaneous iterative reconstruction techniques (SIRT) however, still remain popular for cross-borehole seismic tomography (Ivansson, 1985; Phillips and Fitterman, 1995).

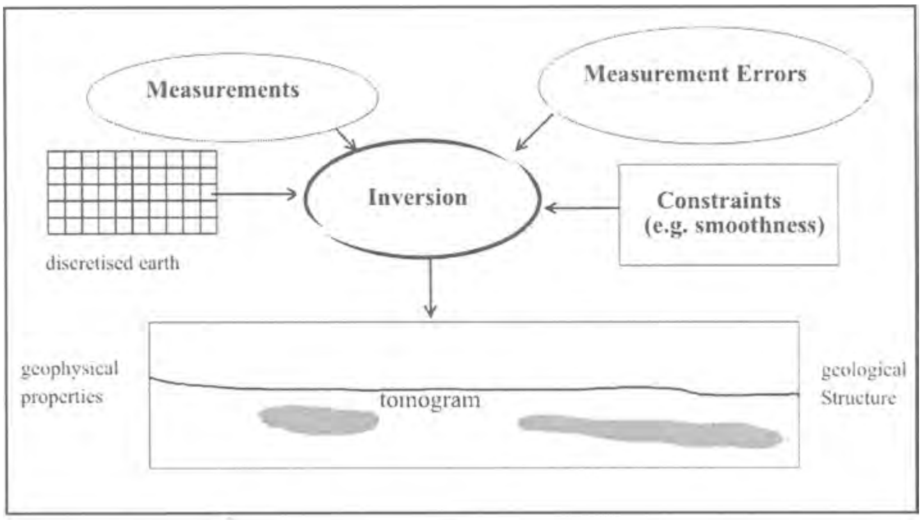


Figure 6.6 *Geophysical inversion*

Box 6.2 *Components of inversion (estimation of resistivities from measurements)*

Typical inversion schemes reduce to the equation:

$(A^TA + \lambda\ (R^TR))\ x = A^T.b$ (eg Constable *et al*, 1987)

where:

R is a matrix defining the "roughness" of the property distribution (resistivities) x.

x is the unknown resistivity vector.

b (a vector) is a weighted function of the data mismatch $(Res_i - Mes_i)^2 / \sigma_i^2$ and

$A_{ij} = J_{ij} / \sigma_i$

Where:

σ_i is the standard deviation of the *i*th measured resistance datum

J_{ij} is the Jacobian partial derivative of the *i*th measurement Mes_i with respect to the *j*th property (resistivity) x_j, ie:

$J_{ij} = \Delta Mes_i / \Delta x_j$

The standard deviation of the errors can be seen to be incorporated into both matrix *A* and vector *b*. This is a non-linear problem, which is solved by an iterative process that requires a means of defining λ. The λ parameter defines the balance between the smoothness of *x* (ie the answer) and the goodness of fit between the real and synthetic measurements.

Therefore, the measurement errors (σ) and the Jacobian (*J*) are important controls in addition to the field measurements (Res) and the smoothness constraint (λ).

Constable *et al*, (1987) describe this in detail for the inversion of 1-D Schlumberger resistivity soundings. This approach has been extended to both 2-D and 3-D inversions of resistivity survey data (eg Sasaki, 1994; Loke and Barker, 1996b).

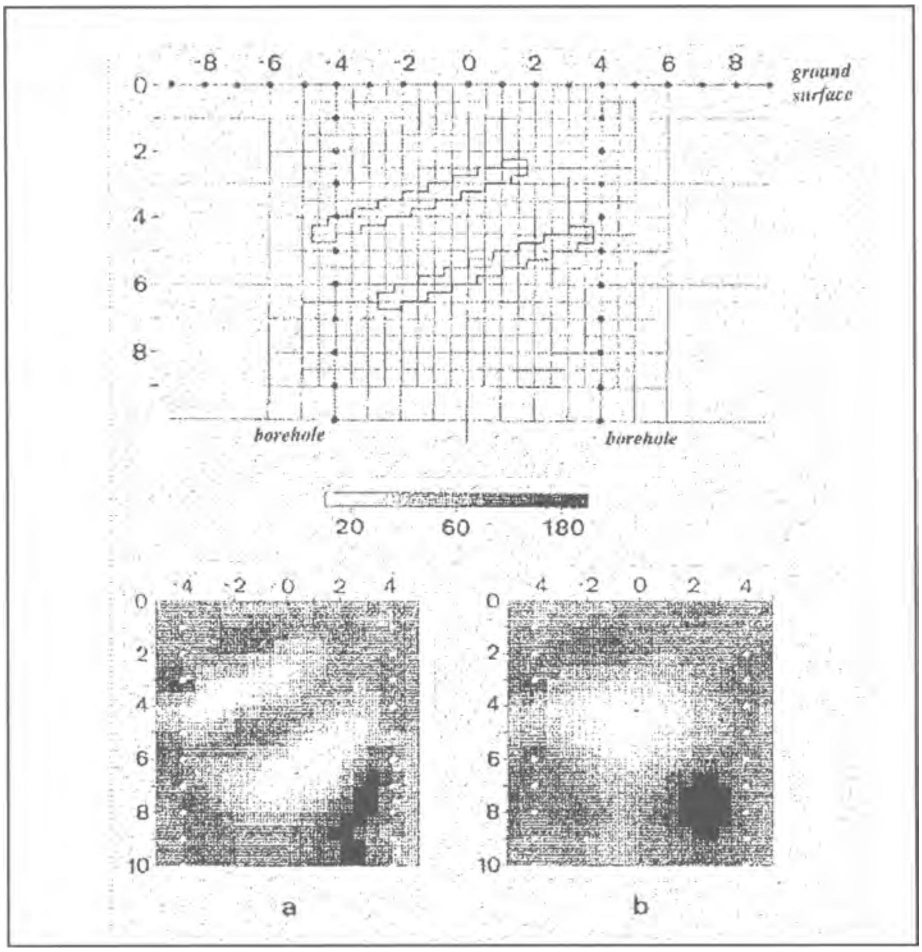


Figure 6.7 *Forward modelling in cross-hole resistivity tomography*

An example of cross-borehole resistivity inversion is shown in Figure 6.7 where the structure of a two-component model is reconstructed for one measurement style (pole-dipole, Figure 6.7(a)), but is indistinct using another (pole-pole, Figure 6.7(b)). For testing inversion, forward modelling creates a synthetic measurement dataset (see Figure 6.8 for a simplified explanation of forward modelling). The forward modelling of the 2-D tomography enables the performance of the inversion to be assessed. Two thin targets having 10 ohm-m resistivity, are set in a background of 10 ohm-m for the two measurement styles, ie (a) pole-dipole and (b) pole-pole (Sasaki, 1992). Inspection shows the benefit of optimising the measurement configuration as in Figure 6.7(a).

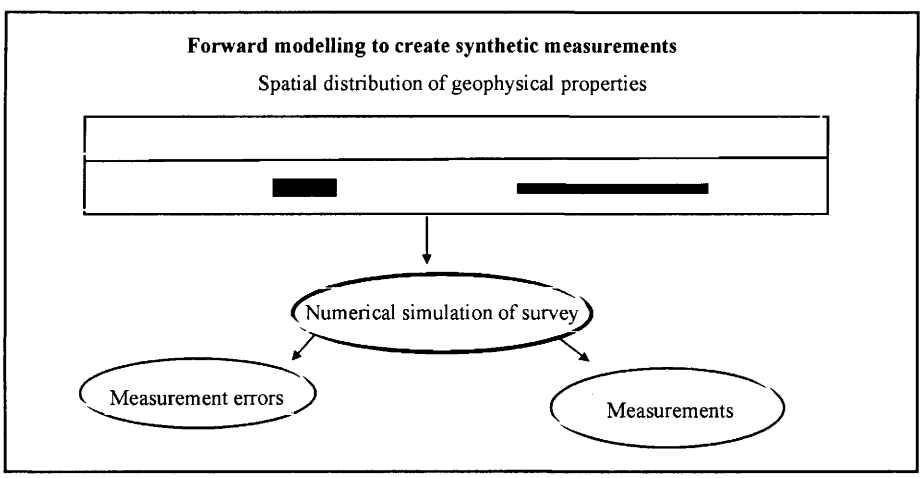


Figure 6.8 *Forward modelling to create synthetic measurements*

While published examples have demonstrated that 2-D and 3-D resistivity tomography can identify subsurface structure, the reconstruction of resistivity values can be unrealistic. Typically, the errors associated with reconstructed values of resistivity can be 100 per cent for noise-free numerical experiments, as shown in Figures 6.7 (Sasaki, 1992) and 6.9 (Loke and Barker, 1996a). Figure 6.9 represents the forward modelling of a rectangular block of 500 ohm-m, set in a background of 100 ohm-m, using two approaches. The benefits of inversion (Figures 6.9 (b) and (c)) compared with pseudo-section (Figure 6.9(a)) are evident, as are the limitations of the structural and property reconstruction.

6.2.3 The role of forward modelling

Constrained inversion techniques, as described above, do not have a unique solution, rather a family of solutions. Arriving at the "best" solution is a major challenge in resistivity inversion, and continues to be a subject of research. The use of forward modelling to create a measurement dataset enables the quality of the inversion process to be assessed objectively (as in Figure 6.8), because unlike the field case the answer is already known. Simulating a field survey allows a client to gain an appreciation of how the tomogram output relates to the distribution of physical properties because, in this case, they should be the same. This device is seen extensively in the literature and has been used to study the effect of random noise, the consensus being that increasing the value of ((see Box 6.2) compensates for errors at the expense of a smoother solution (Constable *et al*, 1987; Sasaki, 1992; Loke and Barker, 1996a).

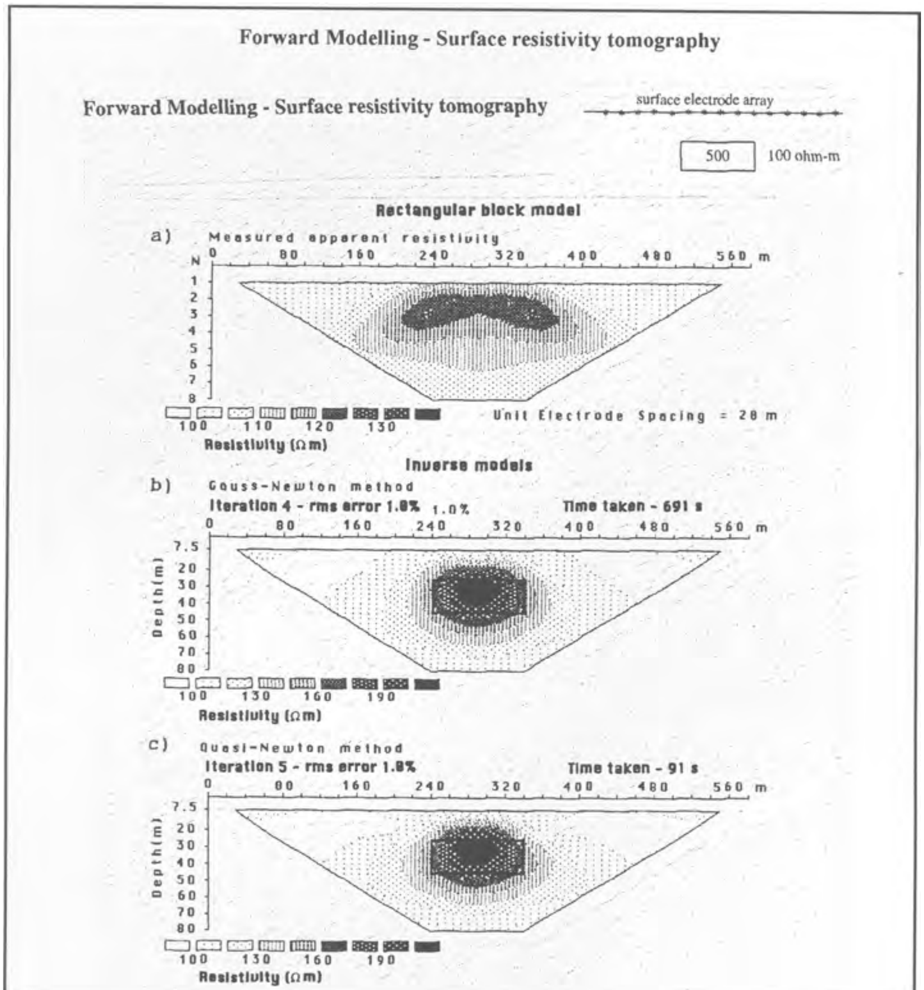


Figure 6.9 *Forward modelling: surface resistivity tomography*

Forward modelling can be used to investigate the reliability of inversions of field data. An example of this approach is shown in Figure 6.10, where a cross-borehole seismic tomogram obtained at a site containing a dipping dyke had been investigated (Jackson and McCann, 1997). Here the dyke is known to intersect one borehole and to intersect the ground surface as shown. The field tomogram, in the upper panel, has a feature intersecting the right hand boundary (ie the borehole) that is thought to be due to the dyke, while the zones of higher values near the upper and lower boundaries are likely to be artefacts due to poor ray coverage. The middle panel of Figure 6.10 displays the tomogram derived from data, obtained by forward modelling of the dipping structure alone. The dipping structure is poorly resolved away from the borehole (on the right), indicating that the field tomogram, while not faithfully imaging the dipping dyke, is consistent with its existence. This is confirmed by the tomogram in the lower panel, which displays the forward modelled result that would have been obtained had the dyke intersected both boreholes. Environmental noise precluded the use of surface detectors that would have enabled the dipping structure to be resolved.

This forward modelling approach is equally applicable to resistivity tomography, but has in general been limited to theoretical publications rather than case histories.

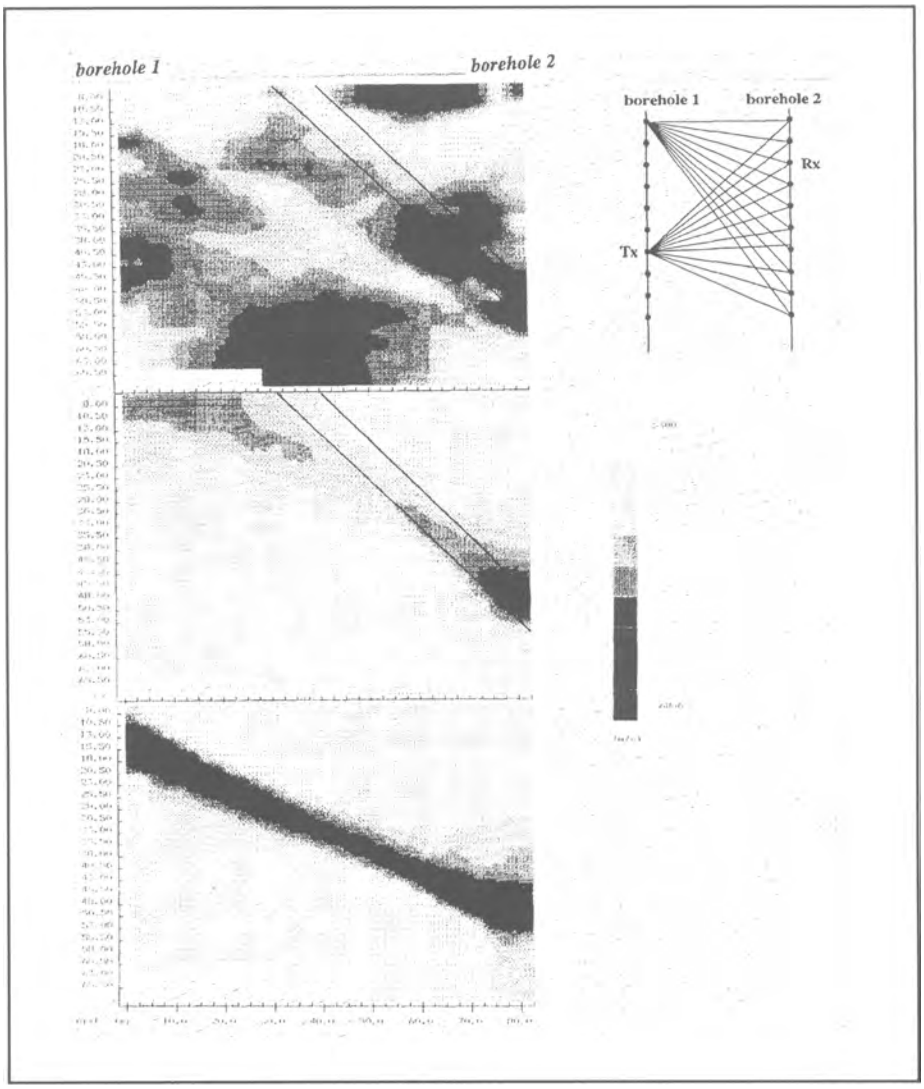


Figure 6.10 *Forward modelling: cross-borehole seismic tomography*

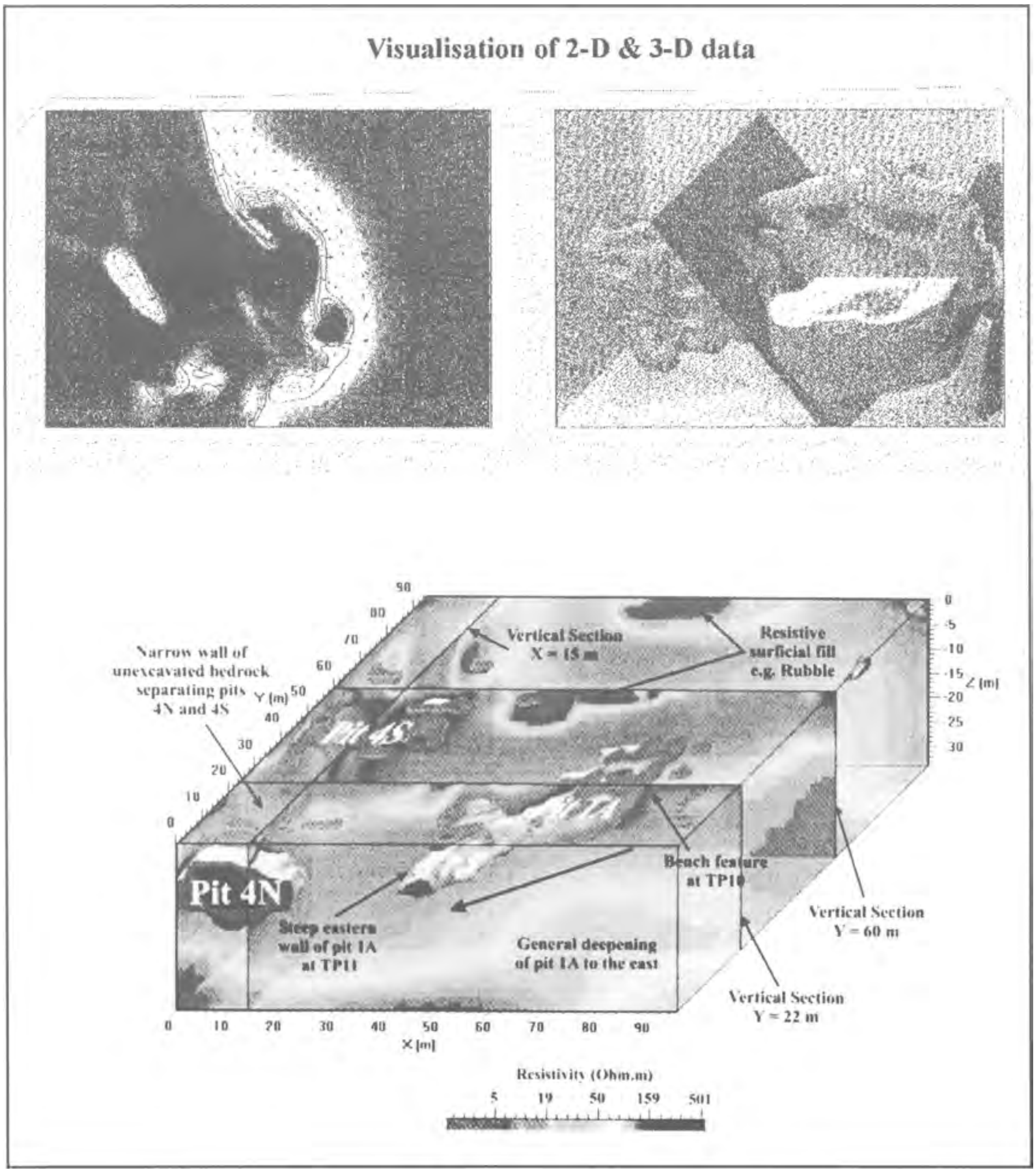


Figure 6.11 *Visualisation of 2-D and 3-D data, (a) combined vector and contour and image plot, (b) 3-D display with overlays (courtesy of Fortner Inc.) and (c) 3-D resistivity measurements characterising tar-contaminate waste deposits (Chambers* et al, *1999)* (for colour version see page 251)

6.2.4 Limitations of current techniques

The development of resistivity inversion is advancing rapidly, but at present there are limitations in two general areas:

1. Spatial and quantitative errors in the reconstructed properties.
2. Lack of quality assurance for the processing.

The spatial smearing shown in Figure 6.7(a) is typical of resistivity tomography and of the current order of errors of size and position. Reductions in the size of these errors can be expected in the future, but note there may need to be improvements in both the inversion processing and the signal-to-noise ratio of the measurements.

The process for inverting resistivity measurements described above is iterative, and may rely on subjective criteria for selection of the degree of smoothness. It is important to know the criteria for selecting the smoothing parameter and the RMS misfit of the solution in a standardised form.

6.3 VISUALISATION

Visualisation techniques have been at the forefront of development, particularly in the last five years with the transfer of sophisticated 2-D and 3-D techniques from expensive workstations to inexpensive PCs. The processing power of PCs is also economical, making them far more cost effective than workstations, with only small performance penalties. 2-D overlay plots and 3-D visualisations are now available to the geophysicist in the field using generic software, having highly sophisticated features including mathematical manipulation of image datasets, industry standard data formats and a low price from the high sales volume. In Figure 6.11 the two upper panels show a 2-D combined vector, and contour and image plot, and a 3-D display with overlays, while the lower panel displays 3-D resistivity measurements obtained from a box-core prior to inversion. Note that software packages for presenting geophysical data usually do not provide the benefits described above.

Geographical Information Systems (GIS) are standard in many geological disciplines, but as yet are not widely used in shallow geophysical studies. They appear to be an ideal candidate system, for handling and displaying data obtained during the multi-method, multi-dataset, rapid reconnaissance mapping, which is becoming increasingly popular. A GIS provides a base map on to which other data may be registered and displayed, a means of manipulating different overlaying datasets, and an interface to databases. A simple example is shown in Figure 6.12 which illustrates the classes of data that can be accommodated using GIS technology: base map at any scale, traverse line location, and contoured data in image form.

Limitations of visualisation techniques are often caused by difficulty in contouring spatially different datasets on consistent grids. This is often not a major disadvantage to geophysical surveys, as all the data will be generated as part of the work and can be gridded in a consistent way. Gridding spatially inconsistent datasets can lead to errors, because there are many techniques available, each with its own strengths and weaknesses depending on the nature of the data. Quality assurance for gridding methods used in visualisation would be beneficial. For example, Figure 6.13 shows that changing the colour scale between images can be misleading. Adjusting the colours of the upper panel provides a tomogram that appears similar to the original model (ie appears to reconstruct structure and values), but when plotted on the same scale as the model (see central panel) it can be seen to be far too small. In addition, the use of standardised logarithmic colour scales, to visualise resistivity inversions, would be more consistent with geological changes and consequently would be more "client-friendly" than linear ones. In general, the geophysics adviser should specify established software packages.

6.4 RECOGNITION OF THE LIMITATIONS OF INTERPRETATIONS

In the past, a limitation of practical geophysical surveys was the assumptions required by the interpretation methods, regarding the geological environment, eg the 1-D approximation of horizontal isotropic layers used for geo-electric sounding. As horizontal isotropic layers were rarely present, these "1-D" limitations were borne in mind during the interpretation of such sounding data. However, the move to geophysical tomography and inversion, has led to a tendency to take geophysical images at face value. This can lead to problems because geophysical techniques cannot, as yet, identify uniquely the anisotropy, small-scale geological structures and heterogeneity that typify the subsurface. Nevertheless, substantial additional knowledge and understanding of a site can be gained through the use of geophysical surveys that have been carefully designed and interpreted.

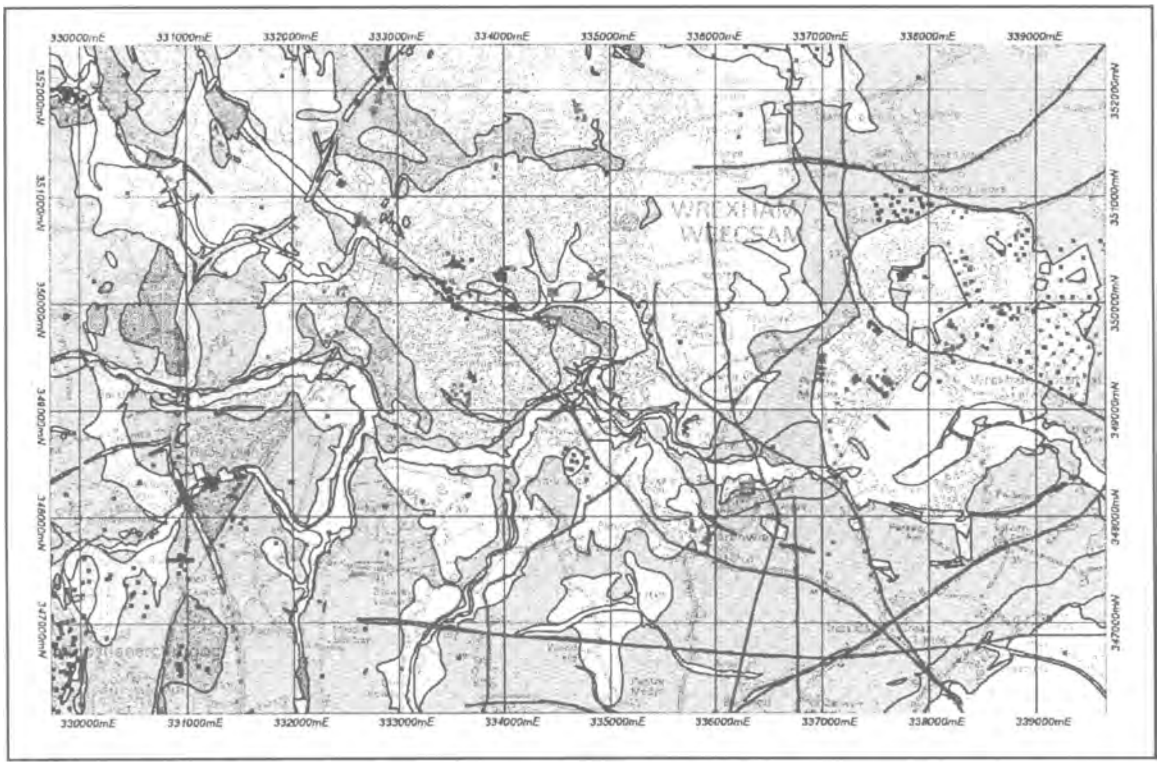


Figure 6.12 *A GIS-based map of the Wrexham area showing seismic lines (Coal Authority and DTI) and borehole locations superimposed on the geology map (generally natural and man-made superficial deposits) over the Ordnance Survey base layer (National Geosciences Information Service, Geoscience Index, British Geological Survey, Keyworth, Nottingham NG12 5GG (www.bgs.ac.uk/geoindex)*

If a survey is to be designed to be sensitive to the client's targets, the combination of desk study with field trials is increasingly accepted as a sensible way to achieve success.

Errors often control both the resolution and the depth of investigation of geophysical surveys. Consequently, an accurate knowledge of the measurement errors and their distribution is essential, particularly if the measurements are to be inverted (Press *et al*, 1996). It is important to make these limitations clear to the client before any fieldwork is attempted, and to take measures to reduce operational noise, eg by scheduling surveys during "quiet" periods. Noise generated by geophysical equipment and other associated instrumentation can be a source of error which should be minimised, eg using normal earthing procedures and testing instrumentation in a controlled environment as part of mobilisation checks.

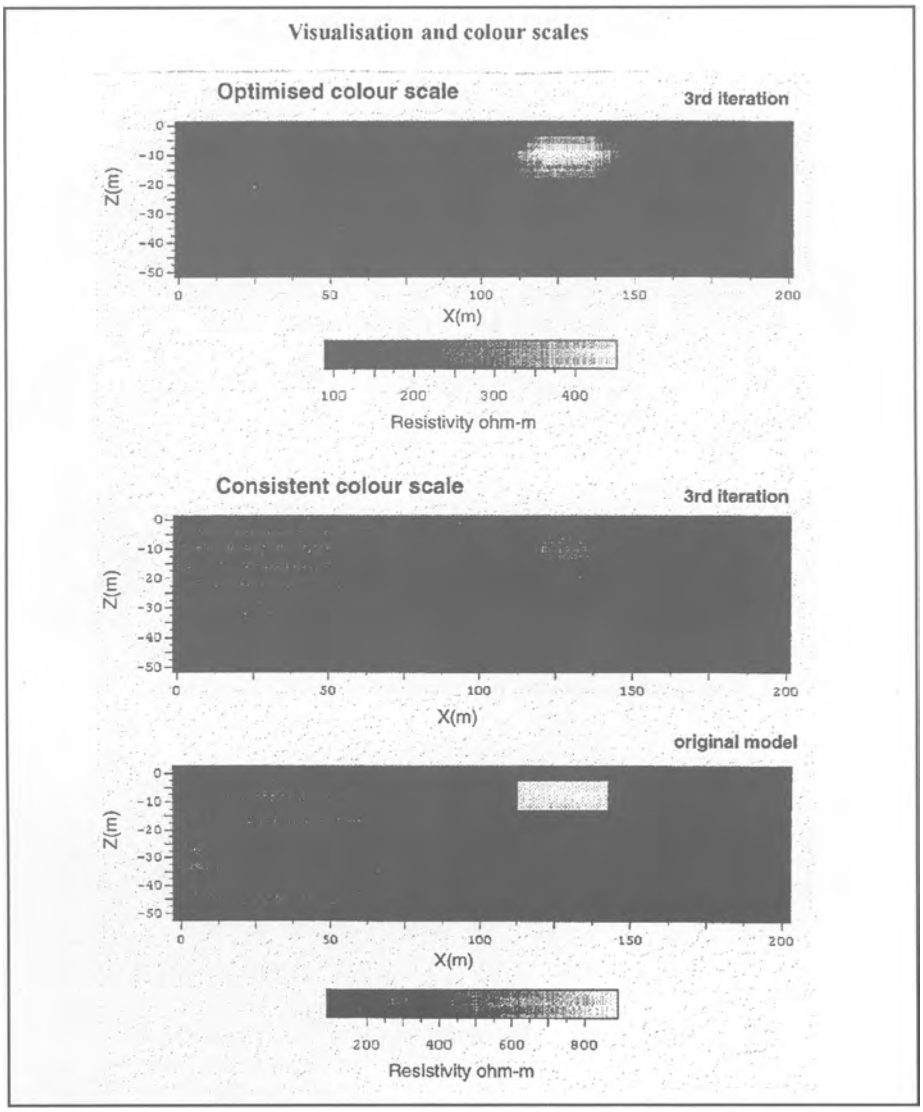


Figure 6.13 *Visualisation and colour scales: the effect of colour scale seen from a forward-modelled tomographic inversion (Jackson* et al*, 1997)*

Calibration on known sites, particularly at low signal levels, is highly recommended. The inversion process is not yet capable of reconstructing the property values as accurately as is desirable (Olayinka and Yaramanci, 2000), and there practical limitations as described above. Consequently, additional surveys should be considered if the uncertainties in the tomogram are consistent with more than one feasible geological ground model.

Spatial aspects of inverted geophysical data can be important. For example the pixel size in a tomogram may be so small, that changing its value would seem to imply a change in measurements that could be far outside the limits of practical detection. Interpolating during both the imaging process and the smoothness constraint used during inversion can result in pixels that are unrealistically small.

Feedback from clients is essential to the improvement of interpretation. This must be based on use of the best methods of presentation, and understanding the limitations of the interpretation and presentation methods, as well as the limitations of the methods of obtaining the geophysical measurements.

Geological Society, London, Engineering Geology Special Publications

Geological applications

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 127-149
doi:10.1144/GSL.ENG.2002.019.01.07

7 Geological applications

7.1 INTRODUCTION

A major use of geophysics in engineering investigations is as a tool in unravelling the subsurface geology. In this fundamental and early application, it is the geology that is the target, and engineering considerations and material properties are secondary. The simplest geological structure, which can be investigated, is a horizontal interface such as that between bedrock and overburden. Geological structures are rarely simple, and surveys have to be designed to tackle complex situations.

Geological structure can be considered as lateral variation in the properties of the subsurface rocks. In its simplest form it might be represented by a single dipping or irregular interface such as a bedrock surface. In more complex situations it might include thickness changes, faults, folds, or igneous intrusions.

The first section examines the measurement of depth to bedrock, as this is probably the most common boundary problem. Other geological structures are briefly considered under different types of geological hazard.

7.2 GEOLOGICAL BOUNDARIES

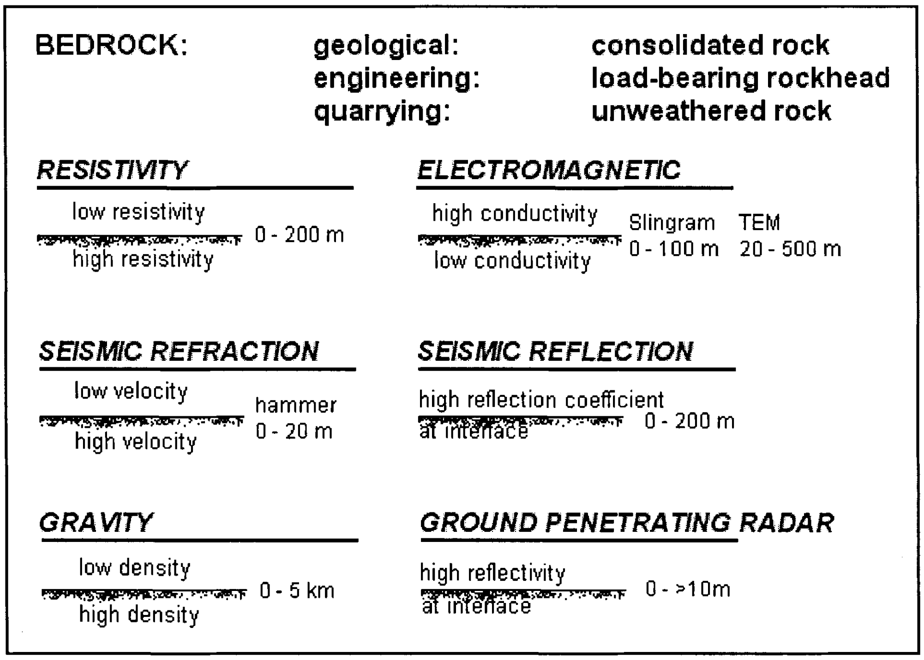
7.2.1 Depth to bedrock

The question of the depth to bedrock and its measurement is a frequent problem for engineering site investigations and groundwater studies (Fig 7.1). However, the definition of what constitutes bedrock depends very much on the field of application. A geologist might define bedrock as the older consolidated rock formations lying below unconsolidated deposits (generally Pleistocene and Recent), but an engineer might define bedrock or engineering rockhead as the level at which the rock has adequate bearing capacity for large structures. Sometimes bedrock will be defined in a contractual way in relation to the particular project. A driller at a quarry site might define the bedrock as unweathered rock with the weathered material being included as part of the overburden.

Although the definition of bedrock may vary, the problem on initial consideration is a straightforward one, ie the determination of the depth to a single interface. Usually the problem involves not only the determination of a single depth value, but an examination of the variation of the bedrock surface as might occur across a sediment-filled channel, within a backfilled quarry, or buried karstic topography. The interpretation of the results, however, might also require evaluation of the lithological variations within the overburden.

The depth to bedrock can be determined by the use of a suitable geophysical technique (Box 7.1). In many cases, however, even a simple geological or engineering situation is not simple in geophysical terms, or the geophysically defined boundary can differ in depth from that defined in engineering or geological terms. It may turn out to be more complex than originally expected and hard to interpret, if difficulties in applying different geophysical techniques have not been anticipated.

Box 7.1 *The definition of bedrock and the various exploration techniques*



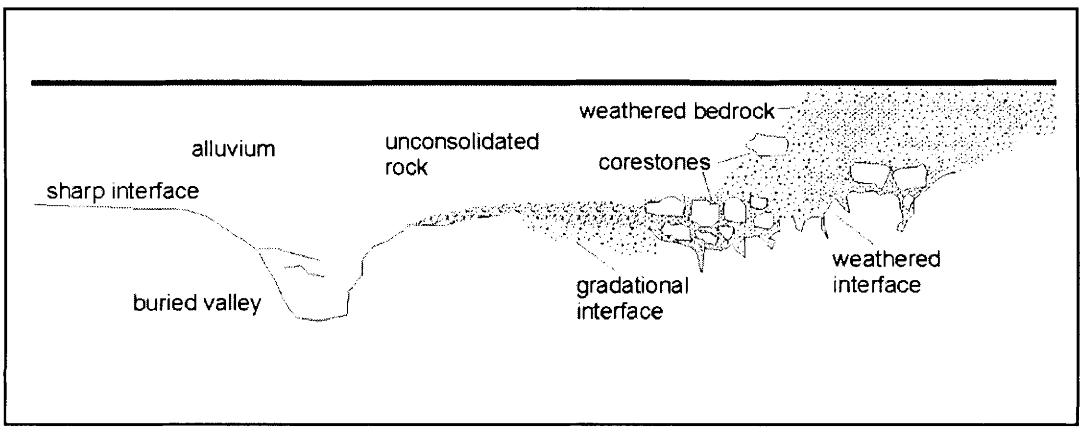


Figure 7.1 *The nature of the bedrock surface*

The geophysical land survey techniques commonly employed to determine the depth to bedrock, are seismic refraction, resistivity sounding and imaging, and electromagnetic (ground conductivity) surveys. Other techniques, such as ground probing radar, seismic reflection, magnetic and gravity, are occasionally used.

The rest of Section 7.2 is about the use of geophysics to determine the depth to bedrock in various situations on land. The use of geophysical techniques in determining depth to bedrock in water-covered areas is described in sections 5.4 and 8.9.

7.2.2 Near-horizontal bedrock

Where a single depth estimate is required at a single location, a resistivity sounding is often the easiest and fastest measurement technique to employ (Section 5.1). However, where several depth estimates are required along a line, either a seismic refraction survey (Section 5.4.2) or a series of resistivity soundings could be made. There is little to choose between them in terms of resolution of the interface depth. However, the seismic refraction technique provides more information on the properties of the bedrock and little information on the overburden, while the resistivity survey provides better information on the overlying strata, but poor information on the properties of the bedrock

The seismic refraction technique has been used for many years for the determination of depth to bedrock. The normal technique involves recording the primary or compressional (*P*) waves refracted along the upper surface of the bedrock, which must have a higher seismic velocity than the overlying material. Interpretation of the data provides layer thicknesses and seismic velocities (Table 5.1). The accuracy of the interpretation can be better than ±1 0 per cent when there is only a single refractor and there is a good contrast in seismic velocity between the layers. However, the error in the interpretation increases if thin or low velocity layers, or lateral velocity variations, are present within the overburden.

A study of secondary or shear (*S*) wave refraction data has to be carried out if information on the elastic properties of the bedrock is also required. The propagation of shear waves in rocks is unaffected by the presence or absence of fluids. It is for this reason, that refraction surveys using shear waves may sometimes be useful for determining the position of rockhead below unconsolidated sand, when the lower part of the sand layer is saturated. In this situation a two-layer *S*-wave case can be studied rather than the more complicated three-layer *P*-wave case.

A water-saturated section of sand or gravel also masks interpretation of a resistivity sounding when the strong negative contrast at the water table, combined with the strong positive contrast at the bedrock, may lead to ambiguity. Such strong water table effects are not common in the UK.

7.2.3 Varying depth bedrock

Where the bedrock is dipping or varies in depth irregularly across the area of interest, seismic and resistivity surveys are still important, but particular techniques have to be employed to take the depth variations into account.

Seismic refraction

In seismic refraction surveying, it is essential that "shots" are fired at each end of the geophone line (ie the line should be "reversed") and at additional points along the spread (Section 5.4). The recorded data can then be interpreted quantitatively using a technique such as the plus-minus method (Hagedoorn, 1959). Modern computer software will display the results as velocity sections, with calculated depths shown relative to the ground surface and velocity values shown for the appropriate refractors.

Seismic refraction techniques are best used to provide detailed information along a line where depth variations, to bedrock and bedrock quality, are of greater interest than variations in the overburden. In this situation the technique provides data efficiently, although relatively expensively if explosives have to be employed.

Resistivity

The same situation may be studied using resistivity sounding by measuring soundings at intervals along a profile. Although each sounding is interpreted assuming the subsurface layers are horizontal, the results are combined to produce a geoelectrical section showing the variation of bedrock along the profile line. Dips of 30o or more can be accommodated with little loss of precision if the azimuth of the electrode expansion is parallel to the strike. A resistivity sounding is best employed where information on layering and the properties of the overburden are of greater interest than information on the bedrock properties. Normally soundings will be sited along profiles, although they need not be equally spaced. This can be an advantage where roads and rivers make it difficult to lay out a continuous seismic line. The measurements are processed taking into account the variation of structure along the line and good approximate agreement with boreholes is often obtained (Box 7.2). In areas where the bedrock varies rapidly, it is more appropriate to carry out electrical imaging surveys. These provide a visual, but more qualitative, picture of subsurface variation, which can be very useful for planning drilling investigations. Imaging surveys are described in Section 5.1.1 and demonstrated in Fig 7.2.

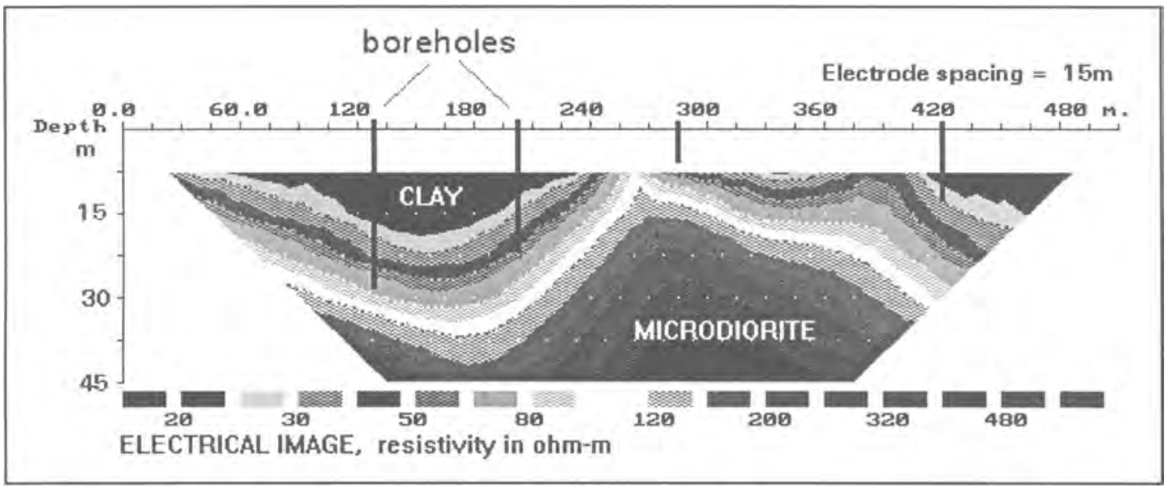


Figure 7.2 *Electrical image and observed depths to bedrock at four boreholes along the route of a proposed tunnel*

Electromagnetic survey

Electromagnetic surveys using ground conductivity instruments that operate in the low induction number field, are frequently employed to provide a qualitative view of bedrock variation, where follow-up drilling or more quantitative geophysical surveys are planned. The technique is fast and cost-effective and should be considered a routine site investigation tool (Section 5.5).

Values of ground conductivity are normally plotted in profile form or as contoured maps of conductivity (milliSiemen/metre or mS/m). These are normally viewed qualitatively to differentiate the areas of thickest overburden (eg where clay of high conductivity overlies a low conductivity bedrock) from areas of low conductivity where the clay is thin or absent. In two-layer cases where formations have laterally consistent conductivity, the survey can give a measure of depth variation. Where the overburden thickness varies, within fairly narrow limits, and the resistivities of the overburden and bedrock do not change appreciably, it is possible to carry out a semi-quantitative interpretation of the data. To do this, it is necessary to have a number of boreholes in the area, which can be used as control. Standard curves can then be used to estimate the thickness of the overburden. Depth values are approximate and should be checked where necessary with drilling or other more quantitative geophysical techniques, such as electrical sounding or seismic refraction.

Box 7.2 *Electrical Resistivity sounding survey to determine depth to bedrock and nature of overlying alluvium.*

This example illustrates the use of resistivity sounding in the site investigation for a proposed road improvement scheme. Along the route shown in Figure 7.3, it was necessary to locate the upper surface of the bedrock, which might be at a depth of 10 m or more. The principal solid formation is Carboniferous Limestone, this being overlain by glacial drift, which comprises glacial till in the east and glacial sand and gravel in the west.

In order to provide information on the thickness and nature of the glacial drift, 18 offset Wenner soundings were measured. A maximum electrode spacing of 64 m was used where possible, although this was reduced to 32 m where access was a problem. Where the proposed route ran along the existing road, the soundings were located 5 m to l0 m to either side of the road boundary in order to reduce any effects of wire fences and services, to an acceptable level. The sounding interpretations were checked on a computer and adjusted to give geological consistency.

The final results were presented as a geoelectrical section, part of which is shown in Figure 7.4. As there is a strong resistivity contrast between the limestone and the overlying glacial material, the depth to the limestone can be interpreted fairly accurately. The depth estimated from the geophysics agrees with the borehole to better than 10 per cent. The drift resistivity varies from high values of around 80 or 90 (m, interpreted as argillaceous sands, to low values of 30 to 40 Ωm, which is typical of glacial till. Here the till appears to fill a channel. The resistivity of the limestone is consistently high at around 800 Ωm, although it appears to decrease slightly in the region of the channel feature.

18 soundings were measured along the line of the proposed route, taking two days and interpretation involved one further day's work.

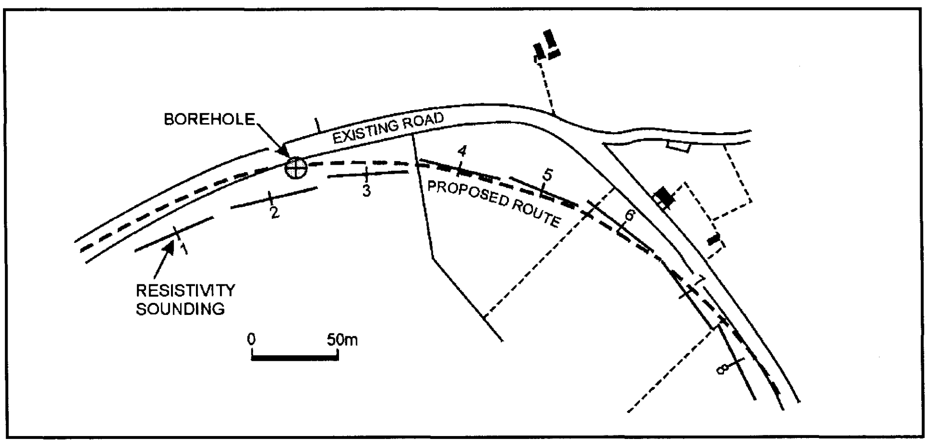


Figure 7.3 *Resistivity soundings positioned along the proposed route of a road construction.*

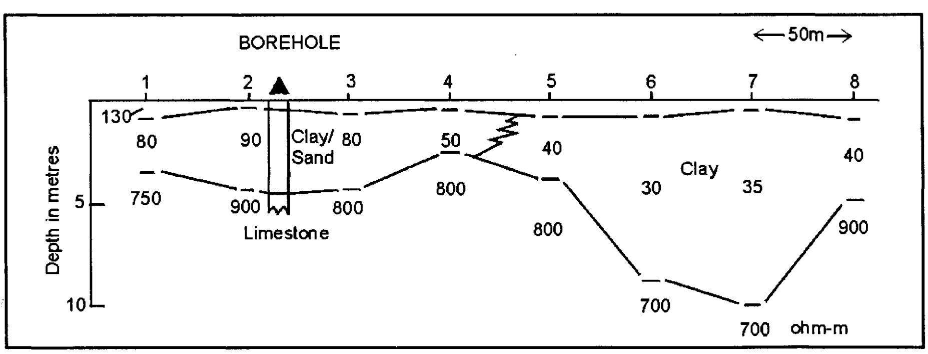


Figure 7.4 *Interpretation of resistivity soundings along road site investigation route shown in Figure 7.3. Resistivities in ohm-m*

It is important to realise that a ground conductivity survey does not supply the quantitative information on earth layering that can be obtained by resistivity sounding or seismic refraction surveys. However, as the technique is quick and cost-efficient, it should be considered for providing data, prior to drilling or for filling gaps between boreholes, or between resistivity soundings. An example is described in Box 7.3 and Figure 7.5.

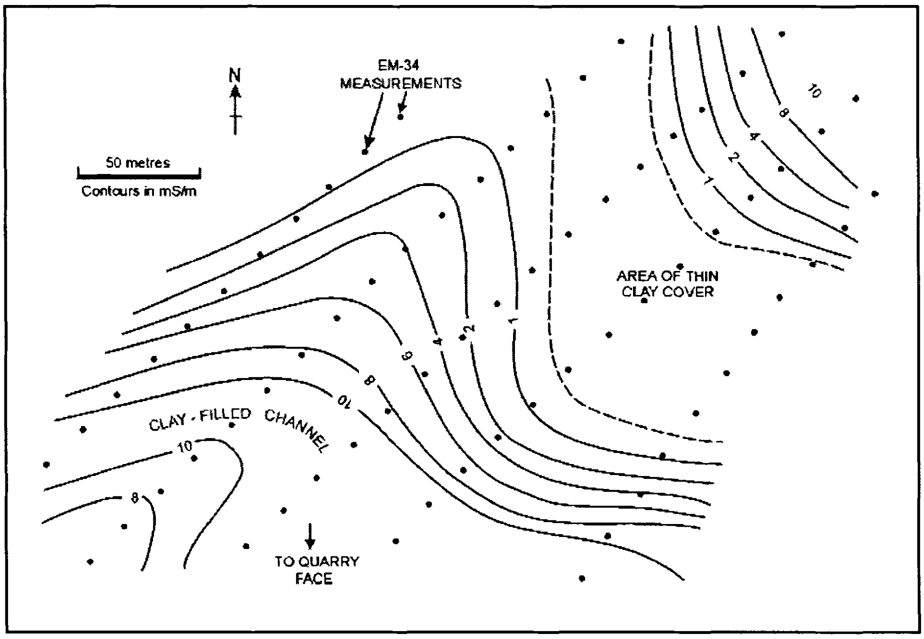


Figure 7.5 *Ground conductivity survey over area of proposed quarry extension, contours in mS/m.*

Seismic reflection

Where there is a good contrast in properties across a bedrock interface, covered by a multi-layered sequence of strata, detailed results can sometimes be provided by a seismic reflection survey, particularly in the depth range 30 to 100 m. However, the costs are higher than with other engineering geophysical methods, due to the capital cost of the equipment and the powerful computer processing required (Section 5.4.2).

Box 7.3 *Ground conductivity survey to estimate depth to hard rock in advance of a proposed quarry extension.*

This example illustrates the use of a ground conductivity survey in delineating variations in the depth to bedrock, in a simple situation where clay overlies a high-resistivity igneous bedrock and where a good resistivity contrast exists. The survey was aimed at determining in detail the depth to bedrock across a buried valley, which was clearly visible in a working quarry face, and was in-filled with Triassic marl to a depth of 25 m. To plan the quarry extension it was necessary to determine the path of the buried valley away from the quarry. The survey was carried out along five lines, 40 m apart, using the Geonics EM34 with 40 m coil spacing. Measurements were taken at intervals of 20 m and a contoured map of ground conductivity produced (Figure 7.5). Apparent conductivity varied widely across the area from near 0 to 19 mS/m. The values of conductivity can be related approximately to the thickness of overburden, the very low values corresponding to known areas of very thin clay cover and the path of the buried valley clearly indicated by the region of high conductivity. A region of thick overburden is also indicated in the north-east.

The two-man investigation took one day, the field survey accounting for half of the time and data interpretation for the remainder.

7.2.4 Very shallow bedrock

The ground penetrating radar technique is able to resolve minor changes in the depth to bedrock when this occurs at very shallow depths and below high resistivity overburden. The depth to which ground radar is presently effective is influenced by the resistivity of the soil and as most UK clay-rich soils have a resistivity of much less than 250 Ωm, the depth of penetration of ground radar is often less than 3 m (Section 5.5.1). Best results are obtained if the survey can be carried out in a dry period, when the soil will have a much higher resistivity.

Although this technique is unlikely to be useful in normal depth to bedrock determinations, it has proved to be particularly successful in the accurate measurement of depth to rock or clay bedrock below a peat covering. An example from such a survey is shown in Figure 7.6.

7.2.5 Weathered bedrock

Weathered bedrock represents a zone, frequently of intermediate properties, between the bedrock and overlying overburden. Where thin, this layer cannot be resolved by geophysical methods without additional information. In a seismic survey for example, a thin weathered layer forms a *hidden layer* (Section 5.4), which is not manifest on the time-distance graph and can only be identified through geological, borehole or other control data. In this situation, the depth to bedrock interpreted from the refraction survey is the top of unweathered rock, and the accuracy of depth calculation will be decreased. Parts of the rock that are heavily weathered have a low velocity and are likely to be misinterpreted as overburden, so that correlation with boreholes may at first sight appear poor. An example is provided in Box 7.4 and Fig 7.7

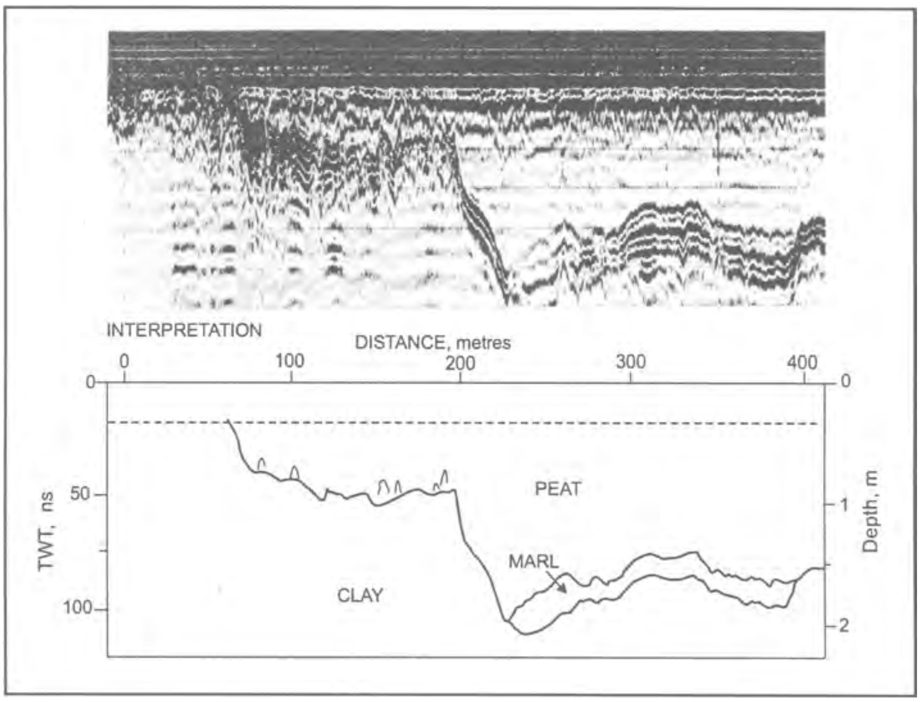


Figure 7.6 *Ground penetrating radar survey over area of peat overburden in Ireland. TWT = two-way travel time in ns*

Weathered strong rock types usually exhibit a lower resistivity than the unweathered rock and, while it depends on the contrast with overlying alluvium, a resistivity sounding often indicates the top rather than the base of the weathered rock.

The interpretation of resistivity soundings tends to be less strongly influenced by fracturing and weathering of the bedrock than the interpretation of refraction measurements. At the site discussed in Box 7.3, resistivity measurements clearly detected the top of the fractured microdiorite, but not the top of the unfractured rock (Barker, 1983).

Generally, resistivity sounding surveys for engineering purposes can be carried out by a one or two man team and are, therefore, somewhat less expensive on a daily basis than seismic refraction surveys. In comparing the two techniques, however, the different types of information obtained and the different rates of coverage should also be considered.

Box 7.4 *Seismic refraction survey to determine depth to weathered bedrock*

This example illustrates the successful application of the seismic refraction method, in determining depth to bedrock, while at the same time demonstrating that the geological interpretation is not as straightforward as might first appear. The survey was carried out where a variable thickness of clay overlies a microdiorite body. The survey was undertaken to determine the varying thickness of clay overburden and the depth to the intact unweathered rock.

The seismic refraction profile consisted of three 220 m spreads. Within each spread, 11 geophones were placed at 20 m intervals and explosive shots were fired at the ends, the mid-points and at 220 m off-end from each of the spreads. A 12th geophone was placed at 10 m from the shot in each case. Single detonators were also fired 5 m in from the end of each spread, to give information on the near-surface layering.

A 12-channel seismograph was used for all recordings with 14 Hz vertical component geophones. Data quality was good and there was generally no difficulty in identifying the first arrivals on the seismic traces. The travel times were corrected for shot depth, and offset to the surface elevation (ie to some horizontal datum), as a plus-minus interpretation (Hagedoorn, 1959) was used, which yields depths relative to the actual geophone surface positions.

Conventional time-distance graphs were plotted from which it was concluded that there were arrivals from several interfaces. The important layers identified were:

- Layer 1 Surface layer *P*-wave velocity V_1 = 400 m/s
- Layer 2 Intermediate layer *P*-wave velocity V_2 = 900 to 1300 m/s
- Layer 3 Intermediate layer *P*-wave velocity V_3 = 1800 to 2200 m/s
- Layer 4 Bedrock *P*-wave velocity V_4 = 5500 m/s

Layer 1 was interpreted as topsoil and layer 2 as a thin drift layer. Initially layer 3 was identified as Mercia mudstone, but borehole information obtained along the line of the survey confirmed that weathered microdiorite has a similar velocity and it has been included in this layer.

Layer 4 was interpreted as the unweathered bedrock and depths to the microdiorite were calculated at each geophone position (Figure 7.7). Where the microdiorite is overlain by 20 m or more of Mercia Mudstone, it appears to be unweathered and there is reasonable agreement with boreholes. However, where the igneous rock approaches the surface, it is clear that is it considerably fractured. Weathered. Boreholes suggest that up to 20 m of fractured microdiorite may be present where the bedrock is at its shallowest, but as the velocity of the fractured and weathered bedrock is similar to that of Mercia Mudstone it is not possible to differentiate them.

The field survey took a field team of four, two days, interpretation a further two days.

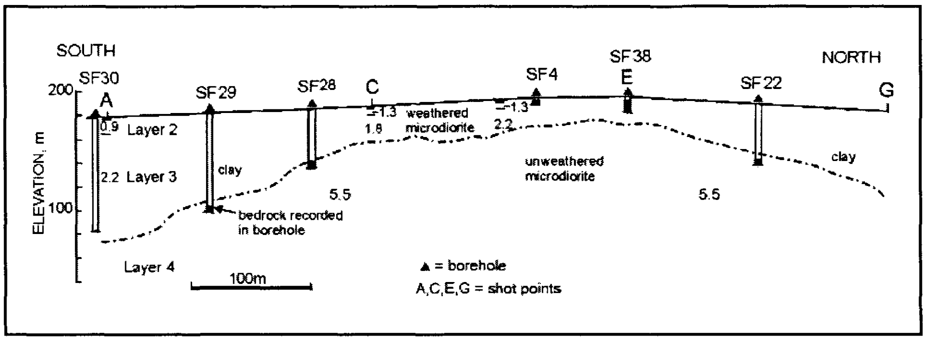


Figure 7.7 *Interpretation of seismic refraction survey over microdiorite overlain by clay, Leicestershire. Seismic velocities shown in m/ms (after Barker 1983).*

7.2.6 Buried valleys

Broad sediment-filled valleys, having gently sloping sides, may be treated as a depth to bedrock survey, in which detail within the valley and information on the layering is also required. Several techniques are suitable.

Seismic refraction can be used to profile across a valley if the base of the valley shows a strong velocity contrast with the overlying sediments. This may be appropriate where the emphasis is on investigating the nature of the bedrock, eg to determine if a geological boundary or fault zone coincides with the valley (see Section 9.5.1).

Resistivity sounding will give more information on the properties of the sediment fill, but less on the nature of the bedrock. Electrical imaging provides detailed cross-sections of valleys, but is most suitable for situations where the bedrock has a consistent resistivity (Section 5.1.1). The resolution decreases with depth so that basal structure may not be accurately defined.

Shallow seismic reflection can provide very good resolution where there is adequate transmission of seismic energy. Where a clay soil is present and problems of reverberation are few, very detailed cross-sections can be obtained. Figure 7.8 shows a seismic section across a sediment-filled valley in Wales. The limestone bedrock and layering within the fill are clear. This dataset was achieved using a hammer and plate source (Brabham and MacDonald, 1997).

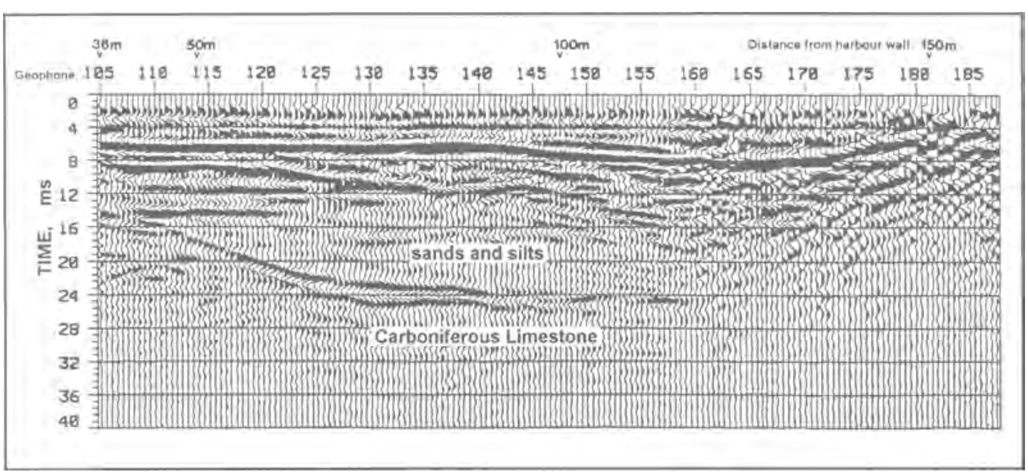


Figure 7.8 *Shallow reflection section across a sediment-filled valley cut into limestone bedrock (After Brabham and McDonald, 1997)*

7.2.7 Glacial tunnel-valleys

Narrow, steep-sided valleys, eg glacial tunnel-valleys and in-filled river gorges, present a different target. Tunnel-valleys are formed by subglacial action. They occur across much of glaciated Britain, although they are most clearly defined in East Anglia (Woodland, 1970). Most of the conventional geophysical techniques can be employed in their location (including resistivity sounding and electromagnetic profiling, sections 5.1.1 and 5.4), but the more quantitative results, from resistivity sounding and seismic refraction interpretation, may have large errors. Geophysical techniques tend to investigate the upper portions of the sediment fill, with poor penetration into (or resolution of) the deeper parts. Clarke and Cornwell (1983) show an electromagnetic (EM34) survey over a tunnel-valley in East Anglia. However, the results here are strongly influenced by the surface cover of glacial sediments, which extend beyond the limits of the valley. Nevertheless, a map of this sort can be produced quite cost effectively. Figure 7.9 shows a geoelectrical section across part of the Stour buried tunnel valley (Barker and Harker, 1984), illustrating the more quantitative nature of this type of survey.

As buried valleys tend to underlie present valleys, which have rivers, railways, major roads, pipelines etc, all running along the centre of the valley. Seismic refraction, electrical imaging and other techniques, which might involve running cables perpendicular to the valley, are generally unsuitable. In such difficult terrain, a gravity survey may be a viable alternative (Section 5.2). Barker and Harker (1984) describe a gravity survey carried out over the Stour buried tunnel valley, when access to the arable farmland was difficult. Subsequent drilling generally agreed with the results, although errors were apparent where the sediment fill changed from clay to gravel.

The gravity method is most suitable for studies of bedrock depths in excess of 50 m in areas of low topography, eg deep sediment-filled valleys. At shallower depths, the measured gravity anomalies are normally too small for accurate interpretation, although if alternative geophysical techniques are unsuitable, high-precision micro gravity surveys could be considered. Gravity surveys are time consuming and costly, but some success has been recorded in the investigation of backfilled quarries in urban areas, where other geophysical methods have proved difficult to use (Poster and Cope, 1975).

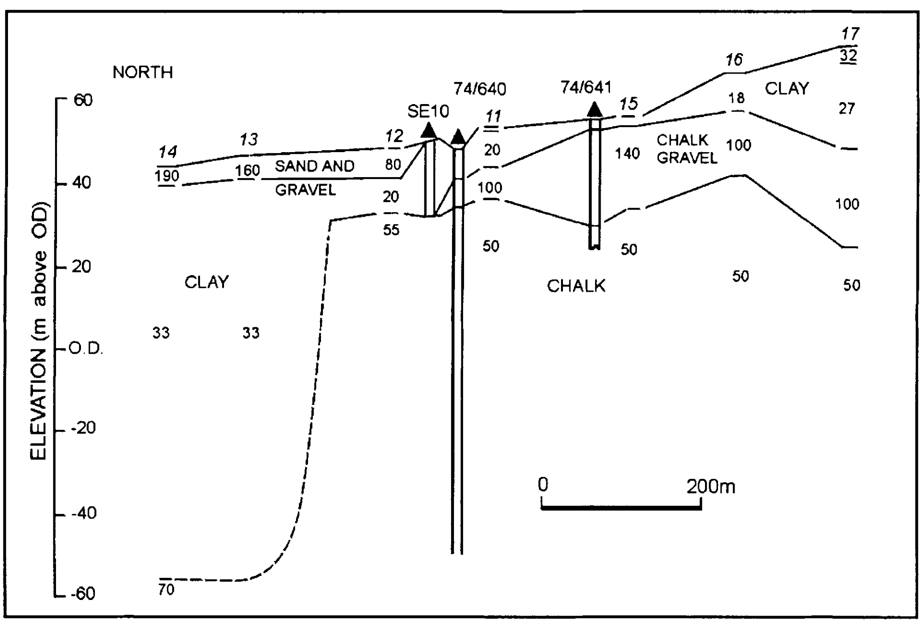


Figure 7.9 *Geoelectrical section across the edge of the Stour buried tunnel-valley, Suffolk. Values of resistivity are shown in ohm-m*

7.3 GEOLOGICAL HAZARDS

7.3.1 Fracture zones and faults

In designing a geophysical survey to delineate the position and nature of faults and fracture zones, it is important to understand the types of anomalous ground conditions that may be present (Box 7.5, Figure 7.10).

Near vertical faults (dip-slip and wrench faults), which produce a significant displacement of strata, can be investigated by a number of geophysical methods. Usually the fault is identified by differences in physical properties between the strata brought into juxtaposition by the fault. Therefore, a fault of this type within a massive homogeneous rock mass, such as granite, would probably not be identified. In contrast, a fault displacing various strata so that shale is brought against sandstone at the surface, should be easily recognisable.

Fracture and fault zones often constitute an engineering hazard. They can be identified geophysically by the contrasting properties of the fracture zone itself, irrespective of the rock types brought together by the fault movement. Geophysical methods are valuable aids to mapping such features, as well as providing an assessment of the fracture state and alteration of the rockmass. Such features are often subvertical and therefore difficult to locate by drilling, even when the boreholes are closely spaced.

Box 7.5 *Geophysical location of fracture zones*

Fractures:	Air-filled, water-filled, debris-filled
Geophysical problem:	Location of lateral change in physical properties of rock. Feature is thin and not laterally extensive, although often extensive in depth.
Techniques:	Electromagnetic profiling Seismic refraction Seismic reflection Electrical resistivity Magnetic Ground Penetrating Radar

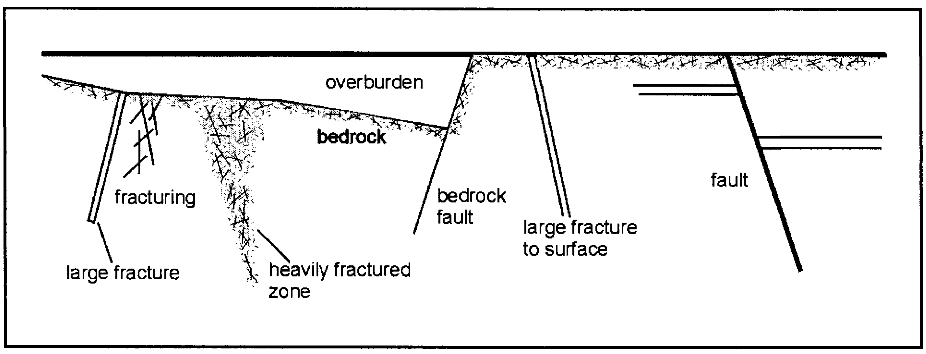


Figure 7.10 *Fracture zones and faults*

7.3.2 Near-vertical faults

The choice of geophysical method will depend on the throw and depth of burial of the faulted strata, as well as the contrast in physical properties across the fault. Table 7.1 provides recommendations for geological and engineering situations.

Table 7.1 *Recommendations of geophysical methods for typical situations*

Throw of fault (m)	Depth of burial (m)	Typical geology	Physical property	Recommended method
0–50	0–50	buried fault scarp limestone/mudstone sequence	velocity resistivity	seismic refraction resistivity/EM
50–100	> 50	basement rocks	velocity density	seismic refraction/reflection gravity
0–>100	0–>50	dolerite dykes and sills	magnetic susceptibility	magnetic

In shallow engineering geophysics, the seismic refraction method is generally the most accurate for mapping the location and calculating the throw of dip-slip faults. A distinctive pattern of time-distance graphs from reverse shooting readily identifies the faults where they are near-vertical (Figure 7.11). An example of its application to the investigation of foundations is described by Gough (1953), who used seismic spreads at different azimuths to map the extent of an up-faulted block of quartzite. The resolution of the seismic technique is limited however, and high-resolution seismic reflection methods might be more appropriate where the throw of the fault is 5 m or less and the depth of burial exceeds 50 m (Figure 2.2).

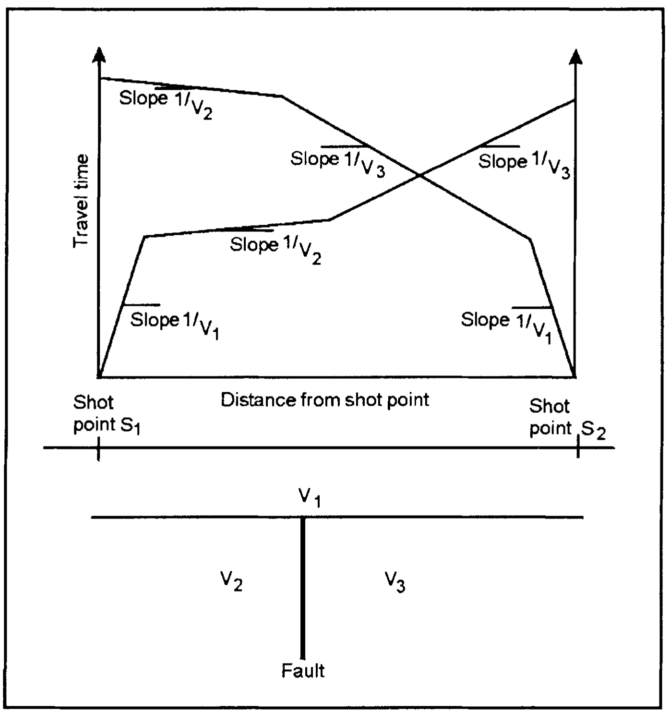


Figure 7.11 *Seismic refraction time-distance graph across a buried vertical fault (after Clayton et al, 1982)*

Recent application of electrical imaging has proved successful in the location of faults where there is a good resistivity contrast (Figure 7.12). Resistivity soundings can also be employed to measure the throw of a fault, if care is taken to orientate the soundings parallel to the fault, although less accurately. Magnetic and gravity methods are usually restricted to the investigation of major faults, particularly where basic igneous rocks or basement rocks are involved. If it is only the location of the fault line that is required, electromagnetic (particularly ground conductivity) surveys are a cost-effective means of mapping the fault, especially when it occurs near the surface. Where the fault cuts basic igneous dykes, it can usually be traced through mapping the positions of the dykes magnetically.

Probably the most cost-effective means of locating near-vertical fracture and fissure zones is by electromagnetic profiling (Section 5.4). The fractures and associated weathering reduce the resistivity of the host rock, and it is this, which is identified on the traverse. Ground conductivity profiling techniques are in common use in Africa to locate water-bearing fissure zones in basement areas for local water supply.

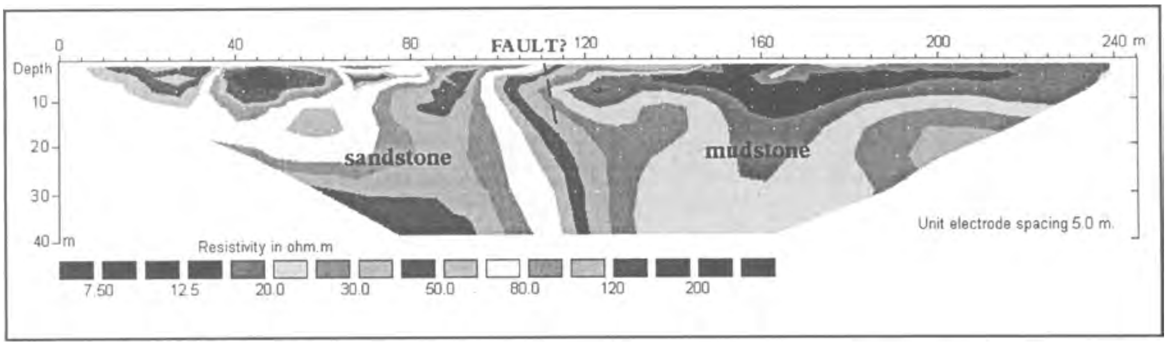


Figure 7.12 *Electrical image across a near-vertical fault between low resistivity Mercia mudstones and high resistivity Sherwood Sandstone* (for colour version see page 251)

Seismic refraction is also an appropriate method for locating near-vertical fracture zones if these are sufficiently wide (Section 5.4.2). Near-vertical fracture zones tend to reduce the *P*-wave velocity resulting in a low velocity zone. This can be identified and mapped when an appropriate field procedure of reverse shooting and overlapping spreads is adopted. A small geophone spacing will also be required, as this defines the limiting width of fracture zone which can be detected. For example, a 10 m geophone spacing is unlikely to define fracture zones of widths much less than 30 m. The Glen Lea fault zone in Scotland is a typical example, which produced a significant reduction of the measured bedrock velocity from 5860 to 2560 m/s (Cratchley *et al*, 1972). Unfortunately, low-angle fracture zones are less readily identified by this technique.

The limitations of resolution of the seismic refraction method in identifying fracture zones at depth can sometimes be overcome by using cross-hole tomography.

7.3.3 Cavities and mineshafts

General considerations

Most natural and man-made subsurface voids present hazards to buildings and civil engineering structures and, where their presence might be expected, it is essential that they are detected prior to construction. Often, as in the case of mineshafts, the voids have a limited lateral extent and their investigation by direct methods, such as drilling and trenching, is expensive and disruptive even with prior knowledge of their probable location. Consequently, there has been considerable effort to develop geophysical methods for use in locating and delineating mine-workings, cavities, and similar features (Box 7.6, Figure 7.13). Although many advances have been made, no one geophysical method has yet been developed that will resolve all problems of this type. A variety of surface traversing techniques is now available to provide readings at close station intervals, for the location of shallow voids, where the lateral dimensions of the void are of the same order as the depth of burial. Both surface and borehole methods need to be considered for the more difficult problem of locating cavities at greater depth.

Box 7.6 *Geophysical location of cavities*

Cavity:	small – large air-filled, water-filled, debris-filled, clay-filled
Mineshaft:	capped, unlined, brick-lined
Mineworkings:	horizontal cavities at depth
Geophysical problem:	location of features with limited cross-sectional area and lateral extension
Geophysical techniques:	electromagnetic profiling and mapping electrical imaging microgravity ground penetrating radar magnetic

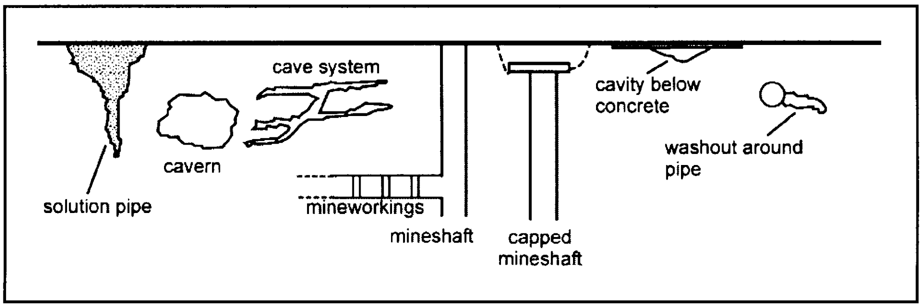


Figure 7.13 *Cavities and mineshafts*

Considerable care has to be exercised in the design of a geophysical survey for cavity location, taking into account the variable nature of the target and the wide variety of geophysical methods and techniques that are available (Fig 7.13). A desk study should be carried out to assess the probable size, depth and shape of the voids, and an engineering appraisal made of the likely sizes and depths of cavities and other features, which could adversely affect the proposed structure. The nature and physical properties of the host rock and the cavity infill material, will also affect the amplitude and width of geophysical anomalies associated with the voids. Environmental noise, such as ground vibration, high magnetic gradients and other site conditions, may have to be assessed in a site visit.

The geophysicist will usually attempt to design the survey and to interpret the geophysical data by modelling the anticipated voids with a regular shape. Mine workings lend themselves to this approach; shafts are usually modelled by vertical cylinders, adits and tunnels by horizontal cylinders, and shallow seam workings by horizontal or dipping slabs. Natural solution cavities are usually more irregular, but solution pipes and caves can initially be considered as cylinders or spheres. More sophisticated computer-aided interpretation techniques can be applied to irregular shapes, if such refinement is considered to be appropriate.

Consideration should also be given to the possibility of detecting the anomalous ground conditions that are often associated with cavities, especially when the size of the void is small compared to the depth of burial. Natural cavities often develop along fault or fracture zones and these may be located more readily by geophysical techniques than the void itself. Subsequent drilling of electrical resistivity anomalies for example, has often proved the presence of caves along fault zones in limestone (Dutta *et al*, 1970). Most subsurface voids, natural or man-made, have some effect on the compaction or moisture content of the overlying ground, and again an indirect approach may be appropriate.

Table 7.2 *Geophysical location of mine-workings*

Type of void	Thickness of cover (m)	Recommended methods	Factors to consider
Mineshafts, wells and dene-holes	0 – 3	Magnetic (total field) Magnetic (gradient)	Local magnetic gradient Shaft infill, capping and lining
		Radar	Ground conductivity
	0 – 6	EM traversing	Pipes, foundations and fences, cavity infill and size
		Microgravity	
	0 – 20	Magnetic (total field)	Iron within shaft
	5+	Cross-hole shooting	Borehole spacing
Mine adits and tunnels	0 – 3	Radar	Ground conductivity
	0 – 6	EM traversing	Cavity infill and size, background noise
		Microgravity Magnetic	Iron within workings.
	6+	Cross-hole shooting	Borehole spacing
Pillar and stall workings	0 – 20	Electrical sounding Microgravity	Cavity size and infill size/depth, infill, terrain, and noise
	20+	Cross-hole shooting	Borehole spacing

A useful approach to this problem is to define the target and to identify the advantages and limitations of all relevant methods and procedures. This has been done in the case of certain types of void, such as mine-workings, mineshafts and cavities in limestone (Bell, 1988; DOE, 1976; McCann *et al*, 1982). It is difficult to summarise this approach without oversimplification, but Tables 7.2 and 7.3 provide some initial guidance.

Natural voids

Voids in rock take a wide range of shapes, sizes and depths and are filled with a variety of materials, so that the choice of geophysical techniques for their investigation will depend on many variables. Indeed there are so many variables, that it is better to review the relatively small number of techniques available for their investigation and discuss their relative advantages and disadvantages.

Table 7.3 *Geophysical location of solution voids in limestone*

Type of void	Size/depth relationship	Recommended methods	Factors to consider
Clay-filled pipes and hollows	Depth: diameter ratio less than 2:1 Max. depth 30 m	EM traversing Magnetic	Depth of investigation/coil separation local magnetic gradient
Sand-filled pipes and hollows	Max. depth 5 m	Radar	Thickness of cover and conductivity
Caves	Depth : diameter ratio less than 2:1. Max depth 30 m	EM traversing Microgravity	Depth of investigation/coil Nature of fill
	>30 m depth	Cross-hole shooting	Borehole spacing
Caverns	>1.0 at less than 10 m cover	Radar EM traversing	Ground conductivity Cavity infill
	>1.0 at 10 m+ cover	Gravity Cross-hole shooting	Cavity infill, terrain Borehole spacing

Ground penetrating radar (GPR). Radar is potentially the most useful technique as it provides the highest resolution and, in good conditions, can penetrate to considerable depth (Section 5.5.1). For location of small cavities below concrete, or washouts close to a buried pipe, a high frequency (200 to 500 MHz) antenna will be required. A shielded antenna will provide better depth of penetration and a cleaner signal, particularly if working within buildings. Cavities at greater depths can only be found if there is little or no clay soil cover and the mother rock is a good transmitter of radar. Figure 7.14 shows the typical clear radar diffractions recorded from cavities between 6 m and 20 m depth in Carboniferous Limestone. Such good penetration could also be expected in unweathered igneous and metamorphic rocks. In these types of rock, cross-borehole radar can be employed to investigate to even greater depths.

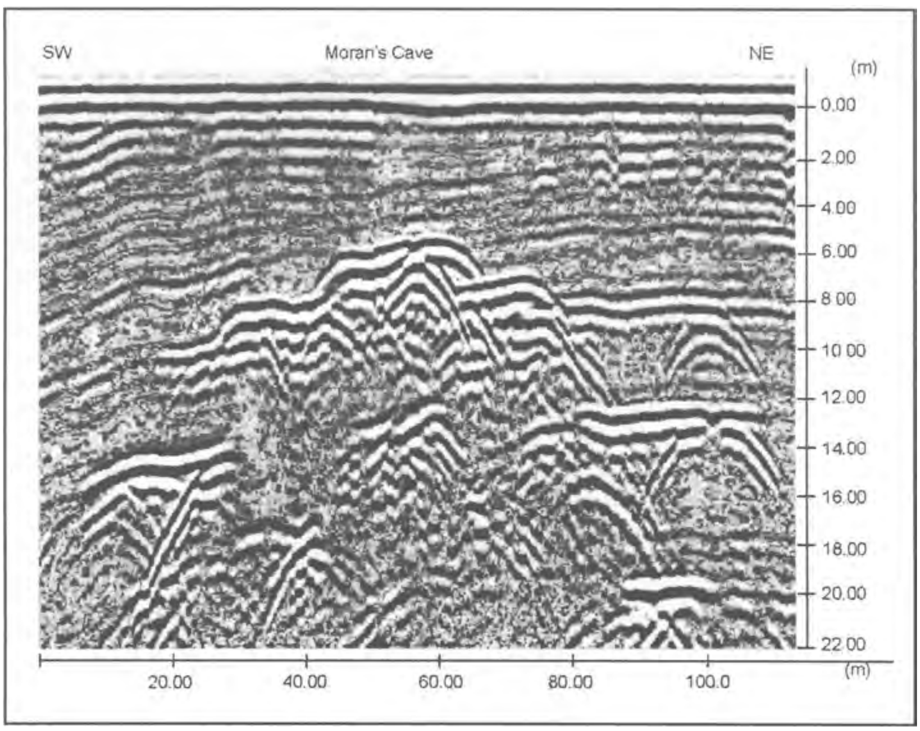


Figure 7.14 *Ground penetrating radar (GPR) profile across cave system in Carboniferous Limestone using 50 MHz antenna*

Gravity. Microgravity surveys have proven to be particularly useful in locating medium-sized cavities in built-up areas (Section 5.2). A modern microgravity survey is capable of defining anomalies of 20 μGal amplitude, ie equivalent to an air-filled cavity of 6 m diameter at a depth of cover of 10 m, with a precision of 2 μGal. The resolution of gravity is proportional to the depth of the feature being investigated and so is best for location of shallow cavities. The best chance of detection is when the cavity is air-filled and has the greatest density contrast. The presence of water or other material reduces the density contrast and hence also the chances of detection. Fortunately it is relatively easy to estimate the usefulness of a microgravity survey with reference to Figure 7.15. This shows the smallest spherical cavity that might be detected at a particular depth of interest for the three cases where the cavity is air or water filled, or has been filled with collapse material from the surrounding rock. In practice (Reynolds, 1997), the amplitude of the anomaly may be increased by the added effect of a zone of reduced density surrounding major cavities. Even if Figure 7.15 suggests that the cavity should be observable, another consideration is whether the expected width of the anomaly is so large that it cannot be surveyed in the space available at the surface. The width of the anomaly is related to the depth of the cavity, and in order to define a significant proportion of the anomaly (necessary for interpretation) a profile length of at least four times (more if possible) the depth will be necessary.

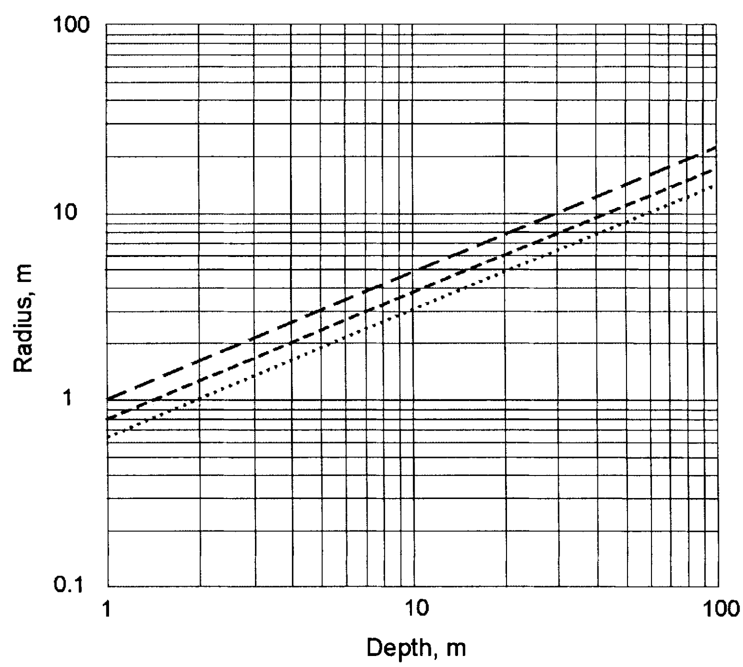


Figure 7.15 *Approximate minimum dimensions of caves, which will produce a measurable gravity anomaly (20μGal). upper line = clay-filled cave, middle = water-filled cave, lower = air-filled cave*

Electrical techniques. Electrical techniques generally have poor resolution, but electrical imaging can be useful in the location of larger cavities or collapse features. The resolution is generally no better than 10 per cent of the depth, even with a good contrast in resistivity between the cavity and surrounding material. Problems of ambiguity are also likely to affect resistivity techniques. Their advantage is their low cost compared with microgravity and greater depth of penetration compared with GPR. Electrical imaging is particularly suitable for delineating collapse features, where the effect of the collapse extends close to the surface.

Electromagnetic. Ground conductivity surveys using the Geonics EM31, or similar instruments, are suitable for low-cost rapid mapping of areas where cavities, culverts and mineshafts may be buried within the top 5 m of the subsurface – particularly where a clay cover is present. Deeper and larger-diameter cavities may be investigated with two coil EM systems such as the EM34 (Section 5.5).

Acoustic tomography. When boreholes are available, seismic imaging of the ground between the boreholes can reveal the presence of voids (Section 5.4). The application to karst features in limestone is discussed by McDowell and Hope (1993).

Abandoned mine shafts

Centuries of mining in the UK, and elsewhere for coal, limestone, metals and other minerals has left a legacy of old mineworkings. Many are unrecorded or are recorded inaccurately and there can be no guarantee of the effectiveness of their treatment, unless it has been carried out in recent years. Where land is to be developed and the presence of an old shaft is suspected, its location has to be determined so that it can be made secure. The location of an old shaft involves a number of stages, of which the desk study is important. Bell (1988) gives a detailed description of the various stages of investigation and much of the following is taken from this work.

In most parts of England mine shafts are circular, while in Wales they are elliptical. The shafts are often lined with stone or brickwork. In Scotland the shafts are usually rectangular and often lined with wood. Shaft diameter ranges from 2 m to 5 m, and the maximum side of the rectangular shafts from 2 m to 6 m. Relatively modern shafts are almost all circular with diameters up to 7 m; they are lined with brick or concrete. Shafts used for ventilation and pumping usually have a smaller diameter than winding shafts.

Many shafts were originally made safe by capping off with turfed-over wrought iron domes, or trees were dropped into the shaft to form a bridge on which to place fill. More frequently, a wooden platform was laid across the buntons some 3 m to 15 m below the surface and topped up with fill. Shafts were generally filled with material at hand, which could include rails, timbers, bogies, scrap metal, as well as mine waste and boiler ash. With time the cap decays and the fill deteriorates and a collapse occurs.

The cost of locating and exposing a mine shaft may be reduced by using geophysical techniques prior to drilling and excavation. The success depends on the existence of a sufficient contrast between the physical properties of the shaft and those of the surrounding ground.

Historically, magnetic surveys have had most success in the location of shafts. If a shaft is lined with iron tubing it will produce a strong anomaly. A brick lining is weakly magnetic, but a wooden lining or open shaft is not. If a shaft is filled with burnt shale or boiler ash, it may also produce a weak anomaly. A strong anomaly will be produced by any scrap ferrous waste in the fill.

Magnetic measurements should be recorded about any potential shaft position on a fine grid pattern (often as close as 1 m). The contoured anomaly maps should reveal anomalies of the type shown in Figure 7.16. In the northern hemisphere, the centre of the positive anomaly is displaced to the south of its source and is accompanied by a weaker negative anomaly to the north (Higginbottom, 1976).

Magnetic gradiometer surveys may be useful where shafts are shallow and occur in magnetically noise-free areas, as the survey is fast and easy to carry out and anomalies are sharper. Most modern instruments enable both total field and gradiometer measurement.

On the other hand, shafts are likely to be located in industrial sites where there is often a considerable amount of magnetic waste. The ferrous waste produces many magnetic anomalies, so-called "false alarms", that to check every one would involve a major investigation. Gradiometer surveys only exacerbate this situation by producing many more anomalies than would a conventional magnetic survey. This problem is often overcome by concentrating the survey around the suspected site of each mineshaft within a 50 m or 100 m square. If it is assumed that old maps show the relative positions of mineshafts accurately, but that their absolute positions are in error, once one or two shafts have been located, some or all of the remaining shafts may be located merely by making the necessary corrections to the mineshaft map.

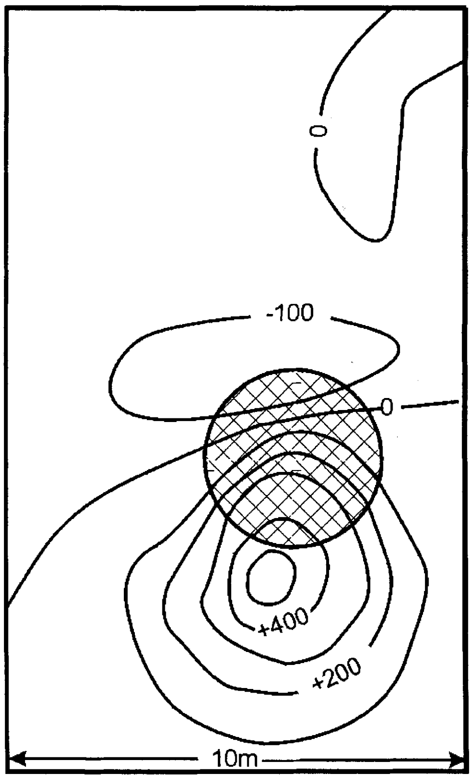


Figure 7.16 *Magnetic anomaly over mineshaft (shaded), which has been capped and partially filled with ferrous material*

Terrain conductivity meters also offer a quick and cost-efficient method of surveying an area for a shaft. The Geonics EM31 is capable of detecting a shaft if it lies within about 5 m of the surface. Shafts might be identified by either a conductivity high (if capped and filled with metal) or a conductivity low (if filled with rubble or wood).

Although the magnetic technique has had considerable success in shaft location, and successful ground conductivity surveys have been published, none of the techniques have proved to be 100 per cent reliable. Consequently, geophysical methods have earned an unfavourable reputation. Nonetheless, geophysical methods are relatively quick and cheap, when used correctly, can be a useful preliminary to direct exploration.

Abandoned mineworkings

Abandoned horizontal mineworkings at depth are generally less of an environmental problem than shafts, although there are occasional instances where it is necessary to locate them. Often the mineworkings are too deep for magnetic surveys to be suitable. In this case, shallow seismic reflection surveys could be used to find the different character between a reflection from the unexploited zone and the mined area. Gochioco (1990) gives an example of a shallow reflection survey across coal mining areas in the US. Where the mineworkings are close to the surface, a microgravity survey might be used. This is particularly useful if sites covered with buildings have to be surveyed. At shallow and intermediate depths in rocks with good transmission properties, ground penetrating radar surveys might be considered.

7.3.4 Landslides

The term "landslide" is applied to a wide variety of mass movement phenomena, ranging in speed of movement from slow soil creep to extremely rapid rock avalanches. These extreme cases are linked by a more or less continuous spectrum of activity, in respect of speed of movement and scale. The landslide materials are similarly varied in lithology and physical properties, ranging from unconsolidated sediments to hard rock.

The study of a landslide in an engineering context is usually carried out to assess its likely influence on a proposed structure or its threat to an existing one. In both cases the same factors need to be considered in assessment of stability of the landslide as follows:

1. The surface area of the slipped mass is often apparent from its topographic expression, but ancient landslides have frequently degraded such that their outlines are obscure, or they may be covered by vegetation. It is also possible that they have been covered either partly or wholly by a later deposit of natural or artificial origin.
2. The thickness of the slipped mass must be determined, so that the form of the boundary surface can be defined. This will be a shear surface in the case of rotational or translational movement, and perhaps a relict surface in the case of a flow.
3. The position of the free water surface is required for stability analysis. The actual water content of the material above the water table is particularly important in the identification of zones of likely instability.
4. The disposition of the various materials within the landslide mass and their geotechnical properties are also important for stability analysis.
5. The monitoring of long-term movements, which could lead to catastrophic failure of the landslide, is essential in areas where there is a high risk to human life.

Traditional site investigation methods concentrate on surface measurements and morphological studies, together with an examination of the slide material and the underlying undisturbed bedrock using drilling, pitting and trenching. In this way the engineering geologist is able to define many of the parameters listed above, for slope stability analysis. Geophysical methods can be used to obtain some of the information and are particularly effective for large landslides. By applying the correct methods it is possible to delineate the lateral extent of the landslide area, define the slope of the slip plane below the slide material, investigate the water regime, and monitor activity within the landslide. McGuffey *et al*, (1996) give an excellent overview, describing the integration of geophysical methods into the subsurface investigation of landslides.

Geological studies

The seismic refraction method is generally applicable to landslide investigation, as the slip material usually exhibits seismic velocities significantly lower than those of the underlying *in-situ* strata. It is particularly effective in the delineation of large prehistoric landslides, which have been generally modified by subsequent erosion. When the topographic features have been modified, the engineering geologist often has difficulty in determining landslide boundaries, as there is little variation in material type. With seismic refraction however, problems occur in areas of dense vegetation and uneven topography along the geophone spread. If available, borehole information should be used to calibrate the seismic sections, as some independent assessment of the change in lithology with depth, generally improves the interpretation of the seismic data.

One of the best examples of the use of the seismic refraction method in a landslide investigation is given by Piteau *et al*, (1978) who carried out a large programme of seismic refraction on the Downie Slide in British Columbia, Canada, to obtain seismic sections of the landslide. They reported that it was possible to identify four distinct zones from these profiles, including the position and depth to the surface of the undisturbed bedrock. Above the bedrock, a zone of altered and possibly disrupted bedrock was distinguishable from the overlying slide material. Similar case histories are described by Lee and Mystkowski (1978), Knight and Matthews (1976) and Miller *et al*, (1980). In each case significant differences between the seismic properties of the landslide material and those of the underlying bedrock are noted. This is referred to in more detail by Bogoslovsky and Ogilvy (1977), who showed that both the compressional and shear wave velocities are lower in the landslide material than in the underlying bedrock. At the same time attenuation of both compressional and shear waves increases significantly.

Vertical electrical sounding is frequently carried out in conjunction with seismic refraction and borehole investigations. However, it is often found that the heterogeneous nature of the landslide, particularly in the vicinity of the electrodes, may produce substantial changes in the measured values of apparent resistivity. This in turn, results in difficulty in the interpretation of the resistivity data, so that in general the depth soundings should not be carried out in a landslide area, without additional information from other surveys to calibrate the results. Both Trantina (1962) and Muller (1977) suggest a combination of electrical sounding and seismic refraction measurements. Electrical imaging, mentioned in Section 5.1.1, has been successfully used by Bishop and Koor (2000) in identifying anomalous geological features behind masonry retaining walls in Hong Kong, in conjunction with additional ground penetrating radar surveys. This latter method may have potential in non-invasive surveys of landslide areas, but high attenuation of the radar signal in saturated clay materials may prevent its use in many possible applications. The magnetic method can be used for the investigation of the very large soil movements associated with flowing landslides. In this case position markers, in the form of very powerful magnets, are lowered to the bottom of uncased boreholes to provide continuous information on displacement (Bogoslovsky and Ogilvy, 1977). The positions of these markers are monitored by repeated magnetic surveys. An interesting use of the magnetic method is found in McDougall and Green (1958). In this case, the direction of magnetisation was used to distinguish between the landslide material and the rock, which has remained *in situ*. At a dolerite scarp of the Western Tier in Tasmania, magnetic surveys suggested that jointed blocks, which had been subjected to sliding, had fallen into a sub-horizontal position, whereas at the lower levels below the slip plane they were only slightly tilted. Here the *in-situ* bedrock was found to be magnetised in an almost vertical direction (ie a magnetic dip of almost 90°), while the slipped blocks had very low angles of magnetic dip.

Hydrogeological investigations

The study of the hydrogeological regime within the landslide, with particular reference to the actual moisture content of the material above the water table, is essential for the evaluation of its stability. Denness *et al*, (1975) carried out an electrical resistivity survey, using a constant-separation Wenner array, to identify zones of low resistivity arising from high values of moisture content in a landslide at Charmouth, Dorset, UK.

They demonstrated how the measured ground resistivity reflects seasonal variations in the moisture content and how these are related to landslide activity. Bogoslovsky & Ogilvy (1977), Knight & Matthews (1976) and Yamaguchi (1977) also mention this approach for the location of wet and potentially unstable zones within the landslide mass. Recently electrical imaging has been used to provide more detailed pictures of moisture variations within a landslide (Lapenna *et al*, 2000).

Ground conductivity mapping is of considerable value in the study of landslides because it is particularly useful for locating the areas of high moisture content, as these are indicated by high values of ground conductivity. Its main advantage is that it is a rapid reconnaissance method, which does not require contact with the ground surface, and can be used in conjunction with ground penetrating radar.

Geotechnical investigations

Most landslides are investigated with boreholes to obtain samples, which then determine the geotechnical properties of both the landslide material and the underlying bedrock. Geophysical methods can also be used to obtain this and related information indirectly, by using known relationships between the geotechnical and geophysical properties of the materials concerned (Chapter 8). In particular, geophysical logging of the site investigation boreholes can be used to study both changes in lithology and variations in the geotechnical properties across the landslide area.

It is also possible for example, to measure the temperature variation down the borehole. Although the *in-situ* bedrock exhibits a smooth increase in temperature with depth, the slide material often has an uneven temperature profile. Other techniques, which have been used in the past, are gamma logging to identify thin clay seams and sonic logs (Piteau *et al*, 1978).

Cross-hole seismic measurements can be used to differentiate the mud flow material from the underlying *in-situ* rock mass. An example of the use of this technique in a survey of the Higher Sea Lane landslide at Charmouth, Dorset, is discussed by Denness *et al*, (1975). A particular feature of this survey was the identification of a permeable layer, which later proved important in the design of remedial drainage work.

Monitoring of movement

Microseismic activity in rocks is related to the sudden release of strain energy, caused by deformation and failure in the crystalline structure of a rock mass. This sudden change gives rise to the emission of a transient seismic or acoustic signal, referred to in the literature as microseismic activity or acoustic emission, which travels from the point of origin to the boundary of the rock mass where it can be detected as a microseismic event.

In the monitoring of slope stability, microseismic activity can be used to predict impending failure within a rock slope and to define areas of active movement. McCauley (1976) makes the following observations about microseismic activity:

1. The rate of occurrence (count rate) of shocks reflects the stability of the landslide area, provided it is compared to the count rate in a stable area outside the slide.
2. The count rate increases as the stability decreases.
3. Count rates should be considered as relative values rather than absolute values.

Cadnam and Goodman (1967) carried out laboratory studies of microseismic activity in small-scale models of landslides and demonstrated that activity increases considerably shortly before failure. The study showed that the activity originates mainly in the central part of the slip surface that develops. Their field work demonstrated that the active part of a large landslide and the location of the slip surface, could be identified from measurements of microseismic activity in boreholes drilled through the slide.

Novosad *et al*, (1977) report the location of an active slip surface in weathered clay shale at Turany, Slovakia, at a depth of about 15 m, where a marked peak in the microseismic activity indicated the position of the slip surface. It is thought that in this case, the noise generated at the slip surface resulted from the breaking of the cement grout surrounding the plastic borehole casing. Similar definition of the slip surface using microseismic measurements is described by Piteau *et al*, (1978) in studies at the Downie Slide, British Columbia, Canada. One of the most interesting and effective uses of microseismic monitoring is described by McCauley (1976), when it was used at the Ponto Marina landslide in California, to minimise the hazard and inconvenience to traffic on the road below the landslide.

It is surprising to find that microseismic monitoring is not used more often in slope stability studies. It may well be that the overall cost of the technique, both in instrumentation and manpower requirements, is higher than that for more traditional methods. However, the possibility of predicting not only impending failure, but also the location of the unstable zone within the landslide, must result eventually in its more widespread use. Certainly, the instrumentation and analytical methods developed for the location of fractures propagating through the rock mass following hydraulic fracturing, described by Batchelor *et al*, (1983), can be directly applied to landslides. The manpower requirements can be considerably reduced, by using the automatic triggering system for recording events, developed by Houliston *et al*, (1982). This means that continuous on-line monitoring can be achieved. Work carried out by the British Geological Survey on the Taren landslide in South Wales indicates that this is essential, as it is extremely difficult to use manual recording methods with an intermittent process, such as microseismic activity. Further studies of microseismic activity during a more active period of landsliding on the Taren landslide, are described by Rouse *et al*, (1991).

Geological Society, London, Engineering Geology Special Publications

Geotechnical applications

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 151-185
doi:10.1144/GSL.ENG.2002.019.01.08

8 Geotechnical applications

Many physical properties of rocks and engineering soils may be determined from geophysical measurements, eg bulk density, porosity and permeability. The most important geophysical parameters, for measuring physical properties, are electrical resistivity (Section 5.1) and seismic wave velocity (Section 5.4). Others, such as thermal conductivity (Section 5.7) are used more directly in engineering studies. Some derived properties need to be modified, usually according to semi-empirical constitutive relationships. For example, the modification of elastic moduli determined by elastic wave propagation methods takes account of larger strains, different mean effective stress and duration. Other geophysical measurements can be translated by empiricism into useful engineering indices (eg rippability from seismic velocity and corrosivity from electrical resistivity).

With the improvements in imaging by seismic, electrical and radar methods (Section 5.5), the ground may be more readily characterised in terms of the distribution of a geophysical or derived physical property, and this may lead to particular engineering design choices.

At the initial stage of site investigation planning, it is often more appropriate to consider the use of geophysical methods in the context of the overall engineering project, rather than in the identification of specific targets or engineering parameters. The main areas of engineering practice, and the associated subject of construction materials, are covered separately in this chapter, but there is a measure of overlap between some areas. For example, the geophysical assessment of bearing capacity is appropriate to bridges, power stations, dams and off-shore structures, and geophysical assessment of construction materials is appropriate to most areas of civil engineering activity.

8.1 GEOTECHNICAL PROPERTIES DERIVED FROM GEOPHYSICAL PROPERTIES

Measurement of geophysical properties enables physical properties to be determined, eg elastic moduli from seismic wave velocities. This section also considers other physical properties of geotechnical significance such as density, porosity and permeability, which may be estimated by geophysical methods.

8.1.1 Elastic modulus and Poisson's ratio

The small-strain elastic moduli are estimated from determinations of S wave velocities taken together with the *in-situ* bulk density (see Table 8.1). Shear moduli can be calculated directly using S waves and the "soils" bulk density, provided the effects of strain level, stress history, deposition and anisotropy are considered (Butcher and Powell, 1997b).

A value of Poisson's ratio (ν) derived from P and S velocities is only meaningful in relatively isotropic ground. Where there is marked anisotropy, causing polarised body waves, care is required, especially if the data are to be used in numerical modelling (Hight *et al*, 1997).

In soils, the derived values may require modification before they can be used in engineering calculations, to take account of first-order sensitivity to strain magnitude

(Figure 8.1) and second-order sensitivity to strain rate, as well as the effects of "effective stress" (Lo Presti *et al*, 1997).

Table 8.1 *Principal elastic waves*

Wave	Designation	Remarks	Propagation velocity
Compression wave	V_P	Particle motion in direction of propagation	$V_P^2 = E(1+\nu)/\rho(1-2\nu)(1+\nu)$ (infinite medium)
Shear wave	V_S	Particle motion normal to direction of propagation	$V_S = (G/\rho)^{0.5}$
vertically propagated horizontally polarised	V_{SVH}		$V_{SVH} = (G_{VH}/\rho)^{0.5}$
horizontally propagated horizontally polarised	V_{SHH}		$V_{SHH} = (G_{HH}/\rho)^{0.5}$
Rayleigh wave	V_R	Retrograde elliptical motion at surface	$V_R = V_S\ (f(\nu)$
Love wave	L	Particle motion normal to direction of propagation in plane of interface	Short λ: $V_1 = (G_1/\rho_1)^{0.5}$ Long λ: $V_2 = (G_2/\rho_2)^{0.5}$
Stonely wave (generalised Rayleigh wave)		Surface wave in elastic half-space where two layers have similar shear wave velocities	0.988 V_S
Conversions at boundary (solid / solid)			
Incident	Transmitted	Reflected	
P	*P, SV*	*P, SV*	
SV	*SV, P*	*SV, P*	
SH	*SH*	*SH*	

Notes: *V* = velocity of propagation of wave; *G* = shear modulus, *E* = Young's modulus: ρ = density: λ= wavelength: ν = Poissons ratio.

Shear waves may be designated with direction of ray propogation shown as well as polarisation direction, eg SVHH is horizontally travelling, horizontally polarised.

Laboratory tests can be used to bridge the strain magnitude gap between seismic methods in the field and prototype strain levels. Such specialised laboratory tests require careful setting up and instrumentation. Special cyclic stress-strain testing of soils and rocks can now be carried out on "undisturbed" or reconstituted specimens over a very wide range of strains, using stress-or strain-controlled tests. The format may be "triaxial cyclic", resonant column, simple shear, ring shear, hollow cylinder torsion or double shear. These testing systems are well described in soil and rock dynamics literature, and provide data on strain ranges approaching those imposed during field seismic testing. These methods of determining "small-strain stiffness" can deal with monotonic and cyclic loading and are now available in many advanced commercial and institutional soil mechanics laboratories.

The most appropriate "modulus degradation" relationship (ie the reduction in modulus with increasing strain) to apply is still a research issue, although for nearly three decades the empirical relationships between cyclic shear modulus and damping, and shear strain and effective stress, have been in use (Hardin and Drnvich, 1972). Recently, Lo Presti *et al*, (1997) have questioned whether such relationships based on resonant column tests are appropriate. It has also become apparent that for some soft rocks and structured soils, the effectively "elastic" behaviour may extend to higher cyclic strains (Nishi *et al*, 1989; Kim *et al*, 1994). Furthermore these questions are no longer restricted to "soil dynamics". The *in-situ* small-strain shear modulus is seen as the starting point for constitutive relationships governing the static deformability of soils and soft rocks (Tatsuoka *et al*, 1997). The relationship between tangent modulus and secant modulus, and effective stress state and stress history, is at the heart of the extension of seismic methods for general geotechnical predictive purposes.

Nevertheless, as Lomnitz (1994 and 1996) has pointed out, there is a remarkable degree of similarity in the modulus degradation curves for a wide range of soils (but not rocks) as may be seen in Figure 8.1. Vucetic and Dobry (1991) have proposed a correlation of modulus degradation with increasing strain related to Plasticity Index for soils. Atkinson (2000) has proposed a design method for routine surface foundations, which uses rigidity (calculated from modulus (E_0) derived from seismic shear wave velocity and failure strength (q_f) and the degree of non-linearity of modulus with increasing strain. Atkinson's proposal therefore, uses data from seismic shear wave measurements and laboratory soil strength tests to estimate foundation behaviour.

Matthews *et al*, (1999) have pointed out that for many ground engineering situations, the relevant strain is within, or close to, the range of geophysical measurements.

8.1.2 Formation density and porosity

These properties can be obtained indirectly, using borehole geophysical logging techniques. A suite of logs including nuclear, resistivity, acoustic and self-potential logs, (Chapter 5), can be provided for relatively shallow boreholes (Keyes, 1990), and the use of "slimline", tools is now widespread in site investigations for major works.

An empirical equation (Wyllie *et al*, 1958) has been used for many years to estimate the porosity of saturated formations from sonic logs and hence by calculation to derive a bulk density assuming a value for the specific gravity of the soil or rock-forming minerals (Box 8.1).

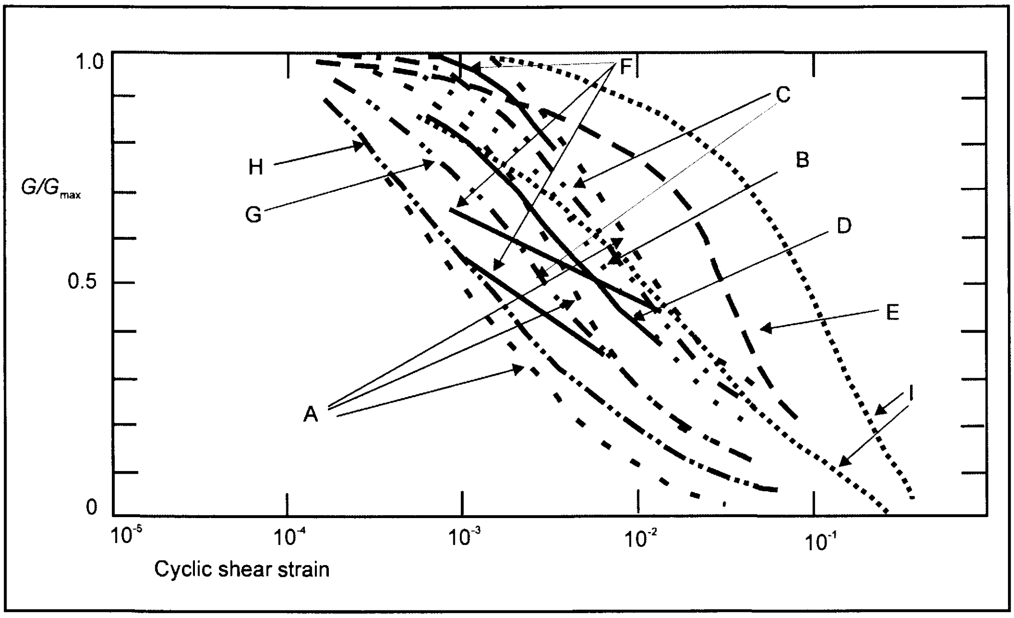
Box 8.1 *Wyllie's equation*

$$1/V_p = n/V_f + (1 - n)/V_m$$

where

n is fractional porosity
V_p is *P*-wave velocity for the formation
V_f is velocity through the pore fluid and
V_m is velocity through the matrix.

Neilson (1996) describes current procedures for estimating porosity and water content from sonic geophysical logs at the Yucca Mountain radioactive waste disposal site. Wehr *et al*, (1995) describe the use of cone penetration testing and freeze probing along with shear wave velocity to estimate void ratio in loose sand, a material that is very difficult to sample.



Key

- A Literature review of cohesive till deposits – mean +- 2σ
- B Literature review of silty clays – mean
- C Quiou Sand – Resonant column test (RCT) and monotonic loading torsional shear (MLTS) Lo Presti *et al*, 1997
- D Neogene sand (RCT) Hight *et al,* 1997
- E Neogene mudstone, consolidated drained triaxial. Go from suspension log, after Izumi *et al* 1997
- F London clay (RCT) and monotonic torsional shear, Hight *et al* 1997
- G Literature review of gravels by Rollins *et al,* 1998
- H Gravels – Seed *et al,* 1998
- I Range of back calculated E_{secant}/E_{dyn} for soft mudstone. Initial E from shear wave and assumed Poisson's Ratio from Tatsuoka *et al* 1997

Figure 8.1 *Shear moduli degradation with increasing cyclic shear strain*

Porosity, *n*, may also be estimated from Archie's Law (Box 8.2) given data on the electrical resistivities of the saturated formations and the electrical conductivity of the pore fluid. An estimate may then be made of the moisture content.

Box 8.2 *Archie's porosity equation (Archie, 1942)*

For sandstones saturated with brine (20 000 to 100 000 ppm), Archie found the resistivity of any one sample to be proportional to the pore-fluid resistivity:

$F = R_t / R_w$

where R_t is the formation resistivity, R_w is the resistivity of the pore-fluid (water), and he designated *F* the formation resistivity factor. He also found a simple relationship between porosity and resistivity that described his results for a variety of saturated sandstones and unconsolidated sands:

$F = 1 / n^m$

where *n* is the fractional porosity and *m* is a constant controlled by the morphology of the pore space.

Archie found *m* had a values of 1.5 and 2 for loose sands and cemented sandstones.

However, radiometric methods are increasingly being preferred in engineering, particularly the gamma/gamma probe for the determination of formation density. This tool can also be used for lithological correlation and identification of formations. Bulk density can be determined to an accuracy of 50 kg/m^3. Further improvements may be made with careful calibration of the source, detectors and instrumentation, and through considerable care in the preparation of the borehole itself. Small-diameter sondes have been used in shallow access holes for geotechnical studies. These holes may be formed by hydraulically forcing tubes into the ground (Meigh and Skipp, 1960).

The gamma/gamma, or density log, measures the apparent bulk density of the saturated formation close to the borehole wall and this includes the effect of both the rock matrix and the contained fluids.

Where drilling mud has not invaded the formation the bulk density g of a rock of porosity, *n* is given by

$$\gamma = \gamma_s - n(\gamma_s - \gamma_w)$$

where (s is the grain density and (w is the fluid density. Hence, the porosity of the formation can be computed from:

$$n = (\gamma_s - \gamma) / (\gamma_s - \gamma_w)$$

The density log includes horizontal and vertical fractures and will tend to indicate higher porosities than a sonic log, taken over a comparable section of borehole, intersected by a steeply inclined fracture or a joint plane. Thus, a cross-plot of porosity, as determined by the two methods, can be used to indicate the presence of significant fracture zones within a rock mass. Moisture content can be estimated by thermal neutron back-scatter techniques, which can also be used to determine porosity in water-saturated ground.

The micro-gravimeter may also be used to estimate earth density *in situ*. Borehole versions of this device have been used to map formation density changes (Robbins, 1980, Black, 1986) and in the detection of cavities. Farnan *et al*, (1994) describe the use of a borehole gravimeter to establish fluid saturation in a North Sea oil reservoir. Calibration tests for density and moisture content are often made using the field density determination methods described in BS 5930.

Density and porosity are determined in the laboratory by saturation and buoyancy techniques. The methods are described in the International Society for Rock Mechanics Commission on Standardisation of Laboratory and Field Tests (1981) and most textbooks on geotechnical laboratory practice.

8.1.3 Permeability

Permeability is an important geotechnical property and one of the most difficult to measure. It is used in settlement calculations for foundation design, the analysis of hazards, eg landslips and soil liquefaction, and for the estimation of water flow into excavations. It is particularly relevant to dam and embankment design, for seepage through, below or around new construction and existing structures. Permeability is a measure of the ease of fluid flow (usually water) through a particular formation.

Distinction should be made between permeability arising from flow in fissures and that associated with inter-granular flow in porous materials. Many attempts have been made to relate permeability to geophysical measurements, to take advantage of low-cost investigations, possibly avoiding the need for boreholes. However, none of the conventional techniques provide a relationship.

Electrical methods are usually related to inter-granular permeability, although a circular ER sounding technique was used to assess anisotropy in fracture state and permeability in karstified limestone (Arandjelovic, 1966).

Theoretical relationships, which govern fluid flow and electric current flow, are very similar (Brown, 1980), except fluid flow is affected by pore size and electrical current is not. It is difficult to envisage an electrical method for predicting permeability, which is applicable to different formations. Equations governing electric current and fluid flow in porous media have been extensively studied (Schopper, 1966).

Seismic methods have also been applied to permeability determinations, but with only limited success. However, there are indications that some progress may be made in the near future. Seismic waves deform a formation, with the possibility of relative motion, between the fluid and the pore framework. Some attenuation may be caused by fluid squirting between pores; this should be dependent on pore size and hence on permeability. This approach has been followed up empirically by Lebreton *et al*, (1978), with mixed results. For fractured rock masses, the evaluation of fracture anisotropy by seismic methods and borehole ultrasonic measurements is a useful approach to assessing rock mass permeability.

The fundamental theory governing the propagation of elastic waves in porous media is due to Biot (1956) and among his many predictions is one involving a change of velocity with frequency, which depends on permeability. This line of research was followed by Hamdi and Taylor-Smith (1982), who successfully predicted permeability during an oedometer test, knowing the porosity, compressional and shear velocities, and the "frame compressibility".

8.1.4 Characterisation from dielectric constants and permittivity

It has been suggested (Mahrer, 1995) that with the increasing use of electromagnetic methods, the governing fundamental physical properties to which they respond may provide useful information on the engineering/environmental characteristics of the ground.

Electromagnetic wave-based methods (Section 5.5), such as ground penetrating radar (GPR) and time-domain reflectometry (TDR), can give information about soils at the micro-level. Properties including moisture content, soil composition, electrolyte composition, consolidation, and cementation affect the fundamental physical parameters, which govern EM propagation.

8.2 GEOTECHNICAL EVALUATION OF GROUND CONDITIONS

8.2.1 Soil corrosivity

It is important to protect steel structures from corrosion. One of the best and most reliable parameters indicating soil corrosivity is the electrical resistivity of the soil at the relevant location and depth. In addition to an assessment of soil corrosivity, the resistivity measurements will also help when deciding on the type of cathodic protection to be installed (if appropriate), ie by galvanic anodes or by impressed current. Useful reviews of the subject maybe found in BSI (1973), King (1977) and Field (1979). Various authors have proposed different classifications of corrosivity based on resistivity values, which differ only in their degree of sub-division. In the UK, the one in CP1021: 1973 *Code of practice for cathodic protection* (Table 8.2) is the most commonly used.

Table 8.2 *British Standard classification of soil corrosivity in CP1021: 1973 (BSI, 1973)*

Soil resistivity (ohm-m)	Corrosivity
up to 10	severely corrosive
10-100	moderately corrosive
100 and above	slightly corrosive

The number and position of the points at which soil resistivity determinations are carried out, for any particular buried structure, should take account of the size of the structure in relation to the probable variation in soil conditions over the site. Practical and economic factors will often limit the number of determinations taken, and the possibility of small areas of low resistivity escaping detection may need to be taken into consideration. On cross-country pipelines in the UK, where soil conditions are variable, it is usual to make resistivity measurements at least every kilometre, with additional readings taken to define the extent of particularly corrosive areas. In the case of some high pressure gas and fuel pipelines, the basic interval may be much smaller, eg 30 m. On a long desert pipeline, where soil conditions are more uniform, resistivity measurements may be taken at intervals of up to 2 km or 3 km.

The surveys should be carried out when the lowest resistivity values are likely to be encountered, the worst conditions being a high water table or following a period of high rainfall. It is general practice to use a Wenner electrode array for the measurements, with the electrode spacing equal to the depth of burial of the pipeline or structure of interest. This erroneously assumes that there is a 1:1 relation between electrode spacing and depth of penetration. In fact the relationship is often more complex, and it is best to carry out soundings periodically to determine the resistivity as a function of depth, and from the interpreted resistivity section, to determine the best electrode separations for the bulk of the measurements. For shallow investigations, non-contacting EM ground conductivity traversing could be used.

Average resistivity values alone are not sufficient indicators of corrosion risk as lateral and vertical contrasts can enhance the risk. Also, in many soils there are microbiological agents which play an important role, and whether or not the environment can enhance their activity can be assessed by measuring the redox potential by probes in the field, at the same time as conducting a resistivity survey.

8.2.2 Soil stiffness profile

Although shear wave velocity depth profiles are in themselves used to characterise a site, eg in Eurocode EC8 parts 1 and 5, engineers often require the small strain shear modulus (G_0 = density x V_s^2), and in numerical modelling of geotechnical problems, the small strain Youngs Modulus and Poisson's Ratio. The developing approach to routine geotechnical analyses for static as well as dynamic loadings requires these small strain properties (Atkinson, 2000). For more complex problems, such as tunnelling, the stiffness anisotropy of the ground is essential as input into modelling, to predict surface settlements (Simpson *et al*, 1996).

In particular, efforts are usually directed towards establishing a stiffness/depth profile, initially in terms of the small strain shear modulus G_0, a Poisson's Ratio and derived values of Youngs Modulus E. The material damping, usually the Damping Ratio D, is also needed for dynamic response analyses and, although the values are usually taken from the literature or laboratory tests, there is increasing interest in deriving values from *in-situ* testing.

Skipp (1995) reviews data requirements for use where numerical models for soil structure interaction are envisaged.

Where the velocity/stiffness depth profile is used to characterise a site, there is usually a geotechnical investigation and local relationships between Standard Penetration Tests (SPT), Cone Penetration Tests (CPT) and shear wave velocity may be useful. However, the uncertainties in such relationships do not corrupt the best estimates of shear modulus, which are preferably derived from seismic data.

Although crosshole seismic methods, using three co-linear boreholes, are generally preferred, other techniques such as the "Seismic cone", down-hole seismic measurements and surface wave methods (Butcher and Powell 1997b, Cueller, 1997, Matthews *et al*, 2000) can add confidence.

It is common practice on larger contracts to supplement crosshole and downhole seismic measurements, with a survey using a geolog borehole sonde which may carry an extensive suite of devices, eg calliper log and a range of electrical resistivity, spontaneous potential, radiometric and sonic units. Besides providing information on stratigraphy and bulk density, the data from such devices can be used to assess how well a plastic borehole liner is coupled to the ground. Sondes usually carry dip and direction recorders, which are useful in cross checking for borehole deviation. Furthermore, sonic logging can show up anomalous zones in more detail.

The development of a stiffness/ depth profile is a matter of expert judgement, and an awareness of the use to be made of the information is needed. In establishing a profile, which may be used for dynamic analysis, care has to be taken not to introduce, as artefacts, reflecting boundaries at positions dictated by apparent stratigraphic contrasts. Account also has to be taken of the resolving capacity of the geophysical methods used (Ricketts *et al*, 1996).

All methods involve uncertainties and these have been examined with special reference to the use of dynamic parameters in numerical modelling. The uncertainties arise from the measurement procedures themselves (pick of events, timing and distance errors). They arise from a mismatch between the value of the parameter being derived and that, which should properly be used (eg neglecting anisotropy, rate of strain), and the representativness of the value derived in what is usually inhomogeneous ground.

It is salutary to note the way uncertainties in small strain modulus are dealt with, where soil structure interaction (SSI) analysis is carried out for nuclear structures.

> Low strain shear modulus shall be varied between the best estimate value times $(1 + C_v)$ and the best estimate divided by $(1 + C_v)$ where C_v is a factor that accounts for uncertainties in the SSI analysis and soil properties. If sufficient, adequate data are available, the mean and standard deviation of the low strain modulus shall be established for every soil layer. The C_v shall then be established so that it will cover the mean plus or minus one standard deviation for every layer. The minimum value of C_v shall be 0.5. When insufficient data are available to address uncertainties in soil properties, C_v shall be taken no less than 1.0. (ASCE Standard 4-98, 1998)

When the information is to be used for dynamic response studies, care must be taken choosing best estimate or characteristic values, since a "conservative" lower bound, as advised in Eurocode 7 for static loading, may not be conservative with respect to dynamic responses.

The response of structures on the surface to earthquakes, show that the properties of the upper 30m to 40 m of the stiffness profile are most important and the detail of the layering to these depths is significant in predicting the response in the higher frequencies (10 to 40 Hz). Lateral variations may however have greater significance at lower frequencies. Where shallow lateral variations are to be explored, the introduction of other rapidly deployed geophysical methods (eg EM, GPR) should be considered.

8.2.3 Rock mass quality and fracture state

Rocks are usually fractured and an assessment of the fracture state is the first task in evaluating the quality of the rock in a mass state (Rawlings *et al*, 1991). In the last 20 years, the concepts of fractal geometry have had an impact on the way in which the fracture state of a rock can be characterised (Turcotte, 1992), and this has offered insights into scaling relationships in rock masses. These approaches have a bearing on statistical models of rock mass behaviour, regarding *in-situ* stress state, deformation and percolation of fluids. Geophysical methods that, in effect, sample the rock mass at different scales, have attracted researchers. A full understanding of the propagation of a seismic wave through fractured rock, involves complex mechanisms of scattering and attenuation. However in practice, until very recently, much simpler approaches have been taken.

Compressional wave velocity is very sensitive to fracture state, especially for dry rock masses (Box 8.3)

Box 8.3 *Example of calculation of the velocity of propagation of seismic waves through fractured rock*

Consider a compressional wave travelling through 20 m of fresh limestone without joints in 5 ms, which is at a velocity V_p of 4000 m/s. The corresponding velocity when 10 water-filled fractures of width 0.05 m have to be traversed can be calculated using the following time average formula (McDowell, 1993):

$$L/V_p \text{ (rockmass)} = Nw/V_{p\ (\text{fracture filling})} + (L - Nw)/V_{p\ (\text{rock material})}$$

Where *L* is the direct path length in metres, N is the number of fractures and w is the average width of the fractures. For this example the velocity is reduced to 3840 m/s and the calculated value if the fractures are filled with air is 3130 m/s. In reality the velocity for dry rock is smaller because of air-filled gaps acting as acoustic barriers with reflection of incident energy, and the recording of longer diffracted path lengths around the ends of a fracture.

Water is a good couplant, and time-averaged formulae for *P*-waves will usually be valid for saturated rock masses and when fractures are filled with soil or secondary mineralisation. In such cases a larger variation of velocity with fracture state will be obtained by measuring shear wave velocities.

Relationships between compressional wave velocity and Rock Quality Designation (RQD), which is partially a measure of fracture state, have been developed. Onodera (1963) suggested that the ratio between the *P*-wave velocity in the field (V_F) and that obtained from intact specimens in the laboratory (V_L) gave some measure of the *in-situ* discontinuities. This is sometimes called the fracture index. Subsequently, Deere *et al*, (1967) established that the square of this ratio (velocity index), expressed as a percentage, is numerically equivalent to RQD. Cratchley *et al*, (1972) found little correlation between fracture spacing and velocity, in tight jointed rock at the Foyers Hydroelectric Pumped Storage site in Scotland, but other attempts have been more successful. A direct empirical relationship between P-wave propagation velocity and a tunnel support requirement has been used by Sjogren *et al*, (1979). Good correlations with both RQD and fracture frequency were established at a damsite in sedimentary rocks in Jordan (El-Naqa, 1996). Results relating seismic velocities to rock mass quality obtained from other sources (New, 1971 and Krishnamoorthy *et al*, 1974) are shown in Table 8.3.

Table 8.3 *Seismic evaluation of rock mass quality*

Rock quality classification	RQD (%)	Fracture frequency (m^{-1})	V_F/V_L	$(V_F/V_L)^2$
Very poor	0–25	15	0–0.4	0–0.2
Poor	25–50	15–18	0.4–0.6	0.2–0.4
Fair	50–75	37019	0.6–0.8	0.4–0.6
Good	75–90	36896	0.8–0.9	0.6–0.8
Excellent	90–100	1	0.9–1.0	0.8–1.0

Recently there has been an increased use of body shear waves or dispersive surface waves in the characterisation of rock masses, with additional information being yielded on anisotropy by polarisation phenomena (Crampin, 1981). Some characterisation of anisotropy, in different geological units, has become more than an academic issue for projects, leading to numerical modelling of foundation and ground response to static and dynamic loading.

The attenuation of seismic waves is also influenced by fractures, particularly in dry rock masses. If constant or repeatable energy sources can be ensured, good transducer coupling is maintained, and multiple geophones are deployed, amplitude attenuation offers a way to estimate damping. Seismic attenuation is usually expressed as a Quality Factor (Q), or the attenuation coefficient formulae, relating these parameters to compressional wave velocity and dominant frequency is shown in Box 8.4. Laboratory measurements of *Q* are discussed in Section 5.4.1.

Box 8.4 *Formulae relating attenuation to velocity and dominant frequency*

$Q = \pi f / \alpha V_p$ or $Q = 8.868\pi/\alpha$

Where V_p, is compressional wave velocity, *f* is dominant frequency and α is in units of decibels per wavelength.

Results relating seismic velocities to rock mass quality obtained from sources are shown in Table 8.4.

Table 8.4 *Relation between Q and α values and rock mass type*

Q	α (db λ^{-1})	Rock mass description
20 – 100	1.36 – 0.27	Clastic sedimentary rocks, eg sandstones and shales
150 – 600	0.18 – 0.05	Metamorphic rocks, eg slates and phyllites
200 – 600	0.14 – 0.05	Igneous rocks, eg granites and basalts

Table 8.5 shows corresponding RMR, V_p and Q values for some Devonian rocks in Ireland. These results are from limited investigations but give an indication of the spread of Q. Values of Q for soils are of the order of 7 to 10 (Malagnini, 1996), whereas for granites Q may vary between 40 and several hundreds. Intense fracture and voids in dry rock masses will result in severe attenuation, ie low Q values.

Table 8.5 *Some results of seismic data analysis with rock mass ratings for some Irish rocks (after Murphy et al, 1989)*

Dominant lithology	Q value	Standard error of Q	V_p (m/s)	RMR
Shale	8.69	2.7	2300	45
Shale and fractured, weathered sandstone	6.2	1.41	2330	47
Sandstone	17.42	5.84	3100	59

Universal engineering index/wave propagation relations are likely to be very dispersed. However, if they are developed locally with a correlation to particular engineering experience, eg tunnel or rock face support, they can be helpful. As vibration-sensing signal processing becomes more sophisticated and presenting data in time and frequency domains easier, new and more theoretically sound indices are likely to emerge.

Research has been active in tomographic representation of the velocity of elastic wave propagation (Fehler and Pearson, 1984; Worthington, 1984; New, 1985) and in the interpretation of borehole logging in terms of rock mass engineering. In the last decade, significant progress has been made in seismic tomography with characterisation of a rock mass by P- and S-wave velocities, amplitude attenuation (Q) and pulse broadening (Cartmell *et al*, 1997).

8.2.4 Rock mass deformability

Seismic methods have been used for many years to determine rock mass deformability under dynamic loading and to assess rock mass deformability under static loading. The results have been used to supplement or constrain findings from field and laboratory static tests. See Box 8.5 for the calculation of "elastic constants" from wave velocities. Coon (1968) published graphs showing a positive linear relationship (with a great deal of scatter) between the static modulus of elasticity calculated from P-wave velocity. A better relationship can be expected if the size of the loading area in the field static test is close to the wavelength of the seismic waves, eg large diameter plate bearing tests or pressure chamber tests compared to shallow seismic refraction results.

Box 8.5 *Calculation of dynamic elastic moduli*

The basic expressions relating compression and shear wave velocities (V_p and V_s) to the classical elastic constants used in engineering design are:

$E_d = 2\rho\ (1+\mu d)\ (V_S)^2$

$G_d = \rho\ (Vs)^2$ (Table 8.1)

$\mu d = (V_P{}^2 - 2V_S{}^2)/2(V_P{}^2 - V_S{}^2)$

where E_d and G_d are the dynamic elastic and shear moduli, ρ is the bulk density and μd is the dynamic Poisson's ratio.

As V_p can usually be measured more readily than V_s, it is tempting to use the expression:

$E_d = \rho\ (V_p)^2\ (1+\mu d)\ (1\text{-}2\mu d)\ /\ (1\text{-}\mu d)$

With an assumed value of 0.25 for Poisson's ratio. This may provide reasonable values for strong, dry, massive and unweathered rock masses, where V_p is greater than 3000 m/s and Poisson's ratio lies between 0.1 and 0.2. However, where the rock mass is weathered, or of weaker material, the Poisson's ratio could be between 0.2 and 0.4; and assuming it to be 0.25 would lead to a gross error in E_d. Measurement of both compression and shear wave velocity is then required. This is also necessary for water-saturated rocks.

The following empirical relationships between Rock Mass Rating (RMR) and static settlement was proposed by Bieniawski (1978) for initial assessments of rock mass deformation at the sites of large dams:

$E_s = 2(\text{RMR}) - 100$

where E_s is the static rock modulus in GPa.

A similar relationship was established for a sequence of sedimentary rocks at the Wadi Mujib damsite in Jordan (El-Naqa, 1996).

Seismic velocity and attenuation results can be used to help establish representative RMR values for an engineering site. RMR involves factors such as intact rock strength, spacing and condition of fractures, and ground water, all of which might be expected to be reflected in seismic measurements. A seismic characterisation would therefore serve, to locate the more expensive large-scale static loading tests, which would be required on a dam site, for example. Once a direct relationship has been established between E_s and E_d for a location, it can be extended to other parts of the site using the seismic data.

Grainger *et al*, (1973) established ranges of V_p for a set of chalk mass weathering grades established by observation (Ward *et al*, 1968), which had been related to deformability under plate loading tests. Figure 8.2 shows an assessment of the performance of a number of predictive approaches for weathered chalk, including surface wave geophysics (Matthews *et al*, 1997).

Where there is strong bedding and contrasting velocities or intrinsic anisotropy, or even regular jointing, the Poisson's ratio determined by seismic means may fall well outside the range expected for uniform isotropic elastic material (Section 8.1.1). Problems of this nature may arise, especially when the parameters are provided for numerical modelling and call for interaction with those carrying out the modelling.

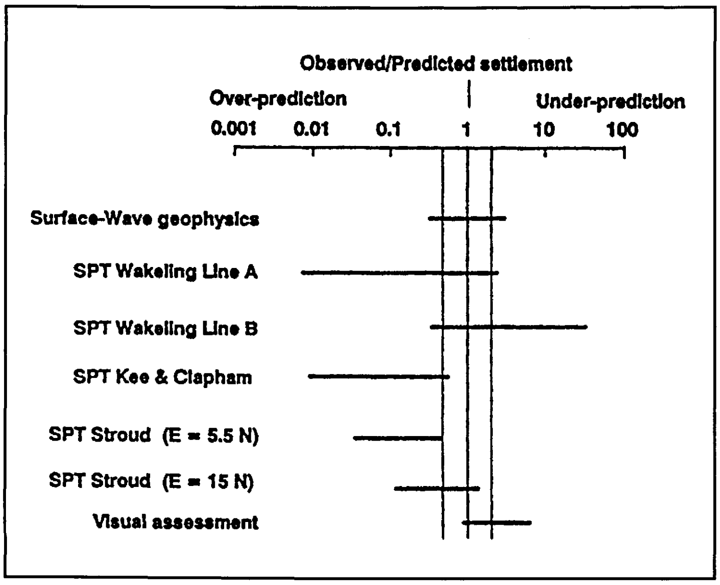


Figure 8.2 *Comparison of observed settlement of a 1.8-m dia plate on weathered chalk loaded to 200 kPa average bearing pressure with predictions based on stiffness-depth profiles determined using a number of* in-situ *methods (after Matthews* et al, *1997)*

Changes in the frequency composition of the shear wave have been the basis of the "Petite Sismique" method, which has received more attention outside the UK. Empirical relations have been developed between the apparent frequency change of the body shear wave and the deformation modulus (Schneider, 1967) with a theoretical justification from Roussel (1968). Bieniawski (1978) evaluates the procedure in the context of rock mass deformation assessment providing an empirical relationship:

$E_s = 0.054f - 9.2$ (Figure 8.4) which appears to be reliable for moderate to strong rocks.

Recent progress has been made in developing relationships between shear modulus and shear strain for soft rocks (Kim *et al*, 1994; Tatsuoka *et al*, 1997) and a degree of verification has been achieved in the monitoring of the behaviour of completed structures.

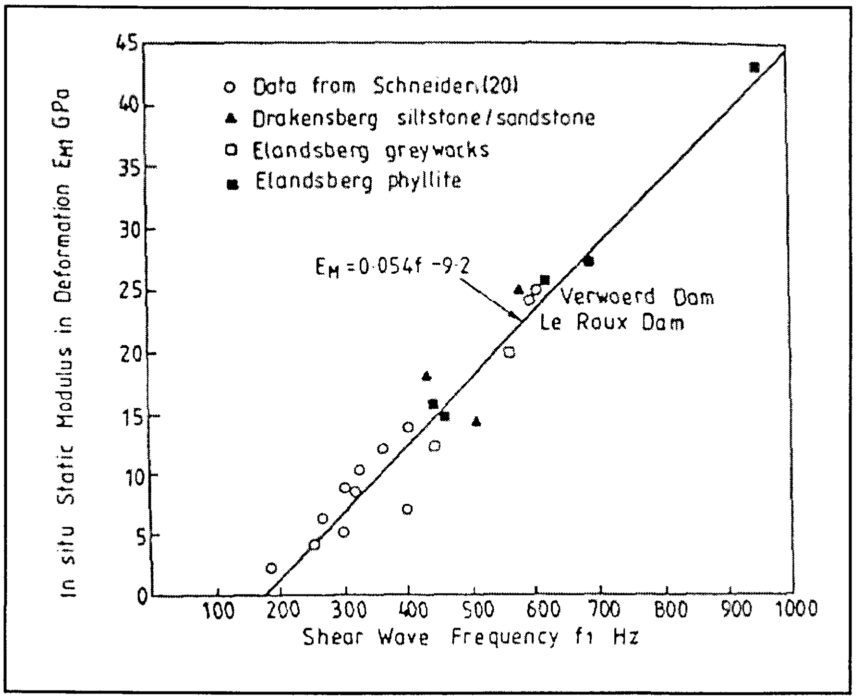


Figure 8.3 *Static modulus of deformation versus frequency of shear wave ("Petite Sismique")*

When the ground is expected to be subject to dynamic loading, the shear modulus, G_d, is usually required (although many numerical models need E_d and Poisson's ratio). This is determined from shear wave velocity as described above. G_d is used in the design of foundations for vibrating machines, the design of underground chambers to withstand earthquakes and external explosions, and in the interaction between the ground and the foundation of structures under earthquake loadings. For many sites classified as "rock", the response of structures with shallow foundations is particularly sensitive to the upper few metres of weathered rock, which is a strong material. However, it has such lower values of V_s compared with the deeper unweathered rock, that there is significant local magnification of motion.

8.2.5 Rippability, diggability and trenchability

Rippability is an empirical measure of the ease with which rocks can be excavated or removed, using modern high-power tractor-mounted rippers. Features of the rock mass that are likely to influence the assessment of rippability include rock hardness and strength, degree of weathering and discontinuities (spacing, persistence, width and infill, distribution and orientation). Generally, the factors that favour ripping can be summarised as:

- open fractures, faults, and other planes of weakness of any kind
- weathering
- brittleness and crystalline nature
- high degree of stratification or lamination
- large grain size
- low compressive strength.

As an extension to the use of seismic velocity data to assess rippability, Stacey and Nobel (1975) attempted to produce a similar relationship for "trenchability". This was intended for investigations that use hydraulic bucket excavators, such as the installation of buried services in new townships. Their limited trials suggest that materials with seismic velocities of up to 1200 m/s should be trenchable.

Table 8.6 *Rippability rating chart (after Weaver, 1975)*

Rock class	**I**	**II**	**III**	**IV**	**V**
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock
Seismic velocity (m/s)	> 2150	2150 –1850	1850 –1500	1500 – 1200	1200 – 450
Rating	26	24	20	12	5
Rock hardness	Extremely hard rock	Very hard rock	Hard rock	Soft rock	Very soft rock
Rating	10	5	2	1	0
Rock weathering	Unweathered	Slightly weathered	Weathered	Highly weathered	Completely weathered
Rating	9	7	5	3	1
Joint spacing (mm)	> 3000	3000 – 1000	1000 – 300	300 – 50	< 50
Rating	30	25	20	10	5
Joint continuity	Non continuous	Slightly continuous	Continuous – no gouge	Continuous – some gouge	Continuous – with gouge
Rating	5	5	3	0	0
Joint gouge	no separation	Slight separation	Separation < 1 mm	Gouge < 5 mm	Gouge > 5 mm
Rating	5	5	4	3	1
Strike and dip orientation*	very unfavourable	unfavourable	slightly unfavourable	Favourable	very favourable
Rating	15	13	10	5	3
Total rating	100 – 90	90 – 70**	70 – 50	50 – 25	< 25
Rippability assessment	Blasting	Extremely hard ripping and blasting	Very hard ripping	Hard ripping	Easy ripping
Tractor horsepower		770/385	385/270	270/180	180
Tractor kilowatts		575/290	290/200	200/135	135

Young *et al*, (1984) attempted to use frequency domain analysis and velocity mapping to relate overburden removal operations to rock mass properties, in opencast mining. The use of small explosive charges to evaluate ground properties has been studied by Fourney and Dick (1995) who used a finite difference code. They modelled the stress pulse after passing through open joints and through different materials. They used particle velocity-time traces and compared the spectra resulting after Fast Fourier Transformations in different materials, but this did not prove a satisfactory way of discriminating between the materials. This was achieved by plotting the logarithm of the particle velocity against the logarithm of the displacement, normalised by the cube root of the charge weight (Figure 8.5). The pulse width was also affected by joints.

Usually, it is not possible to conduct ripping trials with a tractor, and often the formations to be excavated are not visible. For these reasons, the Caterpillar Tractor Company developed the use of the seismic refraction method in 1958, as an aid to the assessment of rippability. The principle was based on the fact that the seismic velocity of a rock formation is related to the factors listed above, and to a large extent represents an index of rock quality. In practice, P-wave velocity data for a particular site are compared with data from previous tests in similar materials, where the rippability is known. For most commonly found materials, a range for rippability in terms of P-wave velocities has been established and charts published (Caterpillar Tractor Company, 1988) for each size and type of machine (see Figure 8.4 for example). Additional charts relate estimated ripper production to seismic velocity. Other manufacturers of earth-moving equipment have produced their own charts, taking into account different tractor horsepower and type, and number of ripper shanks.

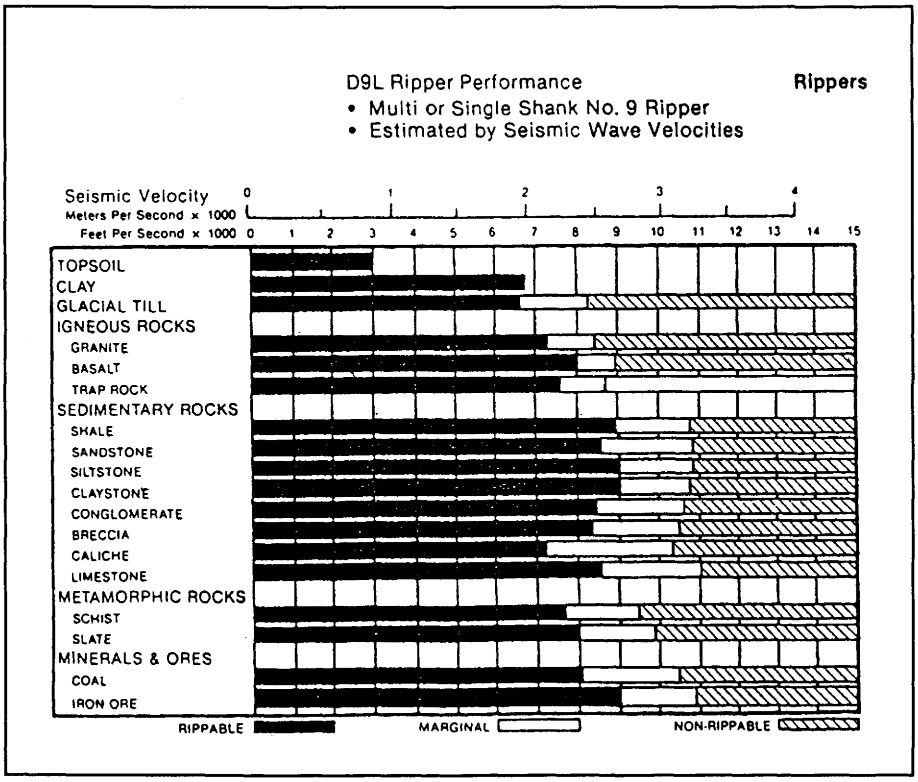


Figure 8.4 *Rippability chart (after Caterpillar Tractor Company, 1988)*

Although these charts are still commonly used, they may overestimate the ease of ripping and should only be used for initial provisional estimates. For example, basalt may prove difficult to rip because of the high rock strength and lack of horizontal fractures, but if columnar jointing were present, it would significantly reduce P-wave velocity values. Similarly, the presence of large corestones in weathered granite rocks may not be indicated. Conversely, misleading high velocities will be recorded where thin surface cemented layers, such as calcrete, overlie weak rock or soil.

Usually, P-wave velocity is just one of several parameters used in rippability assessment systems. For example, Weaver (1975) presented a comprehensive rippability-rating chart (Table 8.6) in which the compressional wave velocity value and the relevant geological factors could be entered and assigned appropriate weightings. The total weighted index was found to correlate very well with actual rippability. This and other systems have been reviewed by McGregor *et al*, (1994), and revised equations produced to assess machine performance and productivity.

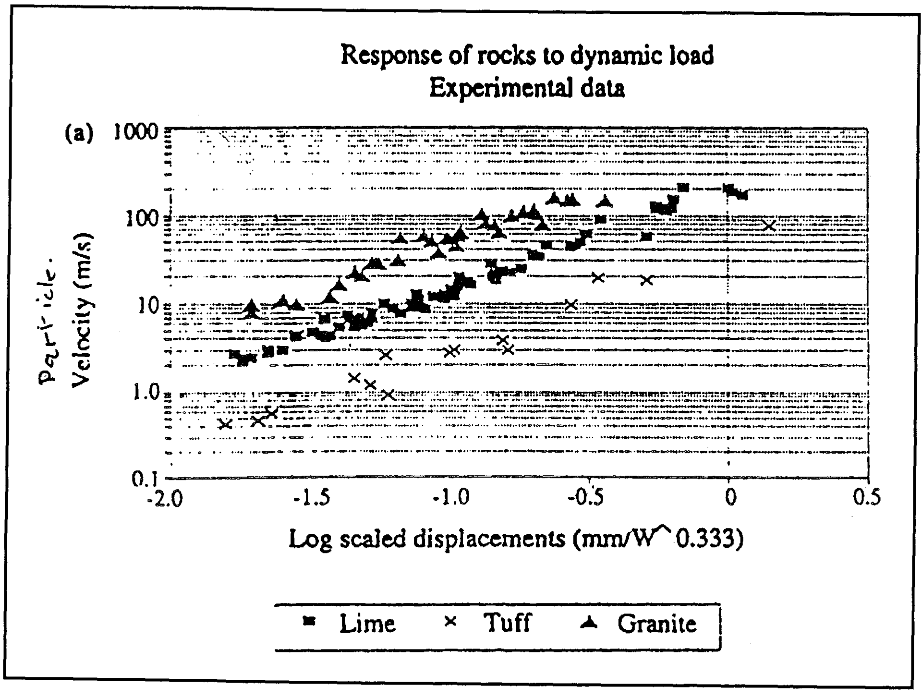


Figure 8.5 *Response of rocks to dynamic load: experimental data (after Fourney and Dick, 1995)*

8.2.6 Liquefaction potential

Soils may suffer dramatic loss of strength under both static and cyclic straining. The behaviour of the soils as a fluid is a well-known feature of earthquakes. Whether or not a soil is in a state where such behaviour may manifest itself, depends on its granulometry and state of packing. Most vulnerable are single-size loose saturated fine sands. The procedures for assessing this vulnerability are described in a report from the Committee on Earthquake Engineering, National Research Council, USA (1985). Where a large area has to be considered, there are obvious attractions in using non-invasive geophysics (eg SASW) to identify potentially troublesome deposits. Figure 8.6 shows a conservative simplified prediction chart for the threshold acceleration to initiate liquefaction, as a function of shear wave velocity and depth of a deposit.

8.3 CONSTRUCTION MATERIALS

This section of the report considers how geophysical techniques can be used to investigate the raw materials needed by construction. Coverage is limited to commonly used materials, produced by the extractive minerals industry (here defined as the non-metallic part of the minerals industry). The use of geophysical techniques in the evaluation of other raw materials of construction can be estimated from the discussion of materials, which have similar properties.

Satellite imagery, aircraft remote sensing and airborne geophysics are not covered, as they are discussed fully in the Geological Society Special Publication No 9 *Aggregates – Sand, gravel and crushed rock aggregates for construction purposes* (Engineering Group of the Geological Society, 1993) in the context of field investigations of deposits.

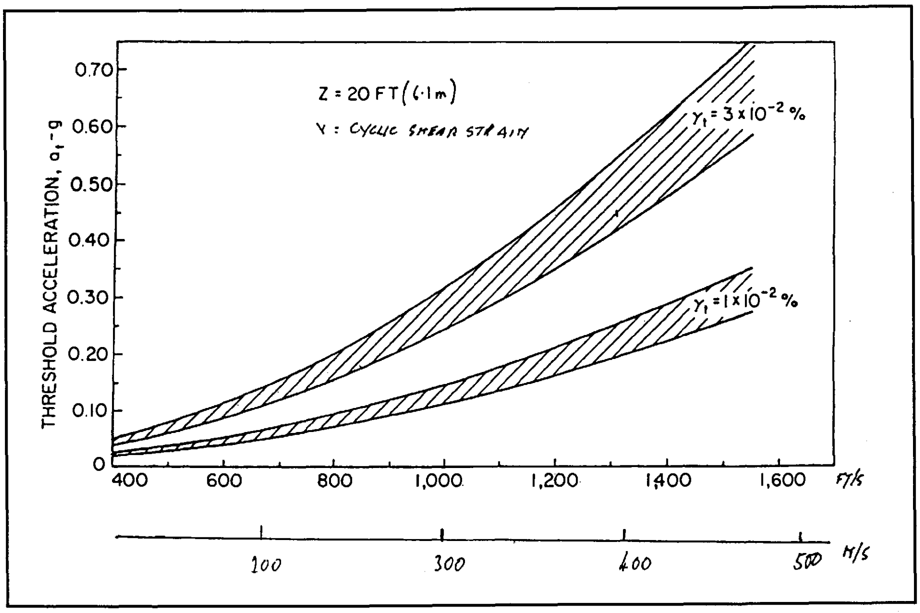


Figure 8.6 *Threshold acceleration to initiate liquefaction versus shear wave velocity*

8.3.1 Sands and gravels

Sands and gravels can usually be differentiated from adjacent rocks using electrical and electromagnetic techniques (Sections 5.1 and 5.5). Clean sands and gravels have a higher electrical resistivity (lower conductivity) than drift deposits with a high clay mineral content and argillaceous formations, but the contrast between dry deposits and non-argillaceous formations of low moisture content may be insufficient for these methods. Difficulties can also be experienced in coastal or desert areas where resistivity contrasts are reduced by saline water.

The location of sand and gravel deposits, or the areas of thickest sand or gravel within a deposit, may be determined rapidly and efficiently using a ground conductivity survey (Zalasiewicz *et al*, 1985). The seismic refraction method (Section 5.4.2) can be used to profile the base of sand and gravel deposits more accurately, but the combined use of electromagnetic ground conductivity surveying and electrical resistivity sounding, with drilling and trenching, is usually more cost effective.

An example of the more quantitative information obtainable with a resistivity sounding survey is shown in Figure. 8.7. Here the high resistivity of the gravel is easily identified and thicknesses are clearly measured.

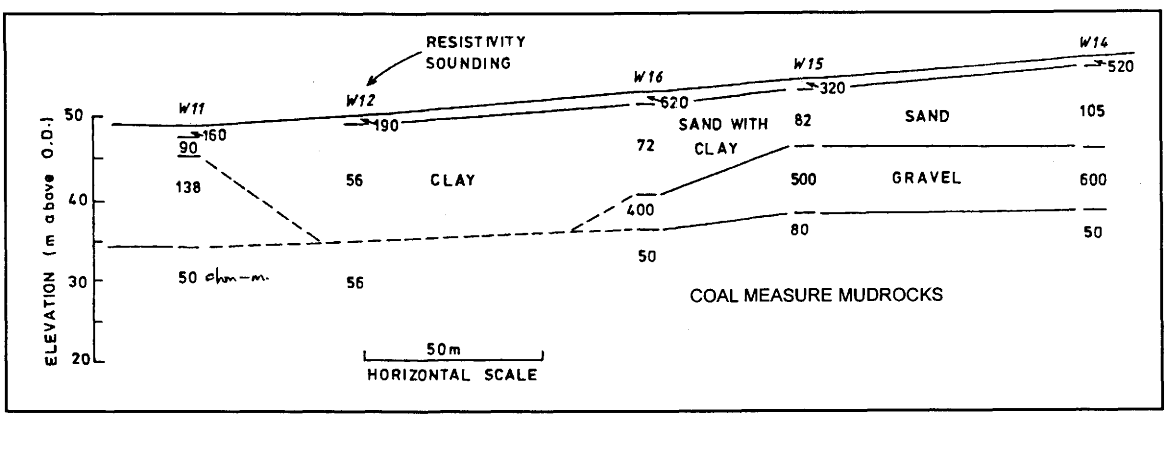


Figure 8.7 *Interpretation of profile of resistivity soundings over an area of sands and gravels. Layer of gravel with high resistivity is clearly identified.*

Hundreds of resistivity surveys have been performed over sand and gravel deposits during the last thirty years, but results have generally been poor, hence the bad reputation for this technique. However, with the introduction of digital resistance meters and improved field and interpretation techniques, a modern resistivity sounding survey is capable of providing useful and accurate, depth and lithological information. In simple geological situations, results can be useful without reference to borehole information in the survey area. In more complex situations, where several different sand formations may be present, borehole control becomes an important prerequisite to an accurate quantitative interpretation.

Ground probing radar (Huggenberger *et al*, 1994) or electrical resistivity imaging could be considered, when high resolution of heterogeneity in gravel deposits is required.

Most near-shore marine sand and gravel investigations incorporate continuous seismic reflection profiling in conjunction with sea-bed sampling and drilling programmes (Section 5.4.3). The seismic survey profiles are usually analysed with side-scan sonar and bathymetric data, to provide detailed evaluation of the sea-bed morphology and sub-bottom geological structure, as discussed in Section 8.9.

8.3.2 Non-argillaceous rocks

Unweathered igneous and metamorphic rocks, and the stronger non-argillaceous sedimentary rocks, are often quarried for use in the construction industry. The engineering qualities required (eg high strength, density and durability) usually relate to formations with high seismic velocity, density and electrical resistivity values relative to unsuitable rock types and drift deposits. Several geophysical methods may be useful.

Historically, seismic refraction has usually been used to determine the depth and thickness of non-argillaceous materials, with a fair degree of success. One of the problems with these materials is that their upper surfaces are often highly weathered and the seismic velocity of the weathered material can be similar to that of the overlying drift deposits. In these situations, the best refractor often occurs at the base of the weathered material (Table 8.7), and depth determinations from seismic refraction surveys are often greatly overestimated, compared to similar determinations using electrical methods.

The choice of technique for this type of investigation depends on whether depth to top of weathered layer, base of weathered layer, or rock quality has to be the most accurate. Barker (1983) gives examples of the use of various techniques in the study of a microdiorite in Leicestershire, and the seismic refraction results for this site are discussed in Section 7.2.5.

Table 8.7 *Typical physical properties of weathered igneous bedrock compared with underlying and overlying materials*

Physical properties	Alluvium	Weathered bedrock	Fresh bedrock
Seismic velocity (m/s)	< 2000	2000 – 4000	4000 – 5000
Resistivity (ohm-m)	< 100	200 – 1000	1000 – 5000
Density (kg/m3)	< 2000	2000 – 2600	2600 – 2800

One of the problems with the investigation of limestones, is the location of areas of poor quality, fractured or dolomitised limestone. Where such areas are shallow, they can be differentiated efficiently using ground conductivity surveys, the good quality limestone exhibiting higher resistivities than the poor quality limestone (Penn and Tucker, 1983).

In some areas, for example where Magnesian Limestone is extracted, thin clay bands can pose a problem in quarrying operations. It is usually impossible to distinguish such thin beds using surface geophysics, but they can easily be detected from their high response on natural gamma logs (Section 5.6.2), run in specially drilled holes (or indeed in the shot holes before their use for blasting). These and other borehole geophysical methods (Chapter 5) can be used to supplement the information derived from the chippings from rotary open-hole drilling.

In all these materials, seismic refraction measurements are often used to estimate rippability for quarrying operations. This application is described in Section 8.2.5.

8.3.3 Clays and argillaceous rocks

Clays and argillaceous rocks can usually be investigated using geophysics, because of their very low resistivities. Table 8.8 indicates the resistivities of selected clays and argillaceous formations, and compares them with those of saturated sands and arenaceous formations, typically found in UK. An even greater resistivity contrast would be expected with dry sands and arenaceous formations.

Qualitative estimates of the thickness of clay overlying an arenaceous layer, and the mapping of sand lenses within argillaceous formations, can be efficiently carried out using ground conductivity surveys. More accurate thickness information may be achieved with resistivity sounding or electrical imaging.

Table 8.8 *Typical resistivities of some UK soils and rocks*

Formation	Resistivity (ohm-m)
Glacial till	20–30
Lias Clay	10–15
London Clay Formation	10–20
Mercia Mudstone	20–60
Bunter Sandstone (saturated)	100–400
Quaternary sands (saturated)	50–100

Geophysical surveys are likely to be most useful where the clay is fairly consistent in its properties. Where the clays are in thin bands or are very variable in nature, eg china clays, surface geophysical surveys may prove to be of less value. Electrical and gamma logs can be run in open holes to identify thin sand seams in clays and argillaceous rocks.

8.4 FOUNDATIONS OF STRUCTURES

8.4.1 Ground investigations

An investigation is usually required to determine the variation in thickness and nature of the rocks and engineering soils within the zone of influence of the proposed structure. For many structures, adequate bearing capacity is provided below the ground surface at bedrock level. Geophysical methods are commonly used to determine the depth to bedrock (Section 7.2) and can also be used to locate potential hazards, such as fault zones and voids (Section 7.3). Such information needs to be established for settlement analysis and the assessment of subsidence risk, as well as for the calculation of bearing capacity. Knowledge of ground water conditions, such as moisture content and salinity, which can be derived from electrical measurements (Section 5.1), is also important. The limitation of boreholes for the investigation of shallow anomalous ground conditions, is illustrated by Dumbleton and West (1974). Surface geophysical traversing techniques enable such features to be mapped in detail at relatively low cost (McDowell, 1981, Venness, 1996) and confirmed by drilling or trenching.

An example of this is the mapping of clay-filled pipes in chalk, using electrical and magnetic methods, at the site of a proposed reservoir in the South of England (McDowell, 1975). The magnetic contour map (Figure 8.8) and magnetic profile (Figure 8.9) show that the arbitrary pattern of vertical boreholes used was not adequate to define the variations in ground conditions at this site. The combined use of geophysical surveying and drilling would have been better.

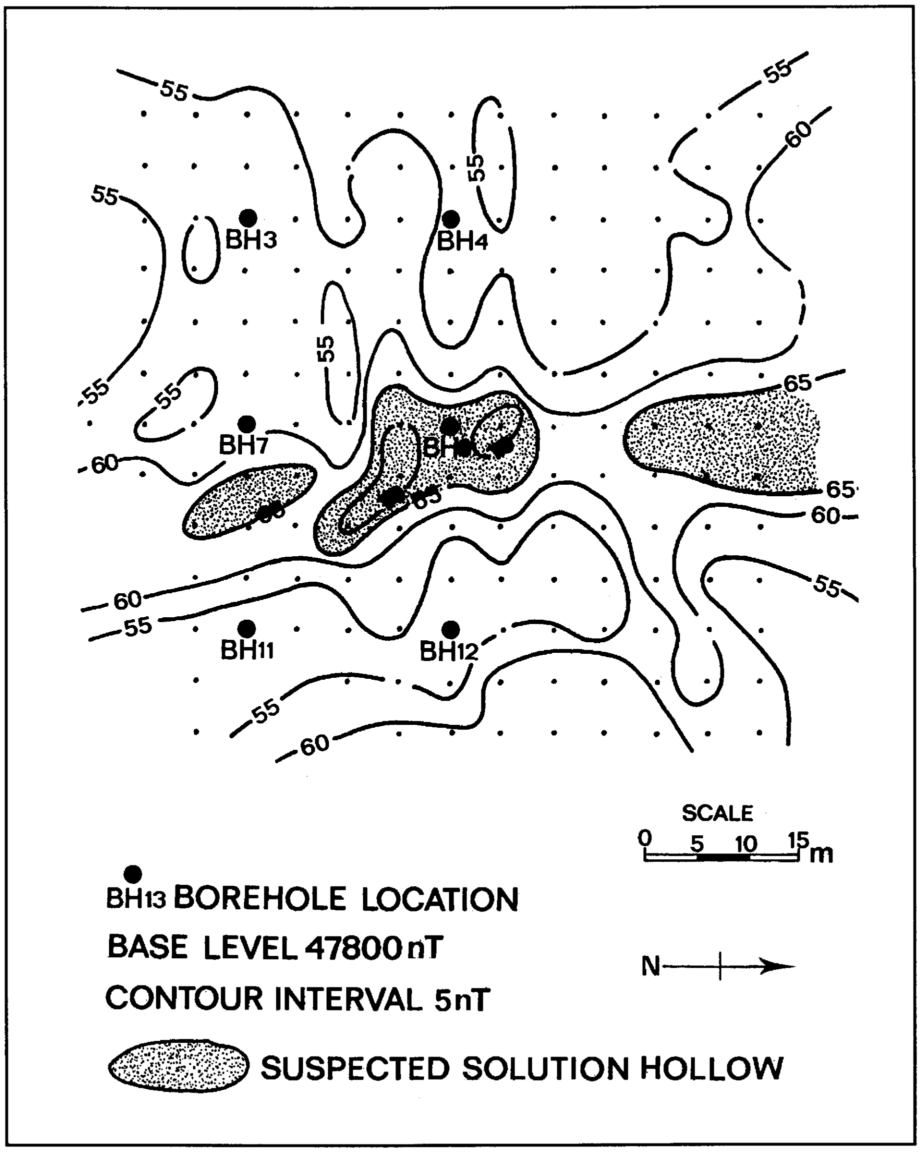


Figure 8.8 *Magnetic field strength map over clay-filled depressions in chalk, Upper Enham, Hampshire (after McDowell, 1975)*

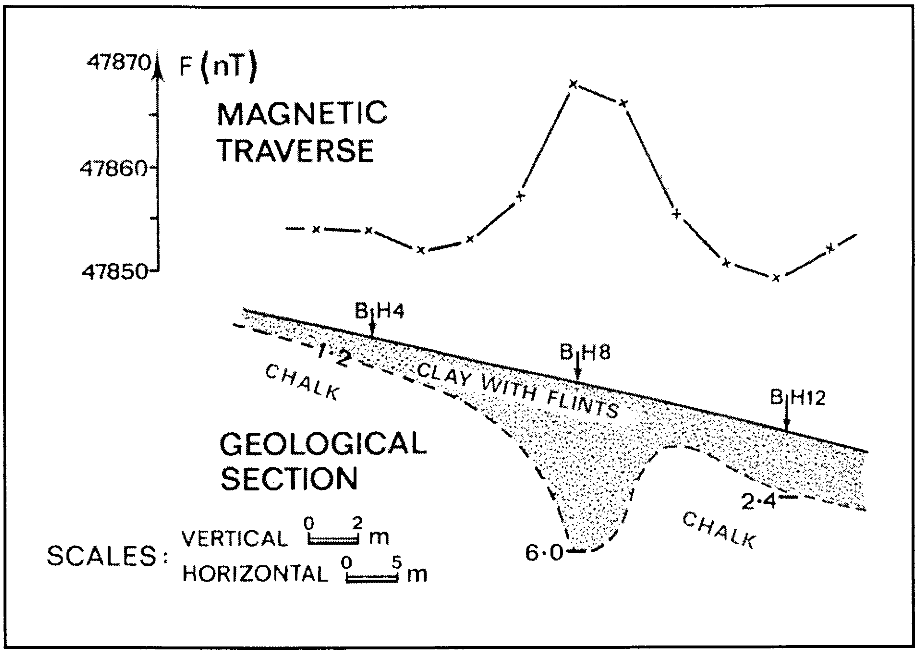


Figure 8.9 *Magnetic profile over the clay-filled depressions in chalk, Upper Enham, Hampshire (after McDowell, 1975)*

8.4.2 Strength profile

The stress applied to the ground by a structure varies with depth. For design purposes, the shear strength profile with depth is required. In the case of engineering soils, the shear strength is normally determined directly by laboratory tests or relatively small-scale *in-situ* tests, eg vane-tests in boreholes, plate bearing tests, static cone penetration tests, or standard penetration tests. Where the ground conditions are variable, the test locations can better be chosen following the results of a site investigation, which incorporates a geophysical survey, to delineate anomalous areas.

Shear wave velocities are commonly used to assess soil stiffness and a variety of techniques have been developed for this purpose (Section 8.1.1).

8.4.3 Settlement estimation

Geophysical methods are often appropriate for mapping ground conditions, which could result in differential settlement, and are generally used in conjunction with direct measurements of settlement. The mapping of peat pockets in gravels and clay-filled pipes in limestones, by electrical or electromagnetic traversing techniques, are obvious applications in this respect.

Values of deformation modulus under static loading conditions are required, to calculate ground settlements in both engineering soils and rocks, although many soils behave elastically only over a small stress range. Seismic wave velocities can be used to calculate dynamic values of Young's Modulus (Section 8.2.4), corresponding to low strain and short duration loading conditions. These modulus values may be used uncorrected, to calculate settlement for soils, when the foundations are of large dimensions, such as a reservoir tank or grain silo, but a reduction factor has to be applied where time-dependent strains are involved (Abbiss, 1983). Shear wave velocity measurements appear to be particularly applicable to the assessment of the deformability of engineering soils and can be measured by a variety of seismic techniques (Abbiss, 1981), including using surface waves (Matthews *et al*, 1997).

Seismic methods are also useful for investigating fractured rock masses and assessing rock mass deformation (see also Section 8.2). A combination of seismic refraction spreads and down-hole shooting can characterise the site into seismic-velocity zones and form the basis for locating more expensive plate loading tests. Alternatively, by determining the seismic velocity index, ie the square of the ratio of *P*-wave velocity through the rock mass to that through representative samples of the rock matrix, a scaling factor can be applied to the dynamic modulus of elasticity calculated from V_p, using established correlations with plate loading test results. These procedures might usefully supplement assessments of rock mass deformation based on the Geomechanics Rock Mass Rating factor (Bieniawski, 1978).

8.4.4 Response to dynamic loading

Dynamic loading is applied to the ground by structures, eg dams, tidal barriers, off-shore platforms, wind power generators and large vibrating machines. Dynamic elastic moduli can be derived directly from seismic wave velocities (Section 8.1), although consideration should be given to the dominant frequency of the seismic waves and the foundation loading. In the case of vibrating machinery, such as electrical generators, which can vibrate within a relatively wide frequency range, the foundation block has to be designed to avoid resonance (CP2012: Part 1: *Foundations for machinery* BSI, 1974). The results of ground investigations at the proposed sites of generators for the Akjoujt Power Station in Mauritania, West Africa, illustrate the advantages and limitations of surface and borehole seismic techniques for this purpose (McDowell, 1990).

8.4.5 Subsidence risk

Ground subsidence has many causes, eg shrinkage of clay soils, landslides, collapse of subsurface voids. The distribution of clay soils can be determined using ground conductivity surveys, as the conductivity of clays is significantly higher than that of granular soils or most of the common rock types. These and other geophysical methods can assist in the investigation of landslips and in the location and delineation of natural solution cavities, in limestones and voids formed by piping in sands.

Usually, at least one geophysical method, or field procedure, can be incorporated advantageously into the investigation of voids (Section 7.3.3), especially if an initial assessment of the size of void that could produce subsidence is available. Collapses of abandoned shallow mine-workings, particularly mine-shafts and deneholes, are often difficult to locate by conventional vertical drilling, because of their limited lateral extent. In such cases geophysical methods can be very cost-effective. Resolution is the main consideration and particular attention should be given to the design of the geophysical survey in terms of method, equipment and field procedures.

Ground subsidence is also common in areas with soluble mineral deposits, such as halite and gypsum, particularly where there has been mining activity. Recent UK examples include the use of acoustic tomography at Lion Salt Works in Cheshire (Adams *et al*, 1992; Clayton *et al*, 1990) and microgravity surveys in areas underlain by gypsiferous Permo-Triassic strata around Ripon in Yorkshire.

8.5 DAMS AND RESERVOIRS

8.5.1 Site location and appraisal

There are many published case histories of the use of geophysical surveying in preliminary dam site and reservoir investigations, such as the use of seismic refraction surveying to map variations in alluvium thickness over limestone and the mapping of a buried valley by the gravity method (Mathiez and Astier, 1958; Hall and Hajnal, 1962). A comprehensive geophysical investigation of an existing dam foundation is provided by Butler *et al*, (1991).

The availability of construction materials will influence the choice of type of dam and indirectly its siting. If a large area is to be investigated, the geophysical surveys can be carried out from the air, electromagnetic methods generally being used to locate clays and magnetic methods to map the location and extent of basic igneous rocks (sections 5.3.3 and 5.5.3). Similar methods can be used for a more detailed materials search on the ground (Section 8.3).

A groundwater investigation of a large area will usually include electrical resistivity or electromagnetic methods (chapters 5 and 9).

8.5.2 Investigations of dam foundations

Prior to construction of the dam, a detailed investigation is required to determine the bulk and local permeabilities of the ground and to assess the stability of the dam and associated structures when the reservoir is full. Seismic refraction spreads are usually set out along and adjacent to, the centre-line of the dam, and at the proposed sites of spillways, diversion tunnels and power stations. Often sufficient boreholes would be available for cross-hole or surface-to-borehole seismic investigations of the rock mass, and similar investigations can be carried out using exploration adits. Variations in the velocity of compressional and shear waves can be related to fracture state (Section 8.2.3).

Seismic methods are also used to assess the deformation moduli of the foundation rocks, particularly for concrete arch dams, where the ratio of the modulus of the concrete to that of the ground is required along the whole length of the dam. Seismic refraction methods can provide velocity values at foundation level, for the entire site, before superficial deposits and weathered rock are removed. These velocities can then be used to assess deformation modulus values under dynamic or static loading conditions (Section 8.2.4). The velocity of the rock mass at foundation level could be reduced by removal of the overburden, especially if blasting methods are used for excavation.

Borehole geophysical logging methods can be used for detailed geological investigations, or to establish the variation of the physical properties of the ground with depth. For example, natural gamma-ray logging can locate potentially hazardous clay seams, and 3-D velocity logging can be used to locate fracture zones, as well as providing P and S wave velocities for modulus calculations (Geyer and Myung, 1971).

8.5.3 Leakage

Potential leakage paths need to be identified at the site investigation stage, whether in the dam foundation, its abutments or around the reservoir area. The mapping of natural cavities and mine-workings often involves the use of geophysical methods. Seismic refraction, electrical resistivity and EM gravity traversing can be used to trace buried channels, which may provide leakage paths (Section 7.2.6). Seepage losses can also occur through "fracture zones", particularly in the dam foundations where permeability could increase with time because of internal erosion. Seismic, EM and electrical methods are appropriate techniques for investigating this particular problem. ER sounding was successfully used at a dam site and reservoir in a karstified limestone area for this purpose (Arandjclovic, 1966).

An associated problem is the location of leakage paths from completed and full reservoirs. If there are preferred leakage paths, it might be possible to locate them by the combined use of seismic refraction surveying and electrical imaging. Self potential (SP) techniques have been used to locate leakage paths from reservoirs and through earthfill dams, eg at the Mill Creek dam in Washington, U.S.A. (Butler and Llopis, 1990). A summary and evaluation of this case study, and a discussion of the use of this technique in water-covered areas, is provided by Reynolds (1997).

8.5.4 Ground treatment

Grouting is often used at dam sites to reduce the permeability of the ground and may also be used to reduce leakage from the reservoir area. Geophysical methods are most commonly applied to locate vertical zones of intensive jointing that require selective grouting, and can be used to assist in both the planning of the grouting programme and the accurate location of boreholes for *in-situ* permeability measurements. At dam sites, horizontal and vertical variations in the compressional wave velocity of the rock mass can be determined and, with corresponding velocities measured in the laboratory (Chapter 5), enable the fracture-index to be calculated (Section 8.2.3). A prediction of the grout take can then be made from the fracture index (Figure 8.10).

Seismic tests have been used successfully to measure the increase in modulus of dam foundations on jointed rocks, as a result of consolidation grouting. The grout holes can be cleaned out, after injection of cement into the ground, and used for cross-hole shooting at appropriate depth intervals. Comparison of the velocities obtained before and after grouting, will indicate how much the dynamic Young's Modulus has increased, and this information can be used to calculate settlement during loading.

8.6 SURFACE EXCAVATIONS

This section is concerned with man-made excavations from the ground surface, eg cuttings, quarries, pits and foundation excavations – but not shafts and adits, which are included in Section 8.7. Forward planning of excavation usually requires an appropriate site investigation, which may include geophysical surveys. Surface geophysical methods can assist the investigation of ground conditions, at sites where extensive excavations are proposed, particularly in drift-covered areas. Borehole geophysical methods are widely used for logging blast holes at open-cast coal pits, eg natural gamma ray logs are used to pick out the clay horizons and gamma-gamma (density) logs are used to locate worked-out coal seams (Section 5.6.2).

Ground vibrations resulting from blasting can be monitored by what are essentially seismic methods, but this subject is beyond the scope of this report.

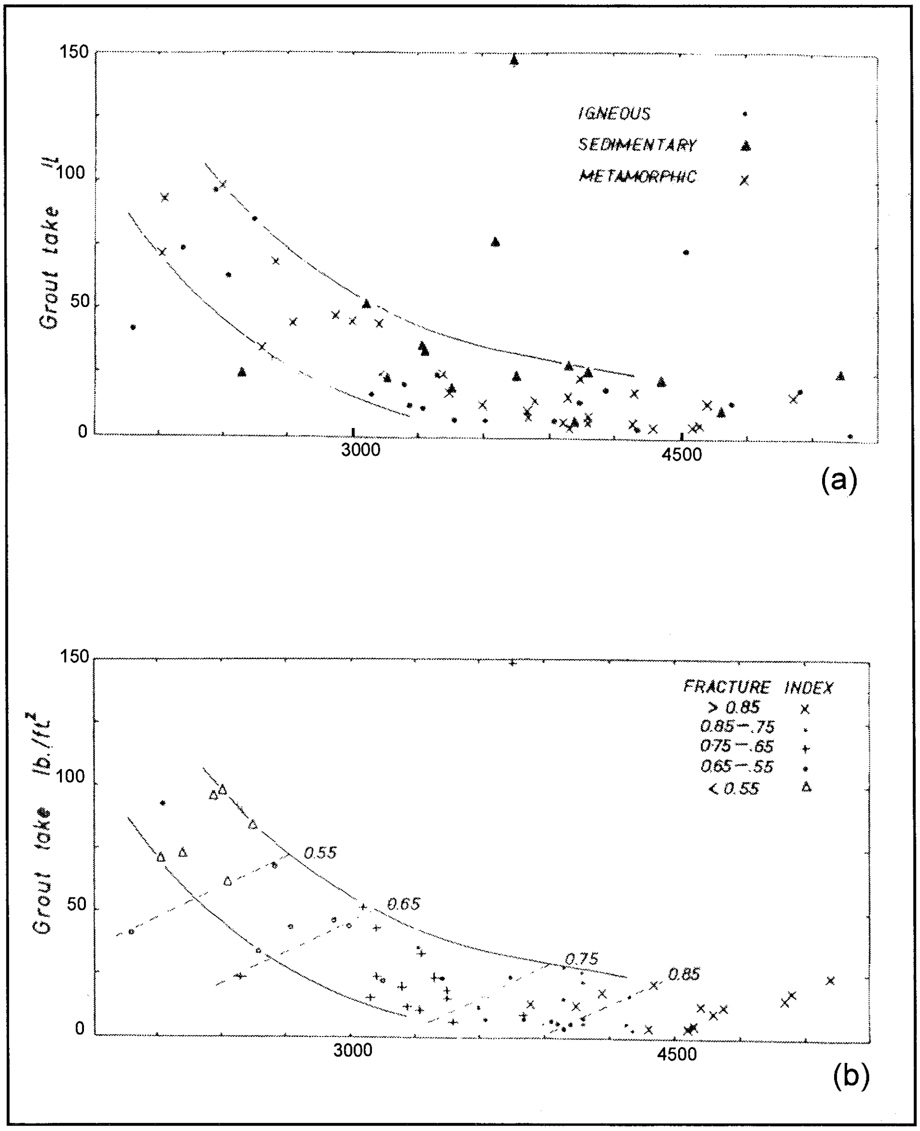


Figure 8.10 *Relationships between longitudinal wave velocity V_P and (a) curtain grout take and rock type and (b) curtain grout take and fracture index F (after Knill, 1970)*

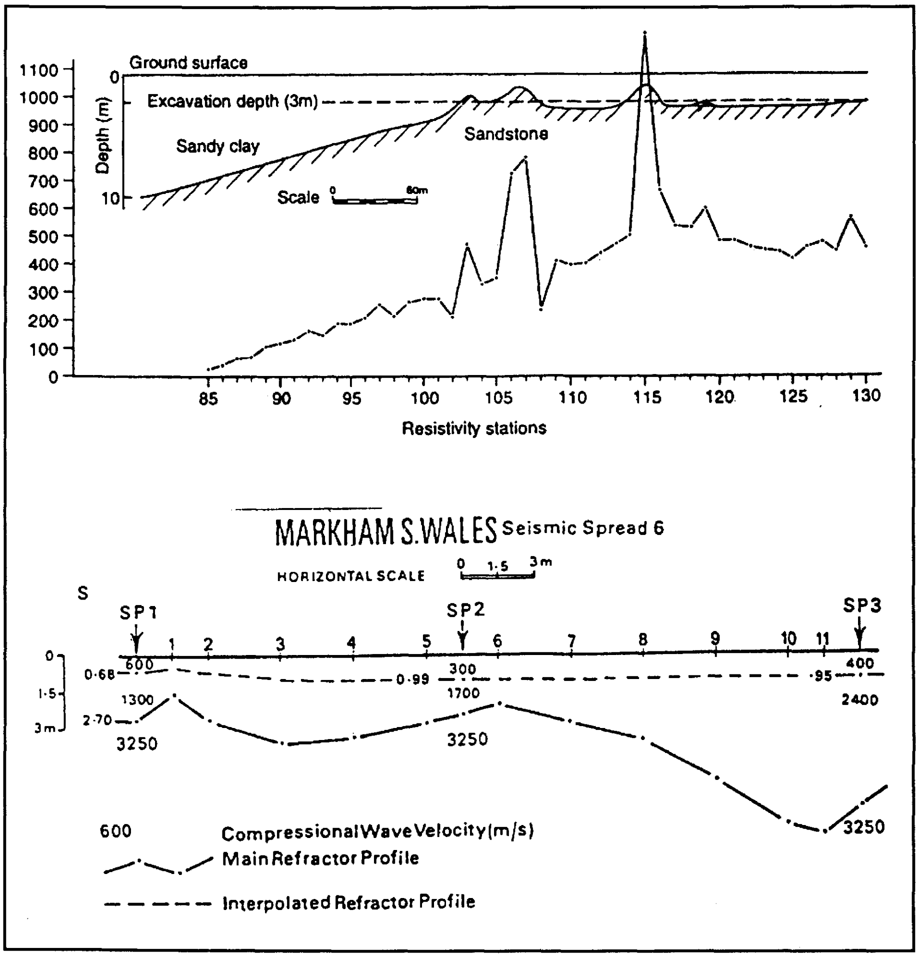


Figure 8.11 *Geophysical surveys for a trunk sewer in South Wales: (a) electrical resistivity profile and rockhead interpretation and (b) seismic refraction profile and velocities (after Prentice and McDowell, 1976)*

8.6.1 Excavation method

Significant reductions in earth-moving costs can be made if drilling and blasting procedures, and damage to excavation plant can be minimised. An assessment of the rippability of rock mass is required, which often involves the use of seismic refraction methods (Section 8.2.5). The seismic refraction survey should be carried out using a procedure that enables each seismic refractor to be continuously profiled, along the whole length of each spread. Figures 8.11 (a) and (b) show some of the results of geophysical investigations obtained at Markham, in South Wales, where excavation for a sewer pipe was required to a depth of 3 m. Electrical and seismic refraction methods were used to assess the depth to bedrock and whether it needed blasting. Figure 8.11 (a) shows the anticipated bedrock profile along the route, based upon the apparent resistivity profile and the results of electrical resistivity sounding. This profile was used to site the seismic refraction spreads. The seismic refraction results, eg Figure 8.11 (b), showed where there were Carboniferous sandstones and mudstones of velocity greater than 3250 m/s, which would require blasting prior to excavation (Prentice and McDowell, 1976).

In-situ seismic velocity values can also be used for initial assessments of the powder-factor, a charge parameter, when blasting is required for excavation (Broadbent, 1974).

Variability in the ground conditions can also affect the choice of machinery for the efficient extraction of engineering materials. For example, at a gravel pit in West Sussex the excavation plant had to selectively win gravel without digging out chalk pinnacles and clay pockets (McDowell and Hooper, 1980). These features were identified by resistivity traversing because of their low electrical resistivity, relative to that of the gravel. Gardener (1992) provides case studies of seismic refraction surveys to evaluate rock quality for dredging and engineering purposes.

8.6.2 Groundwater

The general application of geophysical methods to groundwater investigation is covered in Chapter 9, but specific problems can develop with surface excavations. Dewatering of a sand pit, for example, may produce piping and lead to ground subsidence beneath heavy processing plant, roadways or adjacent properties. Although it is difficult to locate piping by geophysical methods, it should be possible to detect associated crown-holes by electrical resistivity or radar traversing technique, and water-filled pipes by self-potential techniques.

8.6.3 Slope stability

The stability of excavated slopes has to be considered prior to excavation, and a ground investigation may be required to assess the rock mass fracture state or lithological variations that would influence slope stability. Fault zones can be located and fracture anisotropy assessed by surface or inter-borehole seismic methods (sections 7.3.4 and 8.2.3). Seismic refraction surveys can also be used to assess the degree of fracturing behind excavated rock faces as a result of blasting or stress-relief. Borehole logging methods can be used to locate potential failure planes that may be missed by drilling, eg a natural gamma-ray log of a borehole should detect very thin clay seams if an appropriate count rate and logging speed are used. Radar reflection techniques are now available for use within a single borehole, or between boreholes, to map water-filled fissures, eg the RAMAC system described by Reynolds (1997).

8.7 SUBSURFACE EXCAVATIONS

This section is concerned with tunnels, chambers and shafts. Alternative routes for tunnels can be investigated by geophysical methods in much the same way as for other route surveys (Section 8.8). However, as a tunnel investigation is likely to extend to greater depths than for roads and pipelines, a modified field approach, or the use of different geophysical methods may be required. For the investigation of sites for chambers and shafts, borehole geophysical methods are usually more appropriate than surface-traversing techniques.

During construction, geophysical measurements from within the excavation can be used for investigating the rock mass around the excavation. Engineering construction parameters can, in some cases, be assessed from the geophysical parameters (sections 8.1 and 8.2).

8.7.1 Ground investigation

Surface geophysical surveys can provide data, which can significantly extend the geological information obtained from boreholes along a tunnel route. Widely spaced vertical boreholes cannot adequately define irregular bedrock profiles and they may miss buried channels, fault zones, voids and other anomalous ground conditions. Chapter 7 explores the application of geophysical methods to these geological targets and Chapter 9 describes the application in groundwater investigations.

Continuous seismic refraction profiling is particularly appropriate for the investigation of the bedrock profile along tunnel routes where the depth of cover is less than 50 m. The length of the seismic spread and the spacing of geophones should be carefully considered, however. This will enable the maximum information to be obtained for the ground at tunnel invert level and allow adequate lateral definition of near-vertical features such as dykes and fracture zones. Difficulties occur in urban areas because of high background noise levels and anomalous near-surface ground conditions, but these can be minimised by appropriate field procedures and useful, if not highly accurate, results are obtained. An example of this is the mapping of a buried channel where the line of the Flood Brook Sewer crosses the M56 motorway (McDowell, 1986). Other geophysical methods, such as electromagnetic profiling, may be more appropriate when only the location and trend of buried channels is required. A combination of seismic, electrical and borehole geophysical methods were used for the investigation of the route for the A3 Hindhead Tunnel (MacDonald and Chartres, 1994).

Where the depth of cover exceeds 50 m, the spread-length for seismic refraction surveying becomes excessive and alternative methods, such as seismic reflection, gravity methods and magnetic methods (Chapter 5), should be considered. Both gravity and magnetic methods are applicable for mapping faults with large vertical displacements, the contrast in density and magnetic properties of the strata being the deciding factor. Gravity surveys can also be used to map large buried channels and voids (sections 7.2.6 and 7.3.3). More subtle variations, such as small vertical fault displacements, may be resolved by the use of high-resolution seismic reflection techniques. A seismic reflection survey with a Vibroseis energy source successfully investigated the ground to a depth of 180 m for proposed tunnels in Chicago, where adverse noise and ground conditions would be expected (Mossman and Heim, 1972). Detailed structure contours and fault traces were obtained at a very small proportion of the cost of drilling for the same information. Seismic reflection and VSP techniques were also used in the Channel Tunnel site investigation (Arthur *et al*, 1997).

Magnetic surveying is a rapid and inexpensive method of mapping basic igneous dykes and investigating the depth of weathering of basic igneous rocks. Faulting can be investigated indirectly, where dykes have been laterally offset by cross-cutting faults. This technique was successfully used in the investigations of tunnel lines at the site of the Drakensberg Pumped Storage Scheme in South Africa.

The investigation of the sites of chambers and shafts is localised needing only one or a few boreholes to provide the geological information. However, cross-hole tomography by inter-borehole geophysical measurements, using seismic and possibly radar methods, can be used to locate fractures, faults and voids. A wide variety of in-hole geophysical techniques are also available for determining the physical properties of the geological formations.

8.7.2 Investigations from within subsurface excavation

Surface investigations cannot fully determine the ground conditions that will be encountered during construction and additional surveys may be required from within trial or final excavations.

While various geophysical methods have been used in the past to assess ground conditions around and ahead of tunnels (TRRL Supp. Report 171 UC, 1975), one of the main difficulties experienced is incompatibility with construction activity, particularly for seismic surveys.

A variety of acoustic methods is available to evaluate the rock mass around subsurface excavations. Seismic refraction profiling can be used along the floors, walls or roof of the excavation in the same way as seismic refraction surveying on the ground surface. The spread lengths are relatively small and a seismograph with a timing accuracy of 0.1 ms or better is required. Geophones need to be cemented to the rock face or attached to bolts driven into the rock. A velocity profile is obtained which enables the velocity and thickness of the zone of disruption, due to excavation damage and stress relief, to be mapped. This technique, together with *P*-wave tomography and *P*- and *S*-wave along-hole measurements, was used to investigate fracture state and to provide elastic moduli values for karstified chalk around an underground storage chamber in Israel (McDowell *et al*, 1992). Spectral analysis of surface waves (SASW) techniques can be applied to the investigation of deterioration behind the tunnel lining (Cuellar, 1997). These and other methods for investigating voiding behind linings are discussed in Chapter 11.

Radar reflection methods may be applicable in massive crystalline rocks with low moisture contents, for locating fractures, cavities and even vertical boreholes ahead of the working face.

Microseismic activity related to *in-situ* stress variations, rock-bursts and rock falls can be monitored during and after construction by geophysical instruments.

8.8 ROUTE SURVEYS

This section considers the application of geophysical methods to linear engineering structures, such as highways, railways, canals and pipelines. The ground conditions within 10 m or so of the ground surface are of particular interest in such cases. Geologically this zone can be variable because of weathering processes, superficial deposits and mass movement. There can also be the added complication of abandoned shallow mine-workings, ancient foundations and backfilled areas. The application of geophysical methods to specific geological targets is covered in Chapter 7, but ground variations of particular relevance to route surveys are discussed in this section.

8.8.1 Route appraisal

Feasibility studies for route selection in unknown territory should incorporate geophysical surveys, particularly when the linear structure is long or if there are several possible routes. Air surveys with remote sensing techniques are particularly useful in this respect, but these are described in other documents, eg *The Working Party Report on Terrain Evaluation* (Engineering Group of the Geological Society of London, 1982). Regional geophysical investigations can be used to map buried channels, igneous dykes, faults and groundwater conditions (sections 5.3.3 and 5.5.3).

Once a route, or corridor of routes, has been chosen, geophysical methods are usually incorporated into each site investigation stage. For example, rapid EM ground conductivity traversing techniques can be used to assess lateral variations in ground conditions and to locate anomalous ground conditions. Figure 8.12 shows an apparent resistivity profile, based upon data obtained with the Geonics EM31 ground conductivity meter, along a section of the A3M road in Hampshire. It clearly shows water bearing sand lenses within clay, over chalk, as well as the chalk sub-crop.

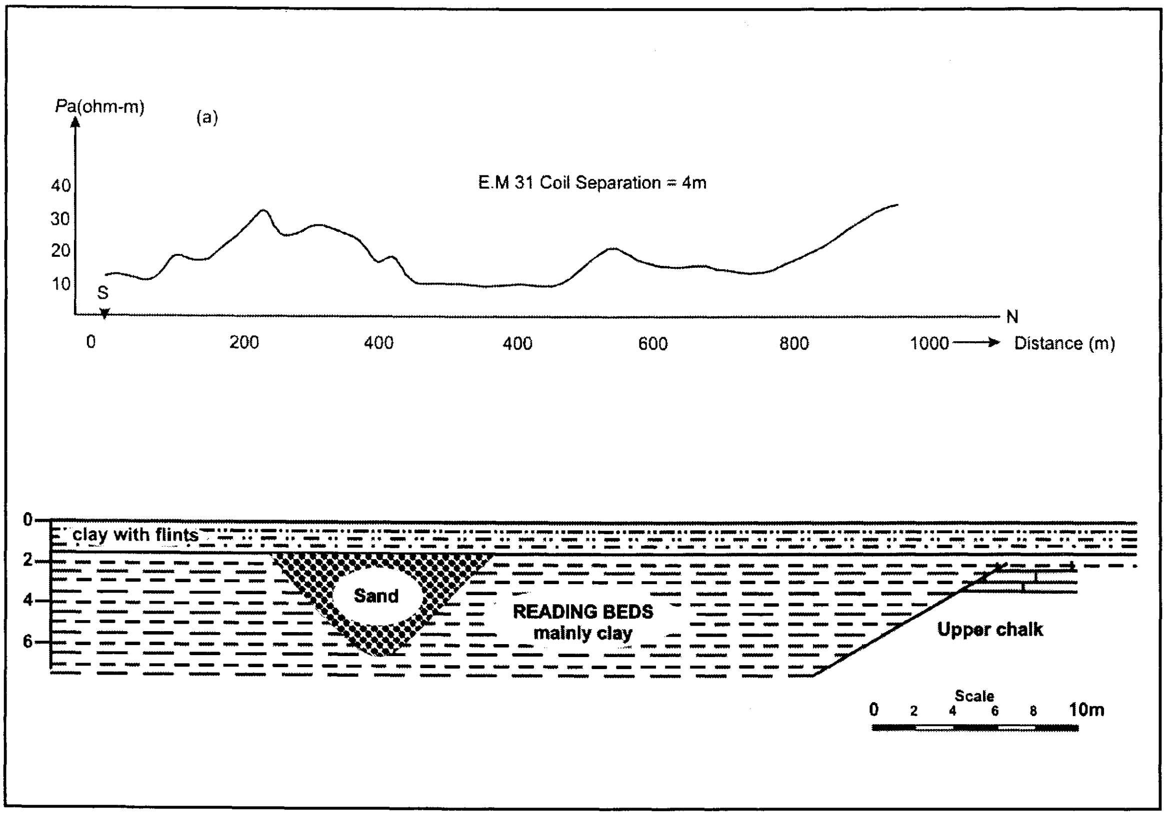


Figure 8.12 *EM ground conductivity profile along A3M route at Horndean, Hampshire*

The seismic refraction method is often considered for route appraisals when a bedrock profile is required. Depths to bedrock can often be calculated to an accuracy of 10 per cent, given an adequate contrast in seismic velocity between the bedrock and the overburden. A continuous bedrock profile, and lateral velocity variations within the bedrock and overburden, can also be provided (Chapter 5). Usually the spread length is less than 50 m for these shallow depth investigations, and a large number of seismic spreads would be required to provide continuous coverage over the whole length of a route. A combined use of EM traversing and seismic refraction surveying of selected locations may be advantageous. This technique can also be used to assess the excavation requirements along routes, indicating areas where blasting is required and providing information that can assist in the selection of excavation plant (Section 8.6.1).

The seismic refraction method is particularly useful for mapping near-vertical zones of weakness within rock masses, which are difficult to locate by vertical drilling. Velocity values obtained are essentially for horizontal ray paths within each seismic layer and are sensitive to near-vertical discontinuities in the rock mass. However, the geophone spacing along each spread and the predominant wavelength must be smaller than the width of the zone of weakness, if these features are to be recognised from time-distance graphs. Ideally, any narrow low-velocity zones indicated by the seismic results should be further investigated by inclined boreholes. Improved procedures in seismic refraction surveying for road construction contracts have been proposed by Stewart *et al* (1997), and Walker and Win (1997).

8.8.2 Embankments, pavements and pipelines

Embankments

One of the most important factors in highway construction is the availability of suitable material for embankments, concrete and roadstone. Geophysical methods for locating sources of suitable rock types, sand and gravel deposits are discussed in Section 8.3.

Compaction of embankments is important to minimise settlement of the road pavement. A higher percentage of air voids is often associated with lower electrical conductivity, especially in the case of chalk or clay fill, and ground conductivity profiling could be used to locate suspect areas. Seismic methods, particularly those incorporating shear wave velocity measurements, or spectral analysis of surface waves, may also be used for this purpose (Cuellar, 1997).

Pavements

Nuclear methods can be used to determine density and moisture content *in situ* without disturbing the road material (Section 5.6). Similar methods can be used to measure the binder content of bituminous and tar mixes, and the voids content of the bituminous surface layer (Kuhn, 1978).

Acoustic methods are sometimes used to investigate the elastic properties of near-surface soils and the layers that make up the road, to evaluate pavement condition and performance. Ultrasonic and small-scale seismic refraction surveys enable the measurement of both compressional and shear waves (Freeme, 1978), which can be used to determine elastic moduli for dynamic loading (Section 8.1.1). Seismic tomographic imaging can provide more accurate modulus values, for thin base and asphalt layers within pavements, than the more conventional falling weight deflectometer method.

Pipelines

The selection of trench excavation methods and decisions between pipe-jacking and tunnelling can be eased by incorporating geophysical methods into the preliminary investigations. Electrical resistivity and seismic refraction methods were used, for example, to investigate a trunk sewer line in South Wales, where access for drilling equipment was very difficult (Prentice and McDowell, 1976). The electrical resistivity results clearly distinguished strong sandstones from weaker mudstones and drift deposits along the whole route, and enabled the selection of locations for more detailed evaluation by seismic refraction.

Corrosion of buried pipes requires an assessment of the aggressiveness of the soils and groundwater along the route. For shallow pipes the rapid electromagnetic traversing techniques are appropriate, although they should be supplemented by electrical resistivity sounding at selected locations (Section 8.2.1). With insufficient measurements it is possible that apparent resistivity values could be recorded that are within a non-aggressive range, while the true resistivity of the ground at the depth the pipe is to be laid is within the aggressive range.

Underground power cables need to be placed within material capable of transmitting heat away from the cable rapidly enough to avoid overheating. A thermal probe can be used to determine the thermal resistivity *in situ* (Section 5.7).

8.9 COASTAL AND OFFSHORE ENGINEERING

Coastal and off-shore engineering is increasing worldwide, because of the civil engineering implications of the exploration and exploitation of oil and natural gas, eg platforms, pipelines, deepwater anchoring facilities and harbours. In densely populated countries there has been an increase in land reclamation and the construction of tunnels, bridges, breakwaters, tidal barrages and sewage outfall works. The investigation and extraction of off-shore sand, gravel and other mineral deposits is another expanding industry. There has been corresponding rapid development of geophysical techniques for geotechnical purposes, such as the extraction of geotechnical information from high-resolution seismic refraction data.

The first stage of the investigation of a coastal or off-shore area, where engineering developments are proposed, is an appraisal of the topography of the region, the nature, distribution and engineering properties of the sediments and rock types likely to be encountered. In the shallow water coastal zone, the geology at (and just below) the sea-bed can sometimes be determined by extrapolating information from the adjacent land, but usually a site investigation is also required. The sea-bed morphology is established by echo-sounding or side-scan sonar surveys (Section 5.4.3) and geophysical methods are used to investigate the geology. Seismic refraction and continuous seismic reflection profiling (Section 5.4.2) are the methods generally adopted in shallow water areas, with high-resolution seismic reflection surveys for off-shore sites. Other geophysical methods may be considered for particular applications, such as magnetic surveying (Section 5.3) for mapping igneous intrusions and faults, and borehole and sea-floor geophysical measurements to assess engineering parameters. An overview of the application of geophysical methods for in-shore and off-shore investigations may be found in McQuillin and Ardus (1977).

Geophysical surveys are used extensively at the planning stage to provide additional geological information for the ground beneath the construction site and the positioning of the investigation boreholes. The cost of investigations over water is increased by unsuitable weather.

8.9.1 Inshore surveys

Most inshore geological surveys use geophysical techniques in conjunction with a programme of sea-bed sampling and drilling. Continuous seismic profiling, side-scan sonar and bathymetric surveys are often undertaken to examine the geological structure at (and below) the sea-bed, and the sea-bed morphology. The three surveys can be operated simultaneously so that recorded fixed positions are identical for each. It is possible to use the records to obtain a simultaneous interpretation of both the sea-bed morphology and the geology at and below the sea-bed. This results in an improved geological interpretation, as possible faults identified by continuous seismic profiling can be checked against outcrop patterns on the sonar records.

High quality navigation methods, such as the Global Positioning System (GPS) and the Differential Global Positioning System (DGPS), are essential to locate the survey lines accurately, relative to the shore-line. A tide gauge is usually installed in a convenient harbour and levelled into a nearby benchmark so that the echo-sounder readings are reduced to the local Ordnance Survey datum level. In very shallow water, the plotted positions of rock outcrops, which appear above water at low tide, can be used to improve the accuracy in plotting sideways-looking sonar records. Care should be taken with the deployment of the sonar transducer in shallow water, as the overall coverage of the sea-floor may be curtailed by the reduction in the overall beam width. A useful and practical review of the use of side-scan sonar may be found in Flemming (1976).

The continuous seismic profiling records provide information on geological structure, as major features are recognisable and can be interpolated between survey lines. It is important to realise that the geological information is portrayed as a series of seismo-stratigraphical groups, whose lithologies can be determined only by sampling of the sea-bed outcrops, or the collection of cores from boreholes. Geological interfaces are traced from the seismic records with basic depth measurements expressed as two-way travel time in milliseconds.

For conversion to true depths, the compressional wave velocities in the various geological units have to be determined, either by laboratory measurements on samples or by sonic logging methods. Borehole results can be used to check and refine the true-depth profiles.

In shallow water, the presence of multiple reflections between the sea-surface and sea bottom can cause problems by masking out the reflectors at (or below) the sea-bed on the records. This effect can be reduced by carrying out the survey at high tide, or removed by subsequent data processing. The use of high frequency sources, such as the "pinger" and "boomer", can improve resolution and enhance the records in the shallow water surveys, but the depth of penetration is limited and it may be necessary to use a "sparker" or air-gun source. It is important that the resolution is adequate for the engineering application being considered. The overall deployment of suitable geophysical surveying equipment and the choice of navigational system depend on the particular environment under investigation. Examples, which illustrate this point are the Crouch/Roach River survey described in Conway *et al* (1985) and the Lyme Regis off-shore survey described by Darton *et al* (1981). Figure 8.13 is a typical continuous seismic profiling record for a shallow depth near-shore investigation.

In shallow water the seismic refraction method may be more suitable than continuous seismic reflection. The relative advantages of the two methods, in the evaluation of rock quality, for dredging and trenching are discussed fully by Gardner (1983). A particular advantage of the seismic refraction method over reflection profiling is the provision of velocity values for the rock, from which estimates of quality can be made. For intertidal areas and narrow estuaries, problems of multiple reflections and possibly side-reflections mean conventional seismic refraction surveys, similar to those used on land, may be more suitable than seismic reflection surveys. The refraction method was successfully used for the investigation of potential bridge sites on the Torridge River estuary in Devon (Prentice and McDowell, 1977).

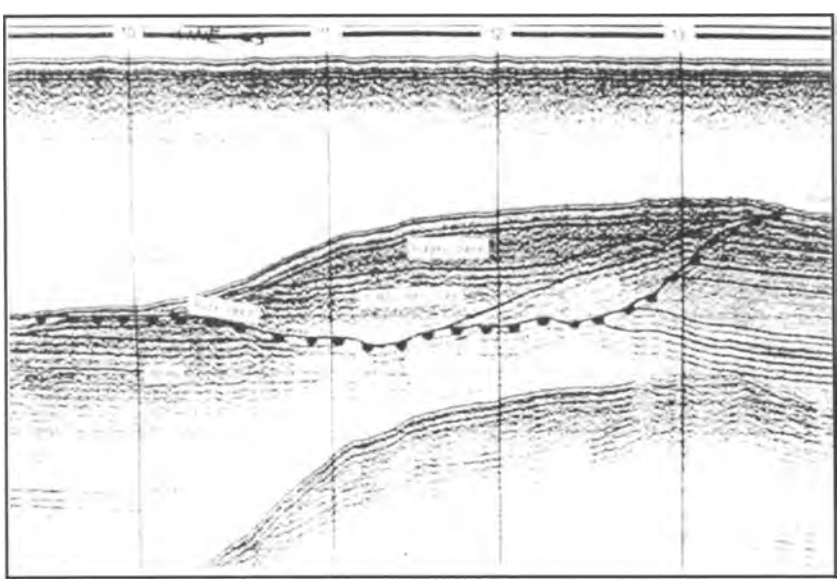


Figure 8.15 *Shallow offshore continuous seismic reflection profile*

8.9.2 Offshore surveys

The selection of sites, for expensive hydrocarbon production platforms offshore, is preceded by a site investigation aimed at identifying potential hazards and defining the geotechnical properties of the sea-floor. Seismic reflection methods are generally used in conjunction with side-scan sonar. Such methods employ sources, which are designed to provide well-shaped and repeatable pulses rich in high frequencies. Sparker, air gun, water gun and special explosives may be used. A rig-site survey will usually cover an area of about 3 km by 3 km, using a 300 m to 500 m grid of lines, with data recorded using an analogue, single channel profiling system. The central portion, an area of 1 km by 1 km centred around the proposed platform site, would be studied using a multi-channel digital recording system and a more detailed line spacing on a 50 m grid. The actual survey parameters and layout will take account of the proposed structures, and full reviews of the required planning of such surveys may be found in Le Tirant (1979) and Games (1986).

The records provided by such surveys are usually presented after processing, with large vertical exaggeration and features appear with apparently high slope angles. The interpreter will look for anomalies, which may be associated with such potentially hazardous conditions as the presence of high-pressure oil or gas at shallow depths. This may appear as a localised abnormally high reflective layer, a "bright spot". A diffuse but acoustically absorbing zone can indicate gassy sediments of high compressibility. Some non-gassy muds overlying reflective bedrock can be mapped in conjunction with sonar and used to define sea-bed morphology. For geotechnical reasons it may also be important to locate sediment-filled erosion features, faults and subcrops.

Facilities are now available to carry out measurements of the geophysical properties of the bottom sediments, from the sea-bed. For example, such data could include shear wave velocity, which may be used to assess appropriate geotechnical parameters. (McCann and Taylor-Smith, 1973).

Geological Society, London, Engineering Geology Special Publications

Geo-environmental applications

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 187-205
doi:10.1144/GSL.ENG.2002.019.01.09

9 Geo-environmental applications

Environmental applications of geophysical techniques concern the location, delineation and monitoring of subsurface, natural and man-derived hazards. Environmental geophysical surveys are concerned with the near surface, typically to depths of less than 30 m. Natural hazards include dissolution cavities, collapsing soils and earthquakes. Man-made hazards arise from the effects of pollution and previous land usage. Geophysical techniques may be applied in the assessment of the condition of derelict or contaminated land and the monitoring of remedial measures.

The use of non-invasive geophysical methods is attractive where contamination is near the ground surface, as they do not penetrate any capping, which minimises the release of gas or the ingress of surface water. In some cases, to find contaminated zones within old landfills and derelict sites, geophysical surveys are the only practical method of investigation.

9.1 INTRODUCTION

The market for environmental geophysics has developed later in the UK than in the USA. Consequently, lessons learnt in the USA can be applied in the UK as activity here increases. In the USA, client confidence improved when it was understood that the geophysical methods used for environmental surveys were initially developed for the mining and petroleum sectors, but it was also recognised that there are special problems in environmental geophysics that require the development of new methods. Two aspects of environmental geophysics practice in North America (Steeples and Nyqyist, 1995; Bates, 1992; Danbom, 1995; Whiteley, 1995; Romig, 1992) that have relevance to the UK are:

1. The encouragement of multi-method, multi-disciplinary surveys and trials.
2. The recommendation for repeated, "time-lapse" surveys as a suitable means of enhancing the response of geophysical surveys to pollutants, in order to overcome the problem of geological heterogeneity masking the response of a mobile pollutant.

9.2 POLLUTION AND CONTAMINATION

Groundwater is the primary resource at risk from pollution and contamination. Geophysical surveys have long been used in groundwater exploration and are regularly employed by water companies in their groundwater investigations. Geophysical methods can be employed at nearly every stage of a groundwater scheme to solve specific problems, or to provide information regarding the subsurface structure that is vital to hydrogeological assessments. Surface geophysical methods can be rapid, complementing borehole logging. Responding primarily to the amount and properties of the water in the pores of the rock, the electrical resistivity technique is used extensively by hydrogeologists. Increasingly, geophysics is used to assess groundwater pollution and in monitoring changes in water quality.

9.2.1 Leachate, pollution and groundwater

A serious environmental concern is the movement of pollutants to the water table and subsequent contamination of the drinking water resource – the source, pathway and receptor. Leachate in a landfill is a hazard that becomes a risk if it has a pathway to groundwater. Geophysics can aid the investigation of pollution of the groundwater resource and of actual and potential pathways in the subsurface.

Surveys to identify faults, fractures, abandoned mine workings and natural dissolution cavities can be essential in the identification of "fast" pathways, along which pollutants can move (Section 7.3). Similarly, aquitards and other barriers to flow, such as thin marl bands, are important controls, which geophysical investigations can identify.

9.2.2 Geophysical "detectability" of pollutants

Geophysical techniques have detected pollutants such as petroleum products, acids, solvents, fertilisers, pesticides, silage, faeces, seawater and leachate.

While planning a survey, the likelihood of detecting pollutants using geophysical techniques can be assessed by:

1. Considering relevant case histories.
2. Using the range of physical properties that can be expected for the ground of a site to predict the sensitivity of each geophysical method to the pollutants being investigated.

For electrically conductive inorganic pollutants (eg leachate or seawater), there are many case histories of their successful detection by electrical resistivity and electromagnetic techniques. Changes in resistivity can be quantitatively related to altered concentrations of ions in solution in porewaters (due to the pollutant). Typically, these pollutants provide the contrast in electrical properties, which can be mapped.

For dense non-aqueous phase liquids (DNAPL), eg tetrachlorethane, and light non-aqueous phase liquids (LNAPL), eg toluene, which are insoluble in water, the following methods have been used:

1. Ground probing radar (GPR) is established as a means of detecting DNAPL solvents and LNAPLs such as toluene, a component of petrol.
2. Complex resistivity surveys have detected toluene as a result of its reaction with clay minerals.
3. Resistivity, GPR, and time-domain reflectometry (TDR) have monitored DNAPL movement in a 9 m by 9 m test cell of sand, at the Borden site in Canada. Neutron borehole logs and push-in resistivity probes provided highly distinct responses (Greenhouse *et al*, 1993).
4. The presence of DNAPL and LNAPL in a water-wet porous medium changes both its electrical resistivity and compressional wave velocity. In the laboratory, it has been shown that sonic velocity can vary by up to 30 per cent as hydrocarbon displaces pore-water. This change in velocity is almost ideal for cross-borehole seismic methods, as it is easily detectable but not so large as to cause vast perturbations to the ray paths. Similarly, electrical resistivity increases because of the presence of non-conducting hydrocarbons.
5. It is important to note that the breakdown of hydrocarbons and their interaction with clays commonly results in a decrease in electrical resistivity. Electrical surveys over such sites may produce results similar to those observed over inorganic contaminants.

Toxic waste is often buried in metal drums or associated with metal objects. Instances where EM, GPR and magnetic methods have detected toxic waste buried in metal drums, near the ground surface are reported by Steeples and Nyqyist (1995) and Phillips and Fitterman (1995). These methods are ideal for such surveys because they are rapid and non-contacting.

Extensive distributions of very low level radioactive mine waste have been mapped by remote sensing techniques (eg Steeples and Nyqyist, 1995).

The presence of methane gas or leachate close to the ground surface can cause distress to vegetation, such that it can be observed through airborne remote-sensing techniques (Sections 5.3.3 and 5.5.3). Thermal imaging can distinguish both gas escapes and leachate leaks from landfill sites, while multi-spectral techniques have been successfully applied to the detection of gas emanating from landfills (Section 5.7).

As the movement of fluids in the subsurface can cause self-potential anomalies, measurements of self-potential have been used to monitor seepage at dam sites, and from hazardous waste lagoons and settlement ponds.

9.2.3 Pollution pathways

Pollutants move along preferred pathways, such as open fractures, orders of magnitude, more quickly than through the host formation. Important pathways along which pollutants migrate include faults, fractures, aquifers, sand lenses, unconsolidated sediments overlying impermeable bedrock, etc. These pathways can be characterised (Phillips and Fitterman, 1995; Bates, 1992) by a range of geophysical methods:

- seismic reflection can define buried channels, and detect faulting and sedimentary structure
- seismic refraction and EM can map the topography of the base of permeable deposits overlying bedrock
- rotational resistivity soundings can sometimes determine fracture orientation
- cross-borehole seismic and radar tomography can detect tunnels, caves, voids, etc; the latter method being sometimes used to detect fractures in crystalline rock.

Seismic reflection processing techniques (Section 5.4.2), developed for petroleum exploration, have been applied to identifying structures associated with pathways. In one example, a drilling programme, costing $2 million, had not detected the cause of leakage at a hazardous waste site in the Rocky Mountains (USA). A geophysical survey found the fault (directly below the site) that was subsequently identified to be the pathway. The cost of the geophysical survey was $20,000, ie 1 per cent of the drilling costs (Steeples and Nyqyist, 1995).

Common depth point (CDP) processing has enabled the near subsurface to be imaged at a resolution suitable for identifying significant geological structure, and delineating subsurface pathways that may not be detected by conventional drilling.

In the UK, borehole logging and borehole wall imaging techniques, developed for use in the exploitation of deep mined coal, have been applied to the detection and characterisation of pathways controlled by fractures. This work is a component of research to define an approach to aid site investigation and remediation of the land, once occupied by facilities associated with coal mining (Onions *et al*, 1996).

GPR (Section 5.5) and comparison with outcrop may be used to evaluate the 3-D heterogeneity of a sandstone formation. Work by McMechan *et al* (1997) demonstrates the potential of geophysics to elucidate fine-scale sedimentary structures, which define the pathways that are of common interest in both petroleum and environmental investigations.

9.2.4 Detection, monitoring and remediation

Selecting the locations for site investigation boreholes on contaminated sites is likely to be best guided by a desk study, although there may be situations where this could be supplemented by statistical methods (Ferguson, 1992). Often, there are considerable advantages from using geophysical surveys to guide drilling programmes; not only may there be a reduction in overall investigation costs, but also more detailed information about the subsurface is provided. Non-invasive geophysical methods can investigate the subsurface, complementing conventional invasive methods that directly sample only a minute fraction of the subsurface volume. The integration of geophysical investigation techniques within multi-disciplinary projects is not yet standard practice, but is essential if the perception of geophysics by environmental and geotechnical specialists is to be generally improved (Danbom, 1995). Multi-disciplinary "geo-science" case histories of colliery site reclamations contain warnings such as: "Guidelines to good practice do not yet exist" and "...poorly designed surveys will lead to failures and a lack of support from the engineers concerned in the redevelopment of land" (Onions *et al*, 1996). This echoes problems that have already arisen in North America (Appendix 1).

The combination of rapid, shallow, inexpensive reconnaissance GPR, EM and magnetic methods, has proved particularly attractive when trial pits are used to "calibrate" the techniques on a site-by-site basis. The increasing use of IT, including position fixing and geophysical data logging systems is providing a marked improvement in the cost-effectiveness of this approach (Steeples and Nyqyist, 1995).

Developed largely in the petroleum sector, there is an increasing application of geophysical borehole logging to environmental problems (Section 5.5). Many interpretational procedures have been integrated within rock-mass characterisation schemes (eg the detection of hydrocarbons) and are directly applicable to detecting both organic and inorganic pollutants. The detection of fractures has advanced through combining borehole logs, borehole wall image logs and flow testing in the borehole (Phillips and Fitterman, 1995).

Given the cost of drilling boreholes, and the need to provide more detailed characterisation of the subsurface, the integration of borehole logging methods with surface geophysical methods could be improved.

Responsive to a very wide range of pollutants and lithologies, electrical resistivity tomography from the ground surface (Section 5.5.1), and between boreholes, is rapidly gaining acceptance. It provides a 2-D resistivity "picture" of the subsurface, which can be used to identify the movement pollutants directly. It has the potential both to detect sources of contamination and to assess pathways controlled by lithology. It facilitates the acquisition of repeat "time-lapse" datasets, enabling pollutant migration and the progress of remediation to be monitored. Figure 9.1 is an example of resistivity imaging of a leachate survey and its interpretation (Barker, 1997). Pollutants such as leachate present ideal targets for resistivity imaging when they control the resistivity of the pore fluid. In this case, leachate results in a greater concentration of dissolved ions, decreasing the resistivity and increasing the ease with which electrical currents flow in the subsurface.

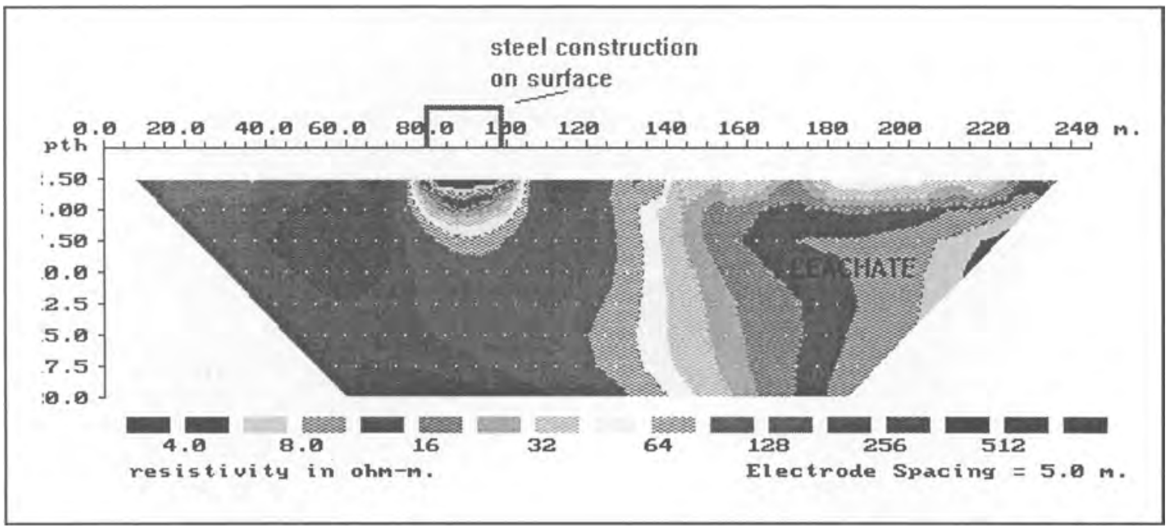


Figure 9.1 *Resistivity image of the subsurface in an area of contaminated groundwater (after Barker, 1997)* (for colour version see page 251)

Time-lapse (ie repeated) surveys have been used to minimise the effects of geological and man-made background heterogeneity on the survey results. Contrasting successive survey results can provide substantial benefits, particularly if the uncontaminated background data are available. This approach may be limited because pre-contamination data may not be available, but examples such as monitoring steam injection, during enhanced oil recovery, have demonstrated the potential of the method. Multiple surveys have been used to map seepage from a number of dams in the USA with many repeat self-potential surveys being made over short periods of time and integrated with resistivity and refraction data (Butler and Llopis, 1990). Repeat surveys over landfill sites can assess the degree of compaction and define the extent of leachate migration (Fenning, 1994). Figure 9.2 shows changes in the distribution of fluids in the subsurface monitored by comparing successive tomographic surveys. The resistivity imaging shows changes in resistivity in the subsurface, after the area had been inundated with water, as a controlled experiment (Barker, 1997).

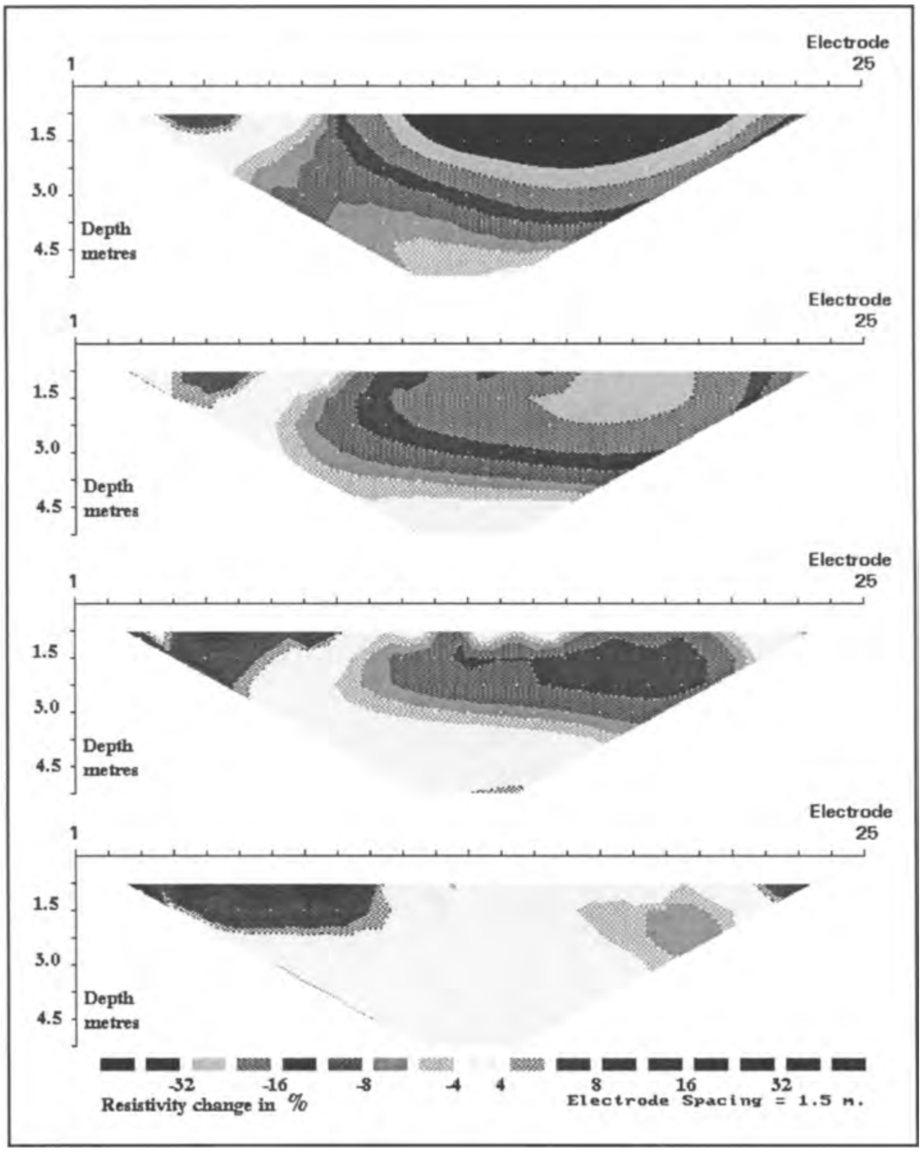


Figure 9.2 *Differencing repeat "time-lapse" surveys (after Barker, 1997)*
(for colour version see page 252)

9.2.5 Rising groundwater levels

Abstraction of groundwater has declined to such an extent in many urban areas of the UK that rising groundwater levels are perceived to be a major future problem (Johnson, 1994). For example, with the decline of heavy industry, London, Birmingham, Liverpool and Nottingham are cities where there is now much less pumping from underlying aquifers.

The widespread closure of deep coalmines has resulted in a cessation of the pumping used to de-water workings. Consequently, groundwater levels are rebounding, as seen in the Durham coalfield (Younger, 1994).

Minewater may become polluted via a number of sources, it may be saline, contain pyrite oxidation products or organic compounds originating from mining operations (Donnelly *et al*, 1998). Consequently, the presence of polluted minewater can be detected using the geophysical techniques described in Section 9.2.2 above. Similarly, polluted and potable groundwater levels may be detected and monitored. Figure 9.3 is an example where EM31 conductivity mapping (Section 5.5) provided a fast, economical method for identifying near-surface water-borne pollution. A plume resulting from the drainage of acid mine waters can be seen to be migrating towards a river system (McNeil, 1997).

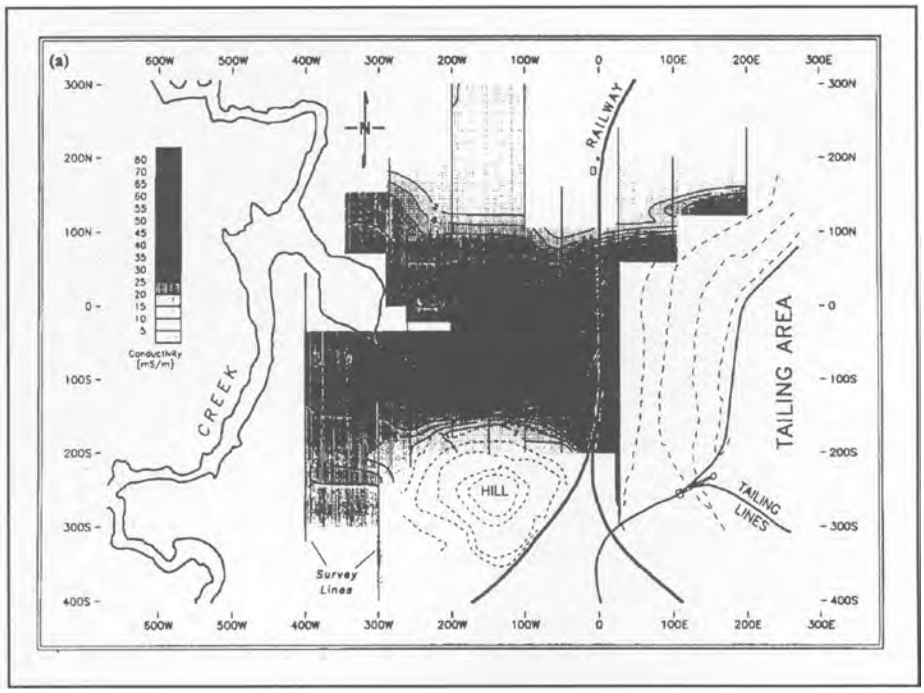


Figure 9.3 *EM conductivity mapping (after NcNeil, 1997)*

9.2.6 Abandoned mineworkings

Following more than three centuries of mining for coal, ores and building materials, abandoned mineworkings are widespread in the UK (Section 7.3.3). Plans describing known, recorded shafts have been shown to be in error in terms of both location and number of shafts likely (Hellewell, 1988; Donnelly *et al*, 1998). Consequently, on exposed coalfields, numerous unknown shafts and shallow workings are likely, presenting ground stability hazards and fast pathways for the migration of pollutants.

Thus, there is a continuing need for rapid non-invasive geophysical methods to detect such shafts and adits. Currently, combined magnetic and EM mapping surveys are the method of choice, and are particularly effective if the workings have been filled with extraneous material or shafts have been lined with magnetised bricks (eg Worthington and Barker, 1977; Jackson *et al*, 1987; Donnelly *et al*, 1998). More detailed surveying, such as resistivity imaging or cross-hole seismic surveys, can delineate relatively large air-filled cavities.

9.3 LANDFILL SITES

9.3.1 Geophysical surveys of landfills

Landfill is a generic term describing sites where solid waste has been disposed in the ground. Landfills have been used over many decades. Earlier disposal regulations were less stringent than today, contributing to many of the present-day problems associated with landfills.

Typical locations of old landfills include disused quarries and gravel pits, often where there are pathways to aquifers. Even in cases where plans are available, the exact position of the landfill may be subject to error because the final construction may not always conform to the initial design plans. There are four main reasons for investigating landfill sites:

1. To survey land prior to change of use (eg for commercial, industrial or residential development).
2. To assess the potential for waste fluids or leachate to contaminate groundwater resources.
3. To detect gases, like methane, generated by the decomposition of waste on the site.
4. To assess the settlement potential of the waste materials.

Intrusive investigation methods, such as trial pits and boreholes, may incur health and safety risks if the fill material is contaminated and the CDM regulations apply. However, these are necessary for calibrating the geophysical data, so that there can be confidence in the interpretation of the survey across the site, especially for areas where intrusive investigations would be impractical.

As geophysical measurements respond to vertical and lateral variations in a physical property of the fill material, such as electrical conductivity, there are two main approaches to carrying out a geophysical survey:

1. Mapping measurements on a grid basis over the ground surface (eg rapid EM techniques). Further investigation of anomalous areas is required, unless existing information indicates a likely cause of the anomaly in the measurements.
2. Measurements made along a horizontal profile, such that the vertical variation of the relevant property is determined. In this case the geophysicist attempts to produce a mathematical model of the geological structure or distribution of landfill material, which will give rise to the measured geophysical data set (Section 6.2).

While it would be ideal to obtain the complete 3-D model of the geological structure or landfill distribution on a site, it has to be appreciated that the cost to do that can be four to five times greater than that for producing a simple contoured geophysical map. Time-lapse imaging can monitor the effects of remedial measures.

Table 9.1 summarises the applicability of different geophysical techniques for the investigation of landfills.

Table 9.1 *Applications of geophysical methods to landfill sites*

	Method / Application	Gravity	Magnetic	Electrical resistivity	Seismic refraction	Cross-hole seismic	Cross-hole electrical resistivity	Borehole geophysical logging	Ground penetrating radar	Constant separation electromagnetic	Variable separation electromagnetic	Very low frequency electromagnetic	Induced polarisation	Thermal infrared
Area of interest	**Site investigation**													
	Determination of thickness of fill material (depth of bedrock)	2	—	4	1	2	—	2	4	—	4	—	—	—
	Determination of lateral extent of land-fill sites	3	3	4	1	2	—	2	4	5	4	3	—	—
	Detection of non-metallic objects	1	—	—	—	1	—	—	4	3	—	2	—	—
	Detection of metallic non-ferrous objects	1	—	2	—	1	1	1	4	3	1	2	—	—
	Detection of ferrous objects	1	5	—	—	1	1	1	4	3	1	2	—	—
	Buried industrial / building waste	—	—	4	1	2	—	—	4	4	4	—	—	—
	Chemical contamination	—	—	5	—	—	3	2	3	5	4	—	2	—
Area of interest	**Groundwater pollution**													
	Hydrocarbon contamination	—	—	—	2	2	—	2	1	4	4	—	—	—
	Leachate migration within and outside landfill site	—	—	5	—	—	3	—	2	5	5	—	—	3
Area of interest	**Gas detection**													
	Gas contamination and movement	1	—	3	3	2	2	—	3	1	3	—	—	4
	Fill settlement													
	Settlement	3	—	1	5	—	—	—	—	1	—	—	—	—
Area of interest	**Operational characteristics**													
	Surveying type and effectiveness	R/P 4	R 5	R/P 3	R/P 3	P 2	P 2	P 2	R/P 4	R 5	R/P 4	P 3	P 2	R 4
	Ease of interpretation	B/D	A	B/C	A/B	B	D	C	A/B	A	B/C	C	D	D
	Overall cost	E	A	D	D	E	E	C	B	A	B	B	B	D

Key to ratings:

1 – 5 Low degree of applicability and effectiveness (1) to high degree of applicability and effectiveness (5)

A – E Low unit cost, simple interpretation (A) to high unit cost, complex interpretation (E)

R reconnaissance

P profiling.

Geophysical assessments covering a wide ranging of activities are an integral part of modern multi-disciplinary geological surveying, in the appraisal of sites for waste storage. These activities can include:

- regional geological interpretation of gravity and magnetic data
- regional seismic reflection surveys
- regional geo-electrical soundings
- site-specific surveys to identify pathways and transport properties within superficial deposits
- interpretation of geophysical borehole logs and imaging data for fractures and mass properties related to connected pathways
- cross-borehole surveys to investigate "whole" 3-D volumes for pathways and mass properties.

9.3.2 Characterising landfill sites

Before embarking on a geophysical survey of a landfill site, a desk study is needed to assess the geophysical characteristics of the geological structure, in which the original void was excavated and the subsequent fill material deposited. Typical geological scenarios in the UK are of quarries in permeable formations, such as sand and gravel pits, fractured limestone, sandstone, brickearth, and estuarine alluvium (Reynolds and McCann, 1992).

From knowledge of the geology of the area surrounding a landfill site, it is possible to predict the geophysical properties of the host material for comparison with those of the fill. The geophysical properties of the fill are, to a large extent, governed by the history of disposal at the site. The material deposited might include inert builder's rubble, household waste, industrial refuse, mine waste, etc.

With time, the geophysical properties of landfill materials can change, as a function of the following parameters, such as:

- degree of saturation
- gas generation
- internal temperatures and variability
- leachate generation
- mobility of leachate
- density and heterogeneity.

For inert materials, the major differences in geophysical properties with time, result from changed compaction and degree of saturation.

The situation in most landfill sites is that the resulting properties of the fill materials are likely to be highly variable, both with depth and laterally over the site. Without some prior knowledge of the filling history, it is more difficult to estimate the average *in-situ* geophysical properties of fill than for other materials. On most sites however, it is possible to carry out preliminary geophysical measurements using a number of methods and, from the results of which, the geophysical parameters for the site can be estimated. Typical ranges of these parameters are given in Table 9.2.

From this initial study, an appropriate geophysical method can be recommended to investigate the particular target.

Table 9.2 *Guide values for the physical properties of bulk landfill materials*

Material	Density (Mg/m^3)	Resistivity (ohm-m)	Conductivity (mS/m)	P wave velocity (m/s)	Temperature (°C)
Rubble	1.5 – 1.7				
Putrescible fill	~1				
Saturated fill		15 – 30	30 – 70	1300 – 1500	
Unsaturated fill		30 – 70	14 – 35	450 – 600	
Uncombusted fill					Ambient – 50

9.3.3 Investigation methods

The two stages of a geophysical investigation of a landfill or contaminated land are:

1. Rapid reconnaissance surveys to examine the general lateral variability of fill materials.
2. More detailed surveys to assess their thickness and their variability both vertically and laterally.

The main use of magnetic (or magnetic gradiometer) surveys is to locate buried ferrous objects or other magnetic materials within the fill, including underground storage tanks and buried steel drums (Section 5.3). The method can be used to determine the lateral extent of landfill sites, because there is often a significant difference between the magnetic character of the fill material and the surrounding rock. In general, the magnetic method is used in the reconnaissance phase of site characterisation, although it may be possible in some cases to obtain information about the internal structure and thickness of the fill material.

The use of geo-electrical surveys to determine changes in the structure of the fill material and the position of the boundary with the surrounding rock mass is affected by:

- variation in the depth to the water table
- significant changes in the relative concentration of leachate in the groundwater.

The EM conductivity method has been widely used to detect zones of contaminated water within the landfill, and movement of this water into the surrounding rock mass, eg monitoring the relative concentration of leachate surrounding a landfill site with leaking lagoons, using successive EM conductivity surveys. EM conductivity methods can also be used to examine the variation of conductivity with depth, within the fill material, and allows the depth to bedrock to be calculated (Section 5.5).

EM conductivity equipment is very sensitive to highly conductive materials within the landfill site, eg metallic objects such as wire. In these cases, the values of conductivity measured can vary wildly and can be significantly less than those measured where polluted groundwater is present.

In recent years, the use of the transient electromagnetic method (TEM) has been increasingly used on landfill sites (eg Hoekstra and Blohm, 1990 and Buselli *et al*, 1990). While the use of resistivity tomography has superseded the standard sounding techniques using the Wenner or Schlumberger electrode configurations (Section 5.1).

Ground-probing radar (GPR) can locate the position of buried objects within fill material and determine its thickness above the underlying bedrock. An electromagnetic pulse is reflected from buried objects or changes in subsurface properties. GPR proved to be the most time-efficient technique during a multi-method geophysical investigation (Roberts *et al*, 1989) at the Thomas Farm landfill site, Tippecanoe County, Indiana, USA. The introduction of lower-frequency high-power antennae (25 rather than 200 MHz) has increased the maximum penetration achieved by GPR to 10 m in the environment of a landfill site, but the presence of high conductivity areas (eg clay capping) on and within the fill material will attenuate the electromagnetic energy. Consequently, penetration may be severely limited.

Gravity surveys are used to map lateral extent of landfills, particularly those within hard-rock quarries. Typically, this method responds to the density contrast between the fill and the surrounding rock mass. Variations in measurements across a site will be associated with changes in the thickness and bulk density of the fill material. Large reductions in the bulk density associated with the presence of gas in the fill may be detectable, but the wide variability of the landfill material itself, makes interpretation difficult.

The resolution achievable with the seismic reflection method is insufficient for shallow landfills. While seismic refraction surveys have been used in the past, they probably would not be considered safe if explosives were required. Seismic refraction has been used to assess the integrity of clay capping over a municipal landfill near Chicago, USA (Carpenter *et al*, 1991). It has also been used to determine the depth of fill-material and the properties of the underlying bedrock at a waste disposal site near Sydney, Australia (Knight *et al*, 1978).

A wide variety of biological and chemical reactions occur within the complex environment of a landfill. In the situation where two zones of groundwater have different chemical (ionic) concentrations, an electrochemical gradient exists that can give rise to a potential difference between the two zones. This effect may be greatest at the landfill boundary, because this is where the most significant contrast in groundwater/ landfill ionic concentrations occurs. In addition, physical flow of water, having high concentrations of dissolved ions, can give rise to streaming potentials, particularly at the landfill boundary. Measurement of these potentials by the self-potential (SP) method can be used to map anomalous voltages associated with the margins of a landfill site.

9.3.4 Pollution near landfills

Geophysical methods have been used in the assessment of potential pollution of groundwater by the emission of waste fluids (leachate) from the landfill sites. As with groundwater studies, electrical methods have been used extensively to investigate pollution near landfills, because the electrical resistivity (and conductivity) of the fill material and the surrounding rock mass, are a function of the electrical properties of the fluids contained within them.

The electrical resistivity method (Section 5.1) has been used to delineate leachate and contaminated groundwater in the Bunter sandstone aquifer in Nottinghamshire, UK (Finch, 1979). In an area with little lithological variation, the level of concentration of chloride ions in the pore water was related to the interpreted resistivity property values. Calibration was achieved using chloride concentrations observed in boreholes in the survey area.

The progression of a leachate plume across a contaminated site can be mapped using successive EM surveys. The greater mobility of the EM equipment gives rise to a far greater density of data than could be obtained from a corresponding resistivity survey.

The Very Low Frequency (VLF) electromagnetic method has been tested at contaminated landfill sites (Section 5.5.1). While the method is recommended for locating high conductivity zones associated with the presence of leachate, it is unsuitable for mapping the near surface.

Electrical methods have been developed to pinpoint leaks in geomembranes (Parra, 1988; Van *et al*, 1991). Parra's method, known as mobile geomembrane leak location surveying (MGLLS) is now used routinely during landfill construction. Passing current from inside to outside the landfill, the method uses a mobile measuring electrode to detect the higher potentials associated with electric current flowing out through holes in the geomembrane. An example is shown in Figure 9.5, where three "pin-hole" sized leaks were detected. The imaging shows three characteristic peak-and-trough anomalies resulting from electrical currents flowing through "pin-hole" sized leaks.

Infra-red thermography is being used increasingly in the aerial survey of landfill sites to detect the leakage of methane gas and leachate (Section 5.7.1).

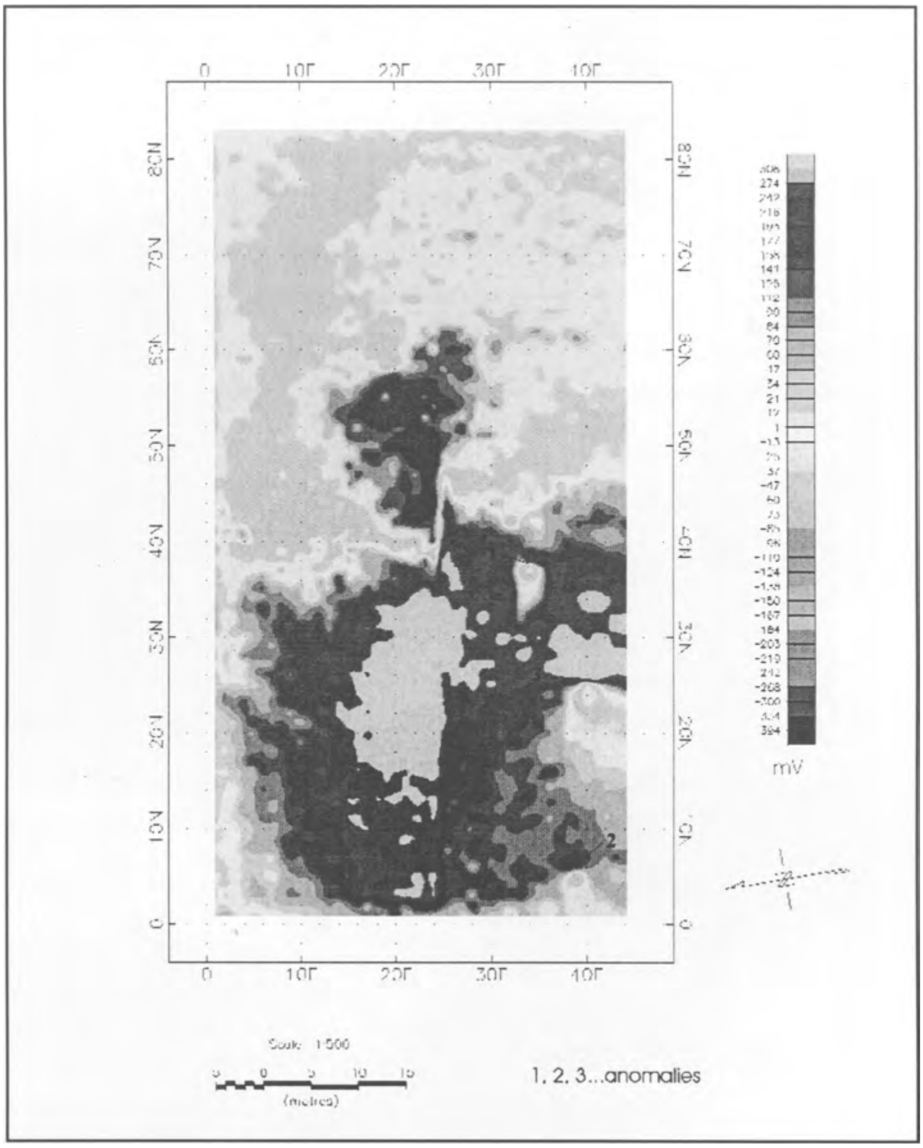


Figure 9.4 *Result of a geomembrane leak detection survey (courtesy of Golder Associates and Solmax Geosynthetiques)* (for colour version see page 252)

9.3.5 Compaction and consolidation of landfill material

In a landfill site, long-term settlement of the fill material will take place as a result of the weight of material deposited. While much of the settlement occurs in the early stages of deposition (primary compaction) further "creep" settlement occurs under conditions of constant stress and moisture content. This is particularly apparent when domestic waste is buried at the site, because long-term settlement is associated with the decay and decomposition of organic matter. In addition there is the potential for sudden (collapse) settlement on inundation of loose fill.

The shear wave velocity of unconsolidated material is related to its compaction and depth of burial. Consequently, shear wave refraction surveys are suited to mapping compaction within the landfill material.

As bulk density is also a function of compaction of the fill material, a high-resolution micro-gravity survey across the landfill site will indicate areas of well-consolidated materials. However, it would be necessary to determine the actual thickness of the fill material, to be sure that changes are not related to variations in the depth to the base of the landfill, rather than density changes related to the degree of compaction.

9.3.6 Anthropogenic gases

The gas generated on a landfill site is usually the result of the decomposition of organic waste when oxygen is excluded, the gas being a mixture of methane, water vapour, carbon dioxide, and some trace elements. The generation of gas within the fill material changes its engineering characteristics and geophysical properties, such as:

- reduced velocity of propagation of compressional waves
- increased attenuation of compressional waves
- decreased bulk density
- increased electrical resistivity.

Gas will move laterally through permeable soils or fissured host rock and reach the lower parts of buildings adjacent to the landfill site, such that potential problems arising from the presence of gas include:

1. Risks of asphyxiation or a localised explosion.
2. Distress to vegetation when methane replaces oxygen at root level in the soil.
3. Differential settlement at the post-construction phase of a development, due to uneven distribution of leachate and gas.

Large reductions in the bulk density, associated with the presence of gas in the landfill, may make the use of a gravity survey a practical proposition but, with the likely variability of the fill material, interpretation of the survey data will be difficult.

A thermographic survey (Section 5.7) locates thermal anomalies only on the ground surface and investigation by geophysical methods may be required to determine their cause, but aerial thermographic surveys of landfill sites can be very cost effective (Titman, 1994) for the following applications:

- heating effects associated with the presence of methane gas
- hot spots on the ground surface resulting from the movement of fluid from the body of the site to the surface
- internal fires
- condensate blockages within gas extraction pipework.

9.4 RADIOACTIVITY AND RADIOACTIVE WASTE

Natural radioactive hazards generally originate from the mining of uranium ores and other radioactive minerals, such as pitchblende, and the presence of radon gas associated with the decay products of the uranium-to-lead series. Man-made radioactive hazards are caused by products originating from electricity power generation, industrial and medical processes, usually in the form of waste.

9.4.1 Natural radioactivity

Hazards, due to radioactivity associated with tailings, resulting from the mining and processing of uranium ore are readily quantified using airborne spectral methods, enabling risks to population to be defined. On the other hand, hazards due to the radioactive gas radon are difficult to quantify.

Radon is one of the products of the decay series, uranium-to-lead. This gas has been linked to lung cancer, and dangerous concentrations can build up in poorly ventilated dwellings. Radon gas has been studied over the past half century. Associated with emanation from faults, it has been used as a survey indicator during uranium prospecting and, it has been suggested, as a precursor to earthquakes. The situation regarding radon gas is highly complex and although rocks can be classified in terms of their potential to emit radon, transport pathways in a formation can be so variable that each site should be considered on an individual basis. Granite, black shale, phosphorites and their metamorphosed equivalents are considered to be major sources. Radon can be detected instantaneously using hand-held sensors. Chemically coated surfaces (alpha track detection) are used to identify the average "flux" over periods of weeks or months; these are mass produced and used for both geological surveys and monitoring living spaces.

9.4.2 Geological appraisal for radioactive waste storage

The storage of radioactive waste in the subsurface requires detailed information regarding all the pathways along which radionuclides might migrate. A detailed knowledge of the geological structure and formation properties thus forms the basis of the hydrogeological models used to predict migration over very long periods of time.

For disposal options, these surveys are inputs to safety cases, which have to take into account timescales extending over thousands of years. Thus data of unprecedented detail and reliability are required, compared with the oil and minerals industries where a resource is exploited over a matter of a few years. The need for quality assurance (QA) has been identified at an early stage. Such geological appraisals have been undertaken in USA, Canada, Switzerland, Sweden, UK and Belgium. In a number of cases, work has progressed to the stage of investigations using underground laboratories, where techniques are developed to identify pathways *in situ*, and have many similarities with the techniques developed for shallow pollution assessment described above.

While rather beyond the usual range of civil engineering applications of geophysics, these techniques have been instrumental in transferring technology and techniques from the oil industry to a wider geological community. An important example is electrical imaging of the borehole wall, where orientated images are used for detailed analysis of sedimentary structure and fracture studies at a resolution of 5 mm (Section 5.1.1). These images are measurements of conductance from which fracture aperture may eventually be predicted.

9.5 AQUIFER DEVELOPMENT

The confines of a porous, water-bearing formation may be defined by various geophysical techniques, the most suitable depending upon the properties of the formation and their contrast with those of adjacent formations. In the initial reconnaissance stage of aquifer development, gravity, seismic reflection, seismic refraction, resistivity, and electromagnetic techniques (EM, TEM) may be used in the delineation of general geology and aquifer structure, for finding faulted and other structural boundaries, and in the location of buried valleys and fractures. Such surveys will minimise the number of exploratory and confirmatory boreholes that would be required.

In the later stage of aquifer development, where detailed knowledge of aquifer properties becomes important, surface and borehole geophysical surveys are an effective means of investigation. At this stage the geo-electrical techniques are perhaps the most widely employed (Nobes, 1996) as, in addition to their use in the delineation of aquifer dimensions, the measurement of resistivity (or its reciprocal conductivity) can be used as an indicator of water quality

9.5.1 Sediment-filled valleys

The investigation of aquifers located in sediment-filled valleys is a typical geological problem, eg investigating the thickness of alluvium situated above bedrock. Geo-electric, seismic reflection and refraction and gravity surveys can all supply relevant, but partial, quantitative information. Although gravity surveys are useful for tracing large buried valleys or channels, quantitative interpretation is not accurate for valleys of much less than 100 m in depth. Shallower valleys are better investigated using seismic reflection, geo-electric sounding or seismic refraction, when more accurate depth information will be obtained. An example is shown in Figure 9.5 of common depth point (CDP) stacked shallow reflection profiling, which is interpreted as three units of clay -rich unconsolidated sediments and thin silty till overlying dolomite bedrock.

In the UK a free water table is not commonly present, as much of the country is covered by glacial tills confining aquifers, so that water levels recorded in observation boreholes are piezometric pressure heads, which cannot be observed geophysically. Even where the aquifer is unconfined, the water table may still not be observable geophysically. In the Chalk for example, saturation above the water table may remain at well over 90 per cent, thus providing no contrast in properties that can be measured geophysically.

Where a free water table is present, such as in gravels and coarse-grained sandstones, it may often be easily observed using geo-electric sounding. A sharp drop in resistivity is typical between the unsaturated and saturated zones of sand and gravel deposits, an order of magnitude decrease from 1000 ohm-m to 100 ohm-m would be typical in the UK. Seismic refraction is also suitable, because the presence of a shallow water table has minimal distorting effect on deeper information. Seismic reflection may suffer from attenuation of high frequencies particularly if the unsaturated zone is clay-free.

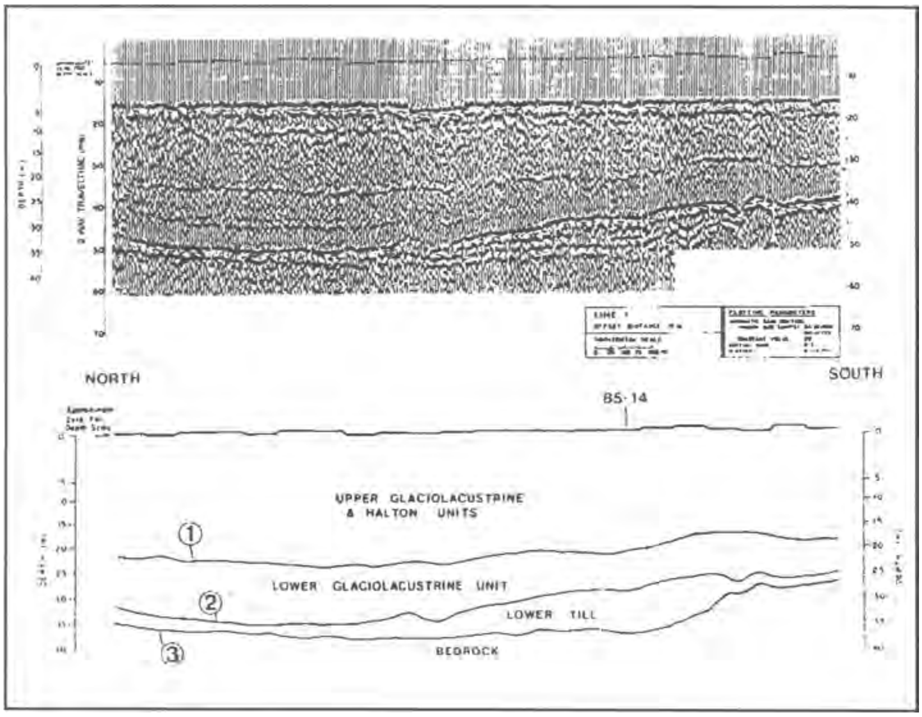


Figure 9.5 *Modern seismic reflection profiling (after Slaine* et al, *1990)*

9.5.2 Protection of groundwater quality

Geo-electrical techniques (Section 5.1) are the most widely employed of all geophysical methods for hydrogeological applications. Information on water quality is deduced from the assessment of electrical resistivity. Water quality is reduced by increases in the concentration of ions in solution, produced by ingress of seawater, sewage, fertiliser, etc. However, the resistivity of a saturated, porous sandstone or limestone aquifer depends not only on the ionic content of the saturating groundwater, but also on its porosity and the amount of conductive minerals (mainly clay) in the make-up of the rock matrix. The accurate determination of water quality can only proceed if the effects of porosity and clay content are insignificant, or can be taken into account. It is often the case, especially in coastal aquifers, that extreme variations in groundwater salinity make it unnecessary to consider matrix conduction effects.

If saline groundwater is close to the ground surface, and knowledge of the extent of the saline groundwater body is required, EM or resistivity surveys are effective, efficient survey tools. Soil conductivity, derived from EM observations, has been used to investigate the encroachment of salt water into arable land, mapping the extent of the affected area as a result of the linear relationship observed between EM conductivity and soil salinity. This relationship varies from site to site and lithology is an important additional factor, which must be taken into account. A similar technique might be employed in mapping fresh water bodies. If accurate depth information is required, resistivity or EM/TEM sounding would be suitable investigative techniques.

Plumes of contaminated groundwater emanating from landfill sites may be recognised from the effect they have on the measured resistivity of subsurface formations. The groundwater resistivity will decrease if its salinity increases, due to the leaching of chemicals from the fill material, and hence the resistivity of the saturated rock will also decrease. In simple situations, ground conductivity profiling can normally be employed to detect plumes of contaminated water.

A plume of contaminated groundwater can normally be detected by resistivity or EM profiling if its width and thickness are more than 20 per cent of its depth and the conductivity of the contaminated water is considerably higher (eg factor of 10) than the surrounding groundwater. In situations where the contamination is slight, and the geological structure is complicated, geo-electric soundings will be more appropriate. It has been shown that measurement of induced polarisation can be a way to detect low levels of groundwater contamination, particularly if clays are present (Olhoeft, 1992).

9.6 NEW METHODS

New geophysical methods are emerging in response to environmental problems, typically associated with urban conditions, while older methods have been adapted and are now being used in the environmental sector for the first time. Techniques have continued to be transferred from petroleum applications. Technological advances are continually improving the efficiency of data acquisition; for example, automatic position fixing and logging during reconnaissance surveys is becoming the norm (Steeples and Nyqyist, 1995).

Of the new approaches, many involve innovative combinations of existing methods, often being multi-disciplinary and multi-method projects. An approach using geophysical, geotechnical, geochemical and hydrogeological methods has been successful in Sydney, Australia, for the detailed investigation of a contaminant plume in a sandy aquifer, originating from a leaky landfill (Ackworth *et al*, 1994). The fate of contaminants from leaky sewerage systems and landfills, has been evaluated in southern Germany using soil gas and tracer studies combined with resistivity, EM, SP and thermal methods (Eiswirth *et al*, 1995). GPR and magnetic surveys have been used to identify buried storage tanks (Fenning and Veness, 1992), while EM "out of phase" and magnetic measurements are commonly used in investigating derelict land; "in-phase" EM measurements have also proven to be useful (Reynolds, 1994). Gravity and magnetic surveys have been used successfully to characterise landfill sites (Hinze, 1990; Roberts *et al*, 1990). Although at an early stage of development, Nuclear Magnetic Resonance (NMR) applied in conjunction with EM and time-domain reflectometry can assess groundwater quality, in the presence of conductive clays that would mask pollutants if EM measurements were used (Goldman and Neubauer, 1994; Phillips and Fitterman, 1995; Nobes, 1996). Complex resistivity measurements have been shown to be capable of mapping hydrocarbons through being sensitive to reactions of pollutants with clay minerals (Olhoeft, 1992).

Common depth point processing applied to shallow seismic reflection and GPR surveys has enabled near-surface geological structure to be imaged and pathways identified (Steeples and Miller, 1990; Miller *et al*, 1995; Nobes, 1996).

EM methods, using radio frequencies, have been developed that are sensitive to dielectric properties and insensitive to surrounding metal or conductive soils that degrade the performance of EM induction and GPR methods respectively (Whiteley, 1995).

Self potential (SP) measurements, known to be sensitive to movements of fluids in the subsurface, have been used to map contamination migration (Coleman, 1991; Corwin, 1990).

Geophysical tomography using radar, seismic and resistivity methods has been applied to the detection of fractures between boreholes, geological structures and the monitoring of pollutant migration, respectively (Phillips and Fitterman, 1995; Jackson and McCann, 1997; Daily *et al*, 1992; Loke and Barker, 1996a).

The integration of surface and downhole logging techniques is showing promise in the detection of hydraulically significant fractures (Onions *et al*, 1996; Paillet, 1993). The incorporation of sensors to cone penetrometer type systems is providing logging capabilities without the need to drill boreholes (Phillips and Fitterman, 1995).

3-D resistivity and GPR surveys have demonstrated substantial improvements in assessing geological structure (Loke and Barker, 1996b; McMechan *et al*, 1997; Chambers *et al*, 1999).

Rayleigh waves, relying on the contrast of Rayleigh wave velocity between the fill and the underlying clay liner, have been used successfully to detect the base of a landfill to depths of up to 8 m (Butcher and Tamm, 1997; Cuellar, 1997). Significant clay capping would have reduced penetration and the quality of the signals.

The assessment of heterogeneity and anisotropy are the subject of research and more detail, both quantitative and qualitative, is required from surveys.

Capacitively coupled resistivity measurements and induced polarisation tomography are the subject of significant research activity at the time of writing.

Many of these techniques have only been demonstrated in ideal situations or are at the early stage of development. A qualified and experienced geophysicist should always be consulted before embarking on any such approach.

10 NDT applications to building and civil engineering structures

10.1 INTRODUCTION

This section deals with the application of NDT techniques to buildings and civil engineering structure circumstances. The information is presented as a series of cascading tables (see Figure 10.1) supported by case histories. The first table lists the types of information that are sought for structures constructed using:

- concrete
- masonry and stone
- metals
- timber
- composite materials.

The subsequent tables link the information sought, with the appropriate diagnostic testing and inspection techniques. In these tables the geophysical methods are in bold text, but also included are alternative methods of investigation and testing, which might supply the required (or complementary) information. The geophysical methods are then summarised after the tables with comments on the effectiveness of the technique to provide the required information. Three case histories illustrate the use of the individual testing/ investigation techniques.

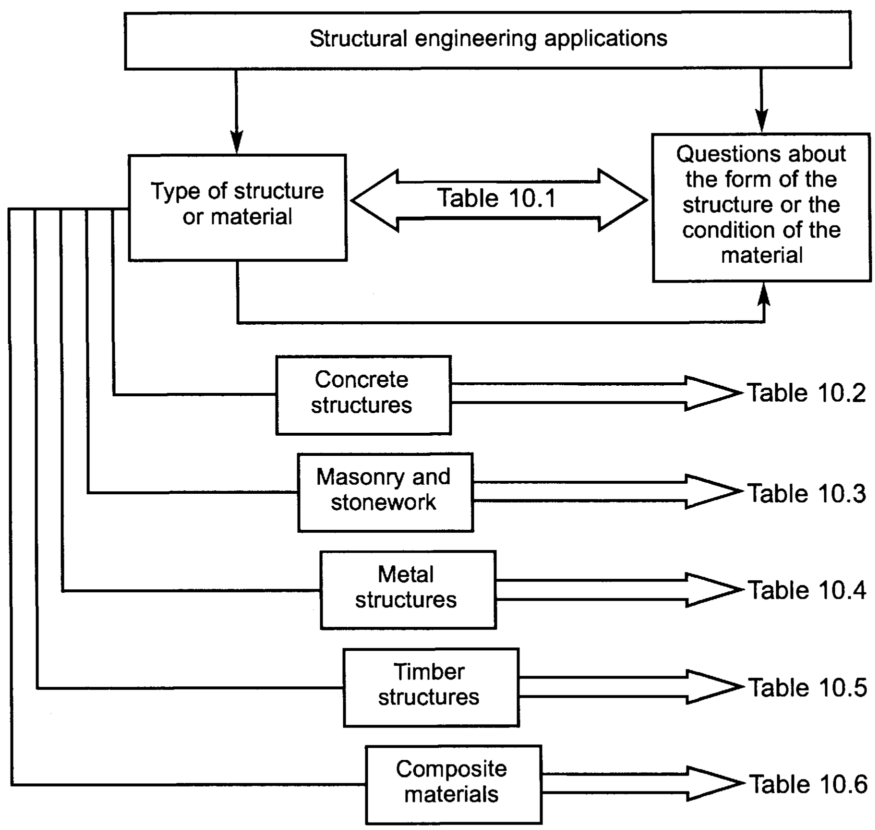


Figure 10.1 *Explanation of the information tables for structural applications*

Table 10.1 provides a simplified guide to the nature of some of the information, which might be sought in various circumstances, for structures constructed using concrete, masonry and stone, metals and composite materials.

Table 10.1 *Guide to the nature of information sought for structures constructed using concrete, masonry and stone, metals, timber and composite materials*

Type of structure or circumstance	Information sought
Concrete structural elements (beams, columns, slabs, pavements, foundations, linings, etc)	Strength / surface hardness
	Concrete thickness, reinforcement position, type, provision and cover
	Condition (corrosion) of steel reinforcement
	Location of prestressing tendon ducts and other steel objects
	Presence of cracking and delamination
	Presence, location and dimensions of foundations
	Presence of voids below slabs / behind linings
	Material properties (strength, stiffness etc)
	Presence of chlorides and chloride profiles, presence of sulfates.
	Moisture content
	Comparative quality/ uniformity of concrete (voids, honeycombing etc)
	Grouting of post-tensioning tendon ducts/ corrosion or other damage to prestressing tendon within duct
Masonry and stonework elements (piers, walls, foundations, linings to tunnels, culverts, shafts, etc)	Strength
	Masonry and stonework thickness
	Presence of voids or inclusions such as metal wall ties and bed reinforcement, etc
	Presence of voids behind linings
	Presence of cracking and debonding of wythes / rings of masonry, and delamination
	Porosity
	Quality (degree of fissuring)
	Durability
Metal structural elements (beams, piles, tunnel linings)	Identification of material
	Material thickness
	Presence of cracking and flaws
	Presence of voids behind linings
	Weld quality
	Length and integrity of piles
Timber	Identification of species and strength grade
	Moisture content
	Identification of type of preservative and glue
	Presence of insect or fungal attack, internal decay and defects
	Type and condition of bolt connectors
Composite materials	Material thickness
	Presence of cracking, flaws or delamination

The following tables provide a simplified guide to the initial selection of testing procedures for each of the categories covered in Table 10.1.

Table 10.2 *Simplified guide to the selection of testing procedures for concrete structures*

Information sought	Diagnostic testing or inspection technique
Strength / surface hardness	*1. Near-surface properties of concrete:*
	Cored samples: examination and crushing, etc
	Penetration resistance tests (Windsor probe)
	Break-off tests
	Internal fracture tests
	Pull-off tests
	Rebound hammer
	2. Representing properties of body of concrete:
	Cored samples: examination and crushing, etc
	Ultrasonic pulse velocity
Concrete thickness, reinforcement position, type, provision and cover	Covermeter
	Subsurface radar
	Physical exposure by excavation or cored sample
Condition (corrosion) of steel reinforcement	Electro-potential mapping
	Resistivity evaluation
	Physical exposure by excavation or coring
	Linear polarisation resistance
	Galvanic current measurement
Location of prestressing tendon ducts and other steel objects	**Subsurface radar**
	Pulse echo tests
Presence of cracking and delamination	Visual inspection / photographic records
	Sounding surveys (tapping, chain drag, etc)
	Examination of cored samples
	Thermography
	Impact echo tests
	Ultrasonic pulse velocity
	Subsurface radar
Presence, location and dimensions of foundations (including piles)	Excavation, physical exposure for inspection, probing, boreholes
	Subsurface radar
	Impact echo
Presence of voids below slabs / behind linings	Excavation, physical exposure for inspection
	Subsurface radar
Material properties Strength, stiffness, etc)	Inspection and testing of samples for strength, other mechanical properties, physical or chemical make-up, condition, durability, etc
Presence of chlorides and chloride profiles, presence of sulfates	Drilled, lump or cored samples for laboratory analysis; incremental sampling required for profile determination
	Site chemical tests performed on drillings
Moisture content	Direct (laboratory) measurement from lump sample
	Direct site measurement upon drilled dust sample using a chemical reagent and calorimeter
	Resistance / capacitance / dew-point probes
	Subsurface radar
	Thermography
Comparative quality / uniformity of concrete	*1. Near-surface properties of concrete:*
	Cored samples: examination and crushing, etc
	Ultrasonic pulse velocity
	Rebound hammer
	Subsurface radar
	2. Representing properties of body of concrete:
	Cored samples: examination and crushing, etc
	Ultrasonic pulse velocity
	Impact echo tests
	Radiography
	Subsurface radar
Condition of pre-stress tendons and grout in tendon ducts	Physical exposure by excavation or coring, coupled with an air test to estimate void volume
	Borescope or optical viewer inspection
	Radiography

Table 10.3 *Simplified guide to the selection of testing procedures for masonry and stonework structures*

Information sought	Diagnostic testing or inspection technique
Strength	• Clay units and natural stone:
	Crushing of units
	Crushing of cores
	• Cement-based units:
	Rebound hammer
	Internal fracture test
	Windsor probe
	• Crushing of units or cores:
	Weak cement-based units
	Helix pull-out
	Crushing strength of unit combined with mortar mix, proportions according to BS 5628
	Split cylinder tests on horizontal cores with and without horizontal diametric bed joints
	• Flatjack test
	• Laboratory test on (large) sawn-out sample
Masonry and stonework thickness	• Visual inspection using core holes
	• Subsurface radar
	• Seismic transmission
	• Borescope
Presence of voids or inclusions such as metal wall ties and bed reinforcement, etc	• Thermography
	• Physical exposure
	• Visual examination of core holes
	• Subsurface radar
	• Seismic transmission
	• Metal detector
Presence of voids behind linings	• Probing
	• Subsurface radar
	• Visual inspection / photographic records
Presence of cracking and debonding of wythes / rings of masonry, and delamination	• Sounding surveys (tapping, etc.)
	• Examination of cored samples
	• Thermography
	• Impact echo tests
	• Ultrasonic pulse velocity
	• Subsurface radar
Porosity	• Sampling and laboratory testing
	• Ultrasonics on laboratory samples
Quality (degree of fissuring)	• Sampling and laboratory testing
	• Ultrasonics
Durability	• Sampling, coring and laboratory testing
	• Ultrasonics

Table 10.4 *Simplified guide to the selection of testing procedures for metal structures*

Information sought	Diagnostic testing or inspection technique
Identification of material	Visual examination
	Chemical analysis of small samples (drilling swarf)
Material thickness	Measurement in small drill hole
	Ultrasonics
Presence of cracking and flaws	Dye penetrants
	Ultrasonics
	Radiography
Weld quality	Visual examination
	Dye penetrants
	Ultrasonics
	Magnetic particle test
	Radiography
Length and integrity of piles	Physical exposure by excavation
	Ultrasonics

Table 10.5 *Simplified guide to the selection of testing procedures for timber structures*

Information sought	Diagnostic testing or inspection technique
Identification of species and strength grade	Visual examination through magnifying glass
Moisture content	Moisture meter
	Direct measurement
	Drying of sample and weighing
	Subsurface radar
Identification of type of preservative and glue	Chemical analysis of small samples
Presence of insect or fungal attack, internal decay and defects	Visual examination
	Subsurface radar
	Ultrasonics
Type and condition of bolt connectors	Visual examination of temporarily unloaded and dismantled joint
	Radiography

Table 10.6 *Simplified guide to the selection of testing procedures for structures constructed in composites and other materials*

Information sought	Diagnostic testing or inspection technique
Material thickness	Subsurface radar
	Ultrasonics
Presence of cracking, flaws or delamination	Destructive examination
	Ultrasonics

10.2 REVIEW OF TECHNIQUES AND APPLICATIONS

10.2.1 Subsurface radar as a structural investigation technique

Matthews (1998) presented the following summary of the application of subsurface radar as an investigative technique for structures, with particular reference to concrete structures (Section 5.5).

Reinforcement location. Generally subsurface radar is very successful for this application, provided orthogonal scanning is used. The ability to detect reinforcement (or similar long targets) depends on the orientation of polarisation of the antennas. For closely spaced bars (< 100 mm) there is little signal penetration and individual bars are unlikely to be resolved. As cover depth increases, the ability to resolve individual bars is again reduced – reinforcement tending to appear as a planar reflector. Radar is unlikely to be able to resolve more than two layers of bars. Smaller bars in joints, or at changes in construction, may not be detected. Generally there is no indication of bar size, except in the broadest sense. Unusual reflection patterns may be encountered with square twisted bars because of their scattering characteristics.

Cover depth. Subsurface radar is very good for the upper layer of bars, but careful velocity and "time-zero" calibrations are necessary. It is sometimes possible to obtain an indication of rear face cover in lightly reinforced sections.

Bar size. Only the broadest indications are possible at shallow cover depths.

Construction details. Overall, section dimensions can generally be estimated well with the benefit of calibration data. The evaluation of smaller details (eg rib widths) is not so successful and radar is not necessarily able to resolve thin or closely spaced interfaces (although it may well detect their existence).

Thickness estimation. Generally subsurface radar is well suited to this purpose, but requires velocity and "time-zero" calibration to achieve absolute indications of thickness. Embedded reinforcement, especially closely spaced bars, reduces the amount of radar energy penetrating into the structure under investigation. The maximum thickness, which may be probed depends on the centre frequency of the antenna, a lower frequency antenna achieving increased penetration, but with reduced resolution.

Voids and delaminations. Radar is effective at detecting features where reinforcing bars are relatively widely spaced. Features, if they are to be resolved, need adequate dielectric contrast. Soft / indistinct edges to voiding / honeycombing, provides a gradual change in dielectric properties, which greatly reduces its detectability during a reflection survey. The presence of moisture in delaminations (ie cracking approximately parallel to surface) and shallow voids increases their detectability, as does an increase in the centre frequency of the antenna employed. Underslab voids 3 mm deep are detectable when filled with water, but air-filled voids may have to be 20 mm deep or more to be detectable – (they may manifest themselves by an increase in the strength of the reflection obtained from the interface). Although thin layers such as delaminations may be detected, it is generally not possible to resolve their thickness (which typically requires a pulse with a much higher centre frequency).

Cracks. Surface / shallow cracks (taken to be approximately perpendicular to the surface) are probably detectable by a 1 GHz or higher frequency antenna, but this is dependent on the magnitude of the breakthrough of the transmitted signal on to the receiving antenna. The ability to resolve crack details is rather limited. Where there is a desire to achieve better resolution of such features a higher frequency antenna may be of assistance.

Cracks are detected more easily if they contain moisture. The presence of chlorides would be expected to increase the reflectivity of a crack or a fracture zone. Cracks expressed at the surface are mapped and classified more effectively by visual methods.

Chlorides. In favourable circumstances, radar has been shown to have the ability to differentiate between areas with and without free chloride contamination on a qualitative basis (assuming that the materials concerned have consistent moisture contents and are not too dry). Semi-quantitative assessment is believed to be possible in favourable circumstances, where the investigation conditions are suitably simple.

Compaction and material density. Comparative results can be obtained in favourable circumstances. The analysis assumes that moisture content, and hence propagation velocity, is consistent along the member, as is the depth of the feature/interface being monitored.

Moisture content. Radar has been used to give indications of comparative changes in material permittivity. Absolute indications of moisture content are more problematic and depend on the nature of the materials concerned. Various workers have employed different procedures to detect changes in moisture content. Some have monitored changes in reflectivity of the surface zone of concrete, to provide qualitative indications of surface moisture variations. Others have employed differences in the velocity of propagation, during transmission through the specimen under test, to estimate changes in average moisture content. Microwave methods are known to be capable of good results and a range of microwave moisture monitors are available commercially for aggregates and unbound materials. In appropriate circumstances, geophysical methods have proved effective in identifying zones of moisture penetration in flat roofs.

10.2.2 Ultrasonic pulse velocity

The ultrasonic pulse velocity technique (USPV) measures the speed of travel of a pulse of ultrasound through the material being tested. It is used for a relative assessment, which is in different members or along a given member, of strength and the detection of imperfections such as voids or fissures, delamination, under-compaction and honeycombing. Calibration against concrete of known strength does improve the accuracy of the estimation of strength. Access is generally required to opposite faces of the member under test. The technique requires precise measurement of the distance between the two ultrasonic heads. The presence of steel reinforcement and moisture can affect pulse velocity values and needs to be considered when interpreting test results. The range may be limited, but can be extended by using lower frequency transducers, although this reduces resolution and discrimination of internal features. In large structures it may be necessary to employ an audio frequency pulse (this is generally termed "seismic transmission") to obtain an adequate range. Comments on particular applications are given below (see also Section 5.4.6).

Strength of concrete. USPV is used to give comparative estimates of strength. The accuracy of the estimates can be improved by calibration using cores.

Comparative quality or uniformity of concrete. USPV can be used to assess variation in strength along a member, although it does not give absolute values (see BS1881).

Presence of cracking and delamination. The use of USPV on stonework and masonry is generally successful, provided that there is good mechanical coupling of the transducers to the material. Its use on concrete is to give indications of the presence of voids, cracking and other imperfections (BS1881).

Integrity: internal decay, comparative strength and stiffness in timber. The USPV technique can be successful for these applications if low frequency transducers are used.

Integrity: presence of cracks, casting flaws in metal. Access is required on one face only. The application is limited by the coarse grain structures and laminations of some wrought iron. Success is dependent on the operator and quality of testing (see BS4124 and BS6208)

Weld defects. Access is required on one face only. Success is dependent on the operator and quality of testing see BS4124 and BS6208.

Wall thickness of hollow sections. Access is required on one face only. Success is dependent on the operator and quality of testing (see BS4124 and BS6208).

Delamination of FRP composites. The technology for this application is readily available. It gives comparative data only.

10.2.3 Impact echo tests, pulse echo, and seismic transmission

The impact echo and pulse echo forms of test involve the propagation of an ultrasonic stress wave through the body of a concrete element, and the detection of energy reflected back to the surface. These methods are generally applied to concrete elements or individual blocks of stone materials. The seismic transmission form of test requires access to two faces of the element concerned, and monitors pulse travel time and pulse attenuation characteristics or both.

They aim to provide information about member thickness and the presence of major internal voids, delaminations or other defects. Mapping of the results enables the existence of thickness variations and the location and extent of defects to be established. The stress wave is typically generated by a single impact on the surface from a special hammer. CIRIA Report 144 (CIRIA, 1997) explains the application of these techniques in the assessment of the integrity testing of foundation piling. Calibration of the velocity of propagation is necessary, to obtain absolute determinations of thickness variations and depths to internal features, otherwise comparisons are made on a relative basis. Comments on particular applications are given below.

Comparative quality or uniformity of material in a member The amount of detail obtained is related to the frequency of the pulse introduced – the lower the frequency the less detail can be resolved.

Delamination. Successful detection of delaminations, depends upon the material properties and the extent of delamination.

Presence of voids. The detection of voids, or inclusions of other materials, is based on the contrast in acoustic properties and on inference from comparisons with unvoided material.

Compressive strength of masonry and stonework. These rely upon empirical correlations with seismic transmission measurements for strength estimation.

10.2.4 Radiography

Gamma- and X-rays have mainly been used to examine the interior of concrete members of limited thickness, to check for the presence of voids, poor compaction, continuity of grouting in post-tensioning tendon ducts, layout of reinforcement, etc. It is an expensive specialist technique, suitable for the survey of relatively small areas of concrete. Special care has to be taken so that personnel are not exposed to harmful radiation. The test requires access to two opposite faces of components. Comments on particular applications are given below.

Comparative quality and uniformity of concrete. Tests cover only a small local area of concrete.

Grouting of post tensioning tendon ducts/ corrosion or other damage to pre-stressing tendon within duct. Tests cover only a small local area of concrete.

Integrity: presence of cracks, casting flaws, weld defects. This is an established technique needing specialist equipment and operators (see BS 2600).

Type and condition of bolt connections. This is a commercially available technique.

10.2.5 Thermography

Thermography creates an heat image of the surface of a structural member. The irradiation of heat from the surface of structural member will depend upon its internal homogeneity. It follows therefore that should a defect be present, such as a crack, the infra-red radiation from the surface will be different close to the defect. The equipment for thermography is portable and can be used remotely from the items to be examined and usually with real time displays of the images. This also allows transient thermography where the change in emissions with time are monitored. The resolution reduces with increasing distance from the structure examined and a free surface is required for surface thermography though more detail can be obtained by transmission thermography where heat is applied to one side of the element and the heat emitted from the other is monitored (Section 5.7).

Presence of cracking and delamination in both concrete and masonry structures is generally successful and available commercially either single surface or transmission thermography. Single surface thermography is only successful for detecting near surface defects.

Moisture content. Successful for near surface detection with obvious problems for transmission thermography.

Presence of voids and inclusions. This can be successful because of the differing thermal properties of the voids and inclusions to the mass of the structure be it concrete or masonry.

10.3 APPLICATION EXAMPLES / CASE HISTORIES

10.3.1 Detection of underslab voids

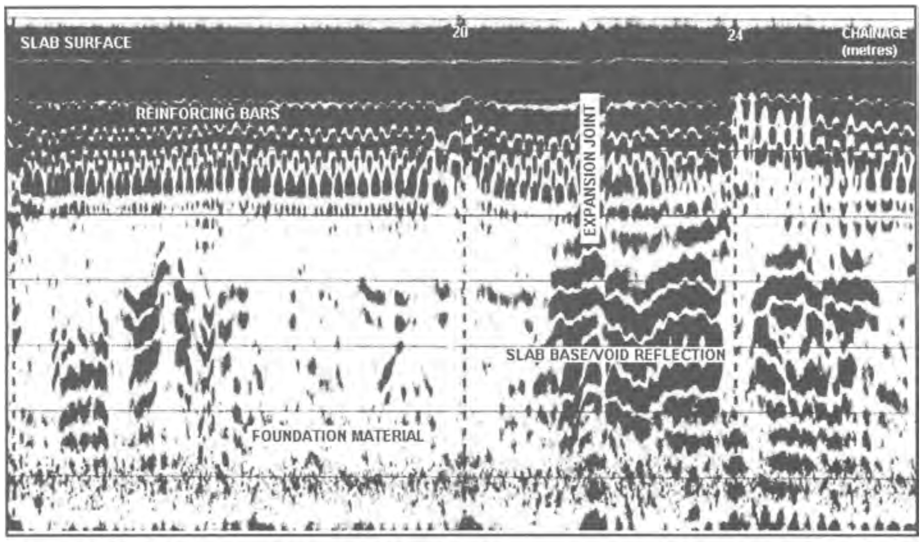


Figure 10.2 *Subsurface radar survey record obtained from a reservoir floor slab (Structural Testing Services Ltd)*

The survey was conducted to confirm details of the construction of a ground-bearing concrete floor slab within a service reservoir, designed to contain potable water and to detect the presence of underslab voiding. The floor comprised an upper reinforced concrete floorslab over an unreinforced concrete slab bearing, on a sandy foundation material. The overall depth of concrete slab construction was in the order of 200 mm. The survey was carried out using 500 MHz and 1 GHz antennas. Data were collected by parallel sweeps at 0.25 m centres.

The graphical record, presented as Figure 10.2, shows the reflection characteristics for a 17 m length sweep. The strong surface reflection/antenna breakthrough is present at the top of the record. Below this an intermittent reflection is obtained from the near surface reinforcing bars with nominal 200 mm spacing.

On the right hand side of the record, a strong reflection is obtained from the dielectric contrast provided by the concrete-air interface associated with an air-filled void beneath the slab (between about chainage 21 m to 26 m). On the left hand side of the record no such reflection is obtained (ie at less that 21 m chainage), because the dielectric contrast between the concrete and the sandy underslab material is small where no void is present. Little radar energy is reflected in such circumstances. There is however, an isolated reflection feature at about 15 m chainage, which may represent a very localised area of underslab voiding.

The underslab voids were drilled and inspected by borescope. They were found to range from about 25 m to 200 m deep. A plan representation of the areas of underslab voiding was prepared by collating information from the graphical records.

10.3.2 GPR used to map condition on wooden structures

GPR can be used to investigate the internal structure of wooden poles and trees by locating anomalies in the wood, particularly those related to differences in water content. Rot or insect infestation, often result in water content change. This case study is a survey carried out in Hong Kong to determine whether rot was present in wooden telegraph poles, which could affect their stability. It was made by one person using a pulse EKKPO 1000 GPR system with 1200 MHz antenna, to obtain a high-definition image of the poles. The results for one pole are shown in Figure 10.3 where the first 2 m of the pole was found to be rotten and unsuitable for further use.

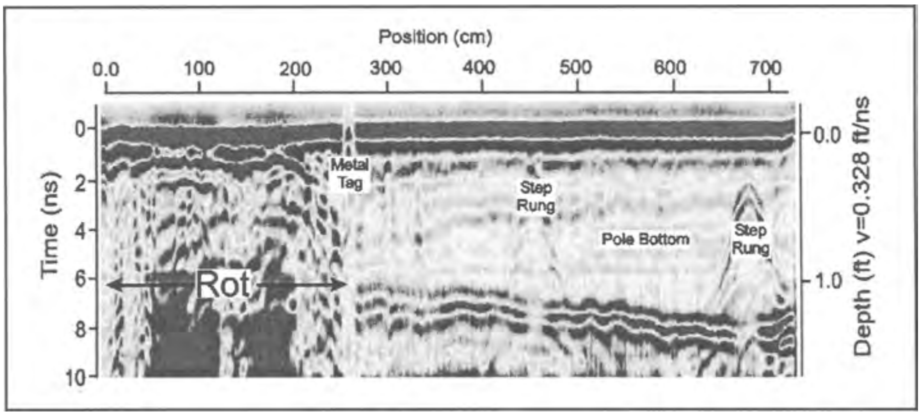


Figure 10.3 *Results of a GPR survey of the timber of a pole (Sensors and Software, Inc.)*

10.3.3 Subsurface radar traverse over a buried pipe

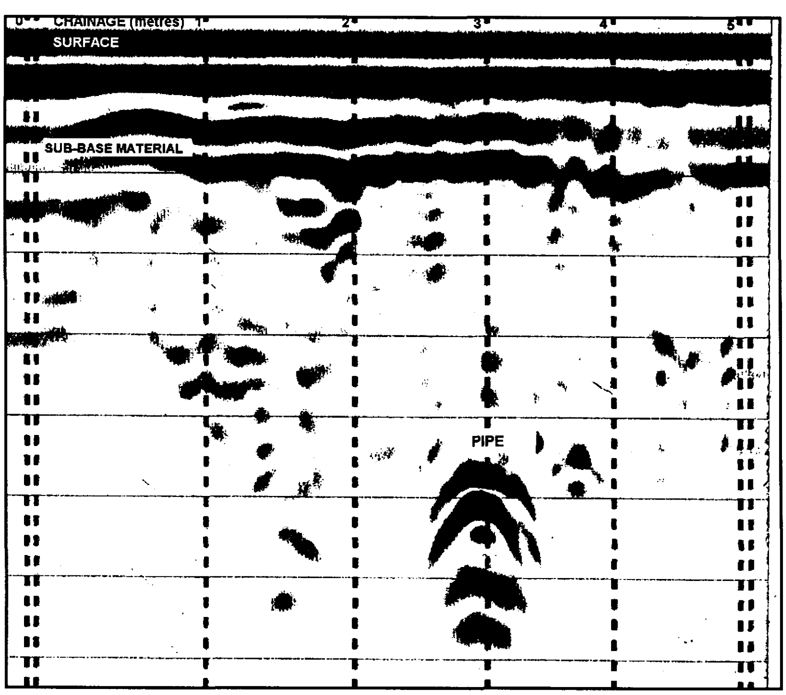


Figure 10.4 *Record of a subsurface radar traverse over a buried pipe (Structural Testing Services Ltd)*

Figure 10.4 clearly shows a buried pipe below the road.

10.3.4 Subsurface radar survey on old masonry retaining wall

Figure 10 .5 shows the investigation by subsurface radar of the face of a brick retaining wall. From the radargram (A), the interpretation of the radar record (B) leads on to a the further interpretation of the different (stepped) construction of the wall (C).

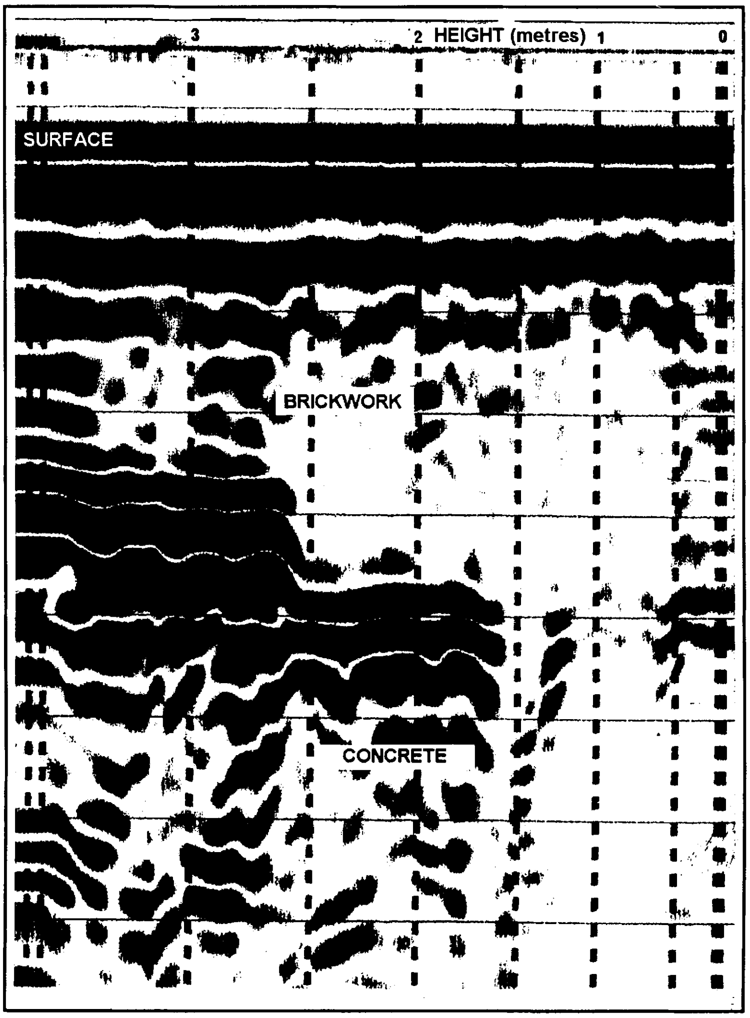


Figure 10.5 *Subsurface radar survey of a masonry retaining wall (Structural Testing Services Ltd)*

Geological Society, London, Engineering Geology Special Publications

Concluding remarks and recommendations for practice

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 219-222
doi:10.1144/GSL.ENG.2002.019.01.11

11 Concluding remarks and recommendations for practice

The concluding remarks lead on to some general recommendations for practice, particularly in the way that the geophysical investigation should be planned, staffed and managed integrally with the whole scheme of investigation.

11.1 CONCLUDING REMARKS

1. A conceptual ground model should be developed for every site under investigation. The model should be based on sound geological appraisal of the site and its surroundings carried out by a geologist and should take account of the geotechnical and geo-environmental objectives of the investigation.
2. The geophysical survey should be designed on the basis of this model, which should be continually reappraised in the light of new information.
3. The geophysical survey data, and their interpretation, will form an integral part of the development of the ground model. Hence, the interpretation of the geophysical data should be carried out within the context of the model, and not independent from it.
4. This implies that the geophysicist has to be regarded as a member of the site investigation team.

11.2 RECOMMENDATIONS FOR GOOD PRACTICE

11.2.1 Planning

As one of the first activities of a construction project, there is often too much pressure applied to mobilise equipment, so that "something can be seen to be happening". As a consequence, insufficient effort and skill are applied to the planning of many investigations. Work that commences in a poorly planned, haphazard way often continues in that way. The following, represents both an overview of the broader requirements for good site investigation practice and recommendations for when geophysics is part of the investigation. Just as the geotechnical adviser needs to be fully integrated into the overall project team, so too should the engineering geophysical adviser and any other specialist adviser.

The team

- appointment of an appropriate geotechnical adviser (GA)
- checking all professionals for suitability, training and relevant experience
- inclusion of an engineering geophysics adviser (EGA) within the team, if geophysics is to be considered
- integrating the GA and EGA into the project team
- establishing a teamwork approach
- encouragement of open and effective communications
- support by the client for the team, in a clearly set out management statement.

The engineering geophysics adviser (EGA)

- identification of the benefits that can be gained from the use of specific geophysical techniques
- appraisal of the uncertainties at the outset
- preparation of a method statement which highlights the benefits and disadvantages of the possible geophysical techniques.

The desk study

- the undertaking, in every case, of desk study
- site reconnaissance by the EGA and GA or their representatives
- appraisal of the general geological, hydrogeological and geotechnical conditions using readily available information
- identification of the nature of potential hazards or features associated with the ground conditions
- development of a conceptual ground model that provides an adequate three-dimensional representation of the site and puts the scale of the project into perspective.

The survey

- establish the objectives and corresponding methodology for the site investigation
- specification of the work so that those involved in the fieldwork can modify its content in the light of what is discovered, the better to achieve the objectives
- identification of suitable techniques for both non-intrusive and intrusive exploration
- pre-planning for phasing of the works and consideration of the early use of geophysical techniques for scoping surveys
- involvement of the designer of the investigation in the supervision of the fieldwork.

The risks

- carrying out a risk assessment to identify residual uncertainties
- modifying the methodology to mitigate or further reduce the uncertainties.

11.2.2 Procurement

The following is a checklist of actions that should be considered in the procurement process for geophysical works.

General

- adopt a teamwork or partnership approach whenever possible
- obtain advice from specialist contractors in the planning stage
- identify clear project requirements
- establish the survey's objectives and purpose
- separate the geophysical survey from the main site investigation contract, wherever possible
- phase the investigation works
- provide background documentation to bidders, particularly the desk study
- allow adequate contingency budget sums for additional work at each stage, so as not to incur additional cost by having to re-mobilise or re-tender extra work later.

The specification

- define the geological setting
- define the overall project (as well as specific needs) so that potential contractors can put their work in its context) and can consider alternatives for added value
- define the performance and acceptance criteria
- provide detailed descriptions of all deliverables, including digital data from both field and office
- allow sufficient programme time for early trialling and calibration.

The contract

- use standard unamended forms of contract wherever possible
- prepare fair remeasurable itemised bills with day rates where appropriate
- identify the overall programme and stage dates
- identify key deliverables and link to stage completion and stage payments
- allow alternative proposals
- adopt clear QA/QC procedures.

Selection of tenderers

- use a short list of appropriately experienced, skilled and resourced contractors
- select and award on the basis of value for money not price
- identify and approve all key staff.

11.2.3 Management

The management of an investigation involving geophysics should take the following aspects into account:

- overall responsibility for the investigation resting with a Geotechnical Adviser (GA)
- the GA and Engineering Geophysics Adviser being a members of the project team
- the EGA being called upon for engineering geophysics advice where appropriate
- clarity in the engineering objectives and appreciation
- from a good geological appreciation, setting realistic geophysical targets
- allowing for adequate pre-planning, desk study and site reconnaissance
- establishing good and open communications
- encouraging flexible team-work or partnership
- controlling risks systematically through appropriate applied risk management techniques
- setting adequate and realistic programme periods for all activities and for each phase
- resisting pressures to condense exploratory activities due to other programme slippages
- providing feedback to EGA, GA and client through post-project audits.

11.2.4 Supervision

Two aspects are highlighted in relation to supervision of the geophysical works.

1. Continual independent but integrated specialist geophysics supervision as part of fieldwork team.
2. Involvement of the designer of the investigation in the supervision and direction of the investigation.

11.2.5 Reporting

The following general aspects relate to good practice in reporting geophysical works:

- identification of deliverables required in detail at outset
- keeping the factual report of the fieldwork separate from the interpretative report
- integrating those providing the geophysical interpretations into the overall site investigation interpretation team
- calibrating, correlating and corroborating the findings
- progressively updating the ground model and re-assessing its relationship with the project.

11.2.6 Feedback

Improvements to practice depend on effective feedback. The following are some of the ways that this can be done:

- identifying successes and shortcomings through post-project audits involving all parties
- seeking to identify ways in which the process can be improved to the benefit of the project or for future projects
- publishing examples of good practice and successful geophysical applications for civil engineering purposes
- advising the geophysics contractors of findings during construction or excavation to learn from successes and failures
- preservation of data for future use, possibly in the Health and Safety file and elsewhere.

Geological Society, London, Engineering Geology Special Publications

References

Geological Society, London, Engineering Geology Special Publications 2002; v. 19; p. 223-241
doi:10.1144/GSL.ENG.2002.019.01.12

References

ABBISS C P (1981) Shear wave measurements of the elasticity of the ground, *Géotechnique 31*, pp 91–104

ABBISS C P (1983) Calculation of elasticities and settlements for long periods of time and high strains from seismic measurements, *Géotechnique 33*, pp 397–405

ACKWORTH I, KELLY B and JANKOWSKI J (1994) Improved contamination assessment of a domestic landfill using integrated geophysical, geochemical and hydrogeological methods, *Water Down Under '94* (Adelaide, 21–25 November 1994) pp 235–240

ADAMS S, McDOWELL P W and HART P A (1992) Ground conditions at Lion Salt Works Site, Marsden, Cheshire, *Proceedings of the 4th International Conference on ground movements and structures, Cardiff* pp 443–458

AMERICAN SOCIETY FOR TESTING MATERIALS (ASTM) (1995) *Standard Guide for Planning and Conducting Borehole Geophysical Logging* (ASTM Designation: D 5753-95, Philadelphia) 8 pp

AMERICAN SOCIETY OF CIVIL ENGINEERS (1998) ASCE Standard *Seismic Analysis of Safety-Related Nuclear Structures and Commentary* pp 4–98

ANNAN A P (1992) *Ground penetrating radar – workshop notes* (Sensors and Software Inc, Canada) p 128

ANON (1981) Suggested method for porosity/density determination using saturation buoyancy techniques, in *Rock characterisation testing and monitoring, ISRM suggested methods* (ed) Brown E T (Pergamon Press, Commission on Testing Methods, International Society for Rock Mechanics)

ANON (1988) Geological Society Engineering Group Working Party Report on Engineering Geophysics *Quarterly Journal of Engineering Geology 21* pp 207–227

ANON (1997) *Guidance on radar testing of concrete structures* (Concrete Society Technical Report No 48) 88 pp

ARANDJELOVIC D (1966) Geophysical methods used in solving some geological problems encountered in the construction of the Trebisnjica Water Power Plant, Yugoslavia, *Geophysical Prospecting 14* pp 80-97.

ARCHIE G E (1942) The electrical resistivity log as an aid in determining some reservoir characteristics Petroleum Technology 5: 1–8 T*rans. AIME 146* pp 54–62

ARTHUR J C R, PHILLIPS G and McCORMICK C R (1997) High definition seismic for Channel Tunnel marine route, Modern Geophysics in Engineering Geology *Engineering Group of the Geological Society 30th Anniversary Conference Liege* pp 347–354

ASTM (1995) *Standard Guide for Planning and Conducting Borehole Geophysical Logging,* American Society for Testing Materials, Designation: D 5753-95 8 pp

ATKINSON J H (2000) Non-linear soil stiffness in routine design (Forty-fourth Rankine Lecture) *Geotechnique* (Vol. L No 5) pp 485–508

BACKUS G E (1962) Long wave elastic anisotropy produced by horizontal layering *Journal of Geophysical Research 67* pp 4427–4440

BAOSHAN Z and CHOPIN L (1983) Shear wave velocity and geotechnical properties of tailings deposits, *Bulletin International Association Engineering Geology 26–27* pp 347–353

BARIA R, JACKSON P D and McCANN D M (1989) Further development of a high-frequency seismic source for use in boreholes, *Geophysical Prospecting 37* pp 31–52

BARKER R D (1983) Comparison of geophysical techniques over the Cliffe Hill Markfieldite, Leicestershire in *Prospecting and evaluation of non-metallic rocks and minerals* (Institution of Geologists, London) pp 57–68

BARKER R D (1997) Electrical imaging and its application in engineering investigations in McCann D M, Eddleston M, Fenning P J and Reeves G M (ed) *Modern Geophysics in Engineering* (Geological Society Special Publication No 12) pp 37–43

BARKER R D and HARKER D (1984) The location of the Stour buried tunnel-valley using geophysical techniques, *Quarterly Journal of Engineering Geology* (Geological Society London, 17) pp 103–115

BATCHELOR A S, BARIA R and HEARN K (1983) Monitoring the effects of hydraulic stimulation by microseismic location: a case study, *58th Annual Technical Conference, Society of Petroleum Engineers, American Institute of Mining, Metallurgical and Petroleum Engineers, San Francisco* pp 1–12

BATES R C (1992) Environmental geophysics in the US; a brief overview, *Geoscientist 2* (2) pp 8–11

BELL F G (1988) Land development. State of the art in the location of old mine shafts, *Bulletin of Engineering Geology 37* pp 91–98

BENSON R C and NOEL M R (1983) *Geophysical techniques for surveying buried wastes and waste investigation* (Environmental Monitoring System Laboratory, Report No 68-03-3050, United States Environmental Protection Agency, Las Vegas)

BERRY K M, COOLING T L and McCASKIE S L (1995) Soil property determination for a seismic study, *Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, Paper 1.59 Vol 3 pp 1073–1077

BIENIAWSKI Z T (1978) Determining rock mass deformability: Experience from case histories, *International Journal of Rock Mechanics, Mining Sciences and Geomechanics Abstracts 15* pp 237–247

BIOT M A (1956) Theory of propagation of elastic waves in a fluid saturated porous solid, *Journal of the Acoustical Society of America 28* pp 168–191

BISHOP I and KOOR N P (2000) Integrated geophysical and geotechnical investigations of old masonry retaining walls in Hong Kong, *Quarterly Journal of Engineering Geology and Hydrogeology 33* pp 335–349

BLACK A J (1986) Borehole gravity surveys, current instrumentation capabilities and applications in Killeen P G (ed) *Borehole geophysics for mining and geological applications* (Geological Survey of Canada, Publication 85–27) pp 181–188

BOGOSLOVSKY V A and OGILVY A A (1977) Geophysical methods for the investigation of landslides, *Geophysics 42* pp 562–571

BOORE D M and BROWN L T (1998) Comparing shear-wave velocity profiles from inversion of surface-wave phase velocities with downhole measurements: Systematic differences between the CXW method and downhole measurements at six USC strong motion sites, *Seismological Research Letters 69, 3* pp 222–229

BRABHAM P J and McDONALD R J (1997) On-shore geophysical methods for coastal and waterway site investigation in McCann D M, Fenning P, Eddlestone M and Cripps J (ed), *Modern Geophysics in Engineering Geology* (Papers from the 30th Annual Conference of the Engineering Group of the Geological Society, Leige, Belgium, 1994) pp 327–336

BRAY D E and McBRIDE D (1992) *Non-Destructive Testing Techniques* (Wiley, Chapter 7, Radiography) pp 113–146

BRITISH STANDARDS INSTITUTION

BS 1881 *Testing concrete Part 203 (1986): Recommendations for measurement of velocity of ultrasound pulses in concrete* (BSI, London)

BS 2600 *Radiographic examination of fusion welded butt joints in steel:*
Part 1: (1983) *Methods for steel 2 mm up to and including 50 mm thick*
Part 2: (1973) *Methods for steel over 50 mm and up to and including 200 mm thick*
(BSI, London)

BS 4124 (1991) *Methods of ultrasonic detection of imperfections in steel forgings* (BSI, London)

BS 5930 (1999) *Code of Practice for Site Investigations* (BSI, London)

BS 6089 (1981) *Guide to assessment of concrete strength in existing structures* (BSI, London)

BS 6208 (1990) *Methods for ultrasonic testing of ferric steel castings including quality levels* (BSI, London)

CP 1021 (1973) *Code of practice for cathodic protection* (BSI, London)

CP 2012 *Part 1: Foundations for machinery* (BSI, London)

ISO 9000-1 (1994) *Quality management and quality assurance standards. Guidelines for selection and use* (BSI, London)

BROADBENT C D (1974) Predictable blasting with in-situ seismic surveys, *Mining Engineering 26* pp 37–41

BROWN R J S (1980) Connection between formation factor for electrical resistivity and fluid solid coupling, in Biot's equations for acoustic waves in fluid filled porous media, *Geophysics 45* pp 1269–1275

BUNGEY J H (1994) *The Testing of Concrete in Structures (2nd edn)* (Chapman and Hall, London) 228 pp

BUSELLI G, BARBER C, DAVIS G B and SALAMA R B (1990) Detection of groundwater contamination near waste disposal sites with transient electromagnetic and electrical methods in S. H. Ward (ed), *Geotechnical and environmental geophysics* (Tulsa Society of Exploration Geophysicists Vol 2) pp 27–39

BUTCHER A P and McELMEEL K (1993) The ability of in-situ testing to assess ground improvement, *Proceedings of the Engineered Fills Conference, Newcastle upon Tyne, 15–17 September*, Thomas Telford) pp 529–540

BUTCHER A P and LORD J A (1993) *Engineering properties of the Gault clay in and around Cambridge, UK,* UK Proc. Int. Symp. Geotechnical Engineering of Hard Soils – Soft Rocks, Athens, 20–23 September (Balkema) pp 405–416

BUTCHER A P and POWELL J J M (1997a) *Practical considerations for field geophysical techniques used to assess ground stiffness,* Proceedings of the International Conference on Advances in Site Investigation Practice, ICE, London, March 1995, (Thomas Telford) pp 701–714

BUTCHER A P and POWELL J J M (1997b) *Determining the modulus of the ground from in-situ geophysical testing,* Proceedings of the XIV International Conference on Soil Mechanics and Foundation Engineering, Hamburg pp 449–452

BUTCHER A P and TAM W S A (1997) The use of Rayleigh waves to detect the depth of a shallow landfill, in McCann D M, Eddleston M., Fenning P J, and Reeves G M (ed) *Modern Geophysics in Engineering Geology* (London, Geological Society Engineering Geology Special Publication 12) pp 97–102

BUTLER D J and LLOPIS J L (1990) Assessment of anomalous seepage conditions, in Ward S H (ed) *Geotechnical and Environmental Geophysics, Volume 2 Environmental Groundwater* (Tulsa: Society of Exploration Geophysicists) pp 153–173

BUTLER D J, LLOPIS J L, DOBECKI T L, WILT M J, COEWIN R F and OLHOEFT G (1991) Comprehensive geophysics investigation of an existing dam foundation, *Geophysics: The Leading Edge 9* (9) pp 44–53

CADNAM J D and GOODMAN R E (1967) Landslide noise, *Science 158* pp 1182–1184

CARPENTER P J, CALKIN S F and KAUFMANN R S (1991) Assessing a fractured landfill cover using electrical resistivity and seismic refraction techniques, *Geophysics 56* (11) pp 1896–1904

CARTMELL S J, CONN P J and PUGH T D (1997) An example of the use of cross-hole tomography in dam wall foundation studies in McCann D M, Fenning P J, Reeves G M (ed) *Modern Geophysics in Engineering Geology* (Geological Society Engineering Geology Special Publication No 12) pp143–153

CATERPILLAR TRACTOR COMPANY (1988) *Handbook of Ripping (8th Edition)* (Caterpillar Inc, Peoria, Illinois) 33 pp

CHAMBERS J, OGILVY R, MELDRUM P, and NISSEN J (1999) 3D resistivity imaging of buried oil-and tar-contaminated waste deposits, *European Journal of Environmental and Engineering Geophysics 4* pp 3–14

CLARKE M R and CORNWELL J D (1983) *The buried glacial channels of the Woolpit (Suffolk) area – a preliminary report* (London, Institute of Geological Sciences Report 83/10) pp 31–36

CLAYTON C R I, GUNN M J, HOPE V S, MATTHEWS M C and McDOWELL P W (1990) An assessment of seismic tomography as a means of detecting voids in salt deposits, *Proceedings of the 6th International IAEF Conference, Rotterdam*) pp 907–912

CLAYTON C R I, SIMONS N E, MATTHEWS M C (1982) *Site Investigation* (Granada Publishing, London)

COLEMAN A R, (1991) The use of the self-potential method in the delineation of a reclaimed landfill site, *Proceedings of the Conference on Planning and Engineering of Landfills*, University of Birmingham, 10th-11th July (The Midlands Geotechnical Society)

COMITE EUROPEAN DE NORMALISATION (CEN) (1998) *Eurocode 8: Design of structures for earthquake resistance* (EN1998)

COMMITTEE ON EARTHQUAKE ENGINEERING 1985, National Research Council, USA

CONSTABLE S C, PARKER R L and CONSTABLE C G (1987) Occam's inversion – a practical algorithm for generating smooth models from electromagnetic sounding data, *Geophysics 52* pp 289–300

CONWAY B W, McCANN D M, SARGINSON M and FLOYD R A (1985) A geophysical survey of the Crouch/Roach river system in South Essex with special reference to buried channels, *Quarterly Journal of Engineering Geology 17* pp 269–282

COON R F (1968) *Correlation of engineering behaviour with the classification of in-situ rock* (PhD thesis, University of Illinois)

CORIN L, COUCHARD I, DETHY B, HALLEUX L, MODOIE A, RICHTER T and WAUTERS J P (1997) Radar tomography applied to foundation design in a karstic environment in McCann D M, Fenning P J and Reeves G M (ed) *Modern Geophysics in Engineering Geology* (Engineering Group Special Publication, No 12) pp 169–175

CORWIN R F (1990) The self-potential method for environmental and engineering applications in Ward S H (ed) *Geotechnical and environmental geophysics 1* (Tulsa Soc. of Expl. Geophys.) pp 127–145

CRAMPIN S (1981) A review of wave motion in anisotropic and cracked elastic media, *Wave Motion 3* pp 343–391

CRATCHLEY C R, GRAINGER P, McCANN D M and SMITH D I (1972) Some applications of geophysical techniques in engineering geology with special reference to the Foyers Hydroelectric Scheme *24th International Geological Congress*, Montreal, Section 13) pp 163–175

CRIPPS A C and McCANN D M (2000) The use of the natural gamma log in engineering geological investigations, *Engineering Geology 55* pp 313–324

CUELLAR V (1997) Geotechnical applications of the spectral analysis of surface waves in McCann D M, Eddleston M, Fenning P J and Reeves G M (ed) *Modern Geophysics in Engineering Geology* (London, Geological Society Engineering Geology Special Publication, No 12) pp 53–62

CULSHAW M G, JACKSON P D and MCCANN D M (1987) Geophysical mapping techniques in environmental planning in Culshaw M G, Bell F G, Cripps A C and O'Hara M (ed) *Planning and Engineering Geology* (Geological Society Special Publication No 4) pp 171–177

DAILY W, RAMIREZ A, LABRECQUE D and NITAO J (1992) Electrical resistivity tomography of vadose water movement, *Water Resources Research 28* (5) pp 1429–1442

DANBOM S H (1995) Environmental Geophysics – A matter of scale *Geotimes 40* 5 May 1995: 4

DARRACOTT B W and LAKE M I (1982) An initial appraisal of ground probing radar for site investigation in Britain, *Ground Engineering 14*, April pp 14–18

DARTON D M, DINGWALL R G and McCANN D M (1981) *Geological and geophysical investigations in Lyme Bay* (London, Institute of Geological Sciences Report 79/10)

DAVIS A G and DUNN C S (1974) From theory to field experience with non-destructive vibration testing of piles (Proceedings of the Institution of Civil Engineers, Part 2, 57 December 1974) pp 571–593

DEERE D U, HENDRON A J jr, PATTON F D and CORDING E J (1967) Design of surface and near-surface construction in rock, *Proceedings of the 8th Symposium on Rock Mechanics, University of Minnesota, 1966* pp 237–302

DENNESS B, CONWAY B W, McCANN D M and GRAINGER P (1975) Investigation of a coastal landslip at Charmouth, Dorset, *Quarterly Journal of Engineering Geology 8* pp 119–140

DEPARTMENT OF THE ENVIRONMENT (1976) *Reclamation of derelict land: procedure for locating abandoned mine-shafts* (Report by Ove Arup & Partners, Contract DGR 482/13, Department of the Environment, London)

DONNELLY L J, DUMPLETON S, CULSHAW M G, SAHEDLOCK S L and McCANN D M (1998) The legacy of abandoned mining in the urban environment in the UK, *Proceedings of the Fifth International Conference on re-use of Contaminated Land and Landfills, 7–9th* July 1998 (Brunel University, London, Engineering Technics Press, Edited by M C Forde)

DUMBLETON M J and WEST G (1974) *Guidance on planning, directing and reporting site investigations* (Transport and Road Research Laboratory Report 625, Crowthorne)

DUTTA N P, BOSE R N and SAIKIA B C (1970) Detection of solution channels in limestone by electrical resistivity method, *Geophysical Prospecting 18* pp 405–414

DYVIK R and MADSHUS C (1985) Laboratory measurement of Gmax using bender elements, *Proceedings of the ASCE Annual Convention: Advances in the art of testing soils under cyclic conditions*, Detroit, Michigan

EISWIRTH M, HOTZL H, LAZAR C and MERKLER G (1995) Detection of contaminant transport from damaged sewerage systems and leaky landfills, *Proceedings of the conference for Groundwater Quality: Remediation and Protection*, Prague, May 1995, IAHS, 225 pp 337–346

EL-NAQA A (1996) Assessment of geomechanical characterisation of a rock mass using a seismic geophysical technique, *Geotechnical and Geological Engineering 14* pp 291–305

ENGINEERING GROUP OF THE GEOLOGICAL SOCIETY (1982) The Working Party Report on Terrain Evaluation, *Quarterly Journal of Engineering Geology* (1982)

ENGINEERING GROUP OF THE GEOLOGICAL SOCIETY (1988) The Working Party Report on Engineering Geophysics, *Quarterly Journal of Engineering Geology 21* pp 207–227

ENGINEERING GROUP OF THE GEOLOGICAL SOCIETY (1993) *Aggregates – Sand, gravel and crushed rock aggregates for construction purposes* (Geological Society Special Publication No 9, London)

EVANS R and LEE M K, (1994) Imaging the Earth's Crust – geophysics at a regional scale, *Geoscientist 4* pp 18–20

FARNAN R A, PIGGIN R H and FLAVENZ O G (1994) The use of deep density borehole gravimeter to establish fluid saturation changes to a North Sea reservoir in *European Association of Exploration Geophysicists 56th meeting* (Technical Programme and abstracts of papers 021)

FEDERATION INTERNATIONALE DE PRECONSTRAINTE (1983) *Inspection and maintenance of reinforced and pre-stressed concrete structures,* FIP Good Practice Guide

FEHLER M and PEARSON C (1984) Cross-hole seismic surveys: applications for studying subsurface fracture systems at a hot dry rock geothermal site *Geophysics 49* pp 37–45

FENNING P J (1994) Comparative geophysical profiles over a completed landfill site *Proceedings of the Third International Conference on Re-use of Contaminated Land and Landfills*, Brunel University London, (M. C. Forde, Engineering Technics Press) pp 279–284

FENNING P J and VENESS K J (1992) Geophysical methods for the location of underground storage tanks (ed) Forde M C *Proceedings of the Second International Conference on Construction on Polluted and Contaminated Land*, Brunel University London, Engineering Technics Press), pp 51–57

FERGUSON C C (1992) The statistical basis for sampling of contaminated land, *Ground Engineering 25* (1)

FIELD E G (1979) Corrosion control in the water industry, *Water Services 83* pp 609–616

FINCH J W (1979) An application of surface electrical resistivity methods to the delineation of spoil tip leachate, *Proceedings Symposium: The Engineering Behaviour of Industrial and Urban Fill*, University of Birmingham, Midland Geotechnical Society c35–c44

FITZGERALD L J, ANGERS A K and RADVILL M E, (1987) *The application of VLF equipment to hazardous waste Site Investigation in New England* (NUS Corporation)

FLEMMING B W (1976) Side-scan sonar: a practical guide, *International Hydrographic Review 53* pp 65–92

FOOKES P G (1997) Geology for engineers: the geological model, prediction and performance, *Quarterly Journal of Engineering Geology 30* pp 293–424

FOURNEY W L and DICK R D (1995) The utilisation of explosive loading as a non-destructive evaluation tool in geologic materials, *International Journal of Solids and Structures 32* (17)

FREEME C R (1978) The application of ultrasonic test methods to the determination of elastic moduli of pavement materials, *Bulletin of the Association of Engineering Geologists 15* pp 63–83

GAMES K P (1986) Digital site surveys: recommended acquisition parameters, *Hydrographic Journal 42* pp 11–8

GARDNER R (1983) Seismic refraction as a tool in evaluation of rock quality for dredging and trenching, *World Dredging Congress,* Singapore, April 1983 pp 251–262

GARDENER R (1992) Seismic refraction as a tool in the evaluation of rock quality for dredging and engineering purposes: case histories in Hudson J A (ed) *Eurock '92* (Chester. British Geotechnical Society) pp 153–158

GARRETT A (1991) *Occam's Razor Physics World,* May pp 39–42

GEYER R L and MYUNG J I (1971) The 3-D velocity log: a tool for in-situ determination of the elastic moduli of rocks, *Proceedings of the 12th Symposium on Rock Mechanics*, University of Missouri, Rolla, 1970 pp 71–107

GOCHIOCO L M (1990) Seismic surveys for coal exploration and mine planning, *The Leading Edge 9* (4) pp 25–28

GOLDMAN M and NEUBAUER F M (1994) Groundwater exploration using integrated geophysical techniques, *Surveys in Geophysics 15* pp 331–361

GOUGH D I (1953) Investigation of foundations by seismic method, *South African Institution of Civil Engineers Transactions 3* pp 61–70

GRAINGER P, McCANN D M and GALLOIS R W (1973) The application of the seismic refraction technique to the study of the fracturing of the Middle Chalk at Mundford, Norfolk, *Géotechnique 2* (3) pp 219–232

GREENHOUSE J P (1991) Environmental geophysics: it's about time, *The Leading Edge 10* (1) pp 32–34

GREENHOUSE M B, SCHNEIDER G, REDMAN D, ANNAN P, OLHOEFT G, SANDER K and MAZZELLA A (1993) Geophysics and solvents: The Borden Experiment, *The Leading Edge* April pp 261–267

GRIFFITHS D H and BARKER R D (1993) Two-dimensional resistivity imaging and modelling in areas of complex geology, *Journal of Applied Geophysics 29* pp 211–226

GUPTA P K, NIWAS S and GAUR V K (1997) Straightforward inversion of vertical electric sounding data *Geophysics 62* (3) pp 775–785

HAGEDOORN J G (1959) The plus-minus method of interpreting seismic refraction sections, *Geophysical Prospecting 7* pp 158–182

HALL D H and HAJNAL Z (1962) The gravimeter in studies of buried valleys, *Geophysics 27* pp 939–951

HAMDI F and TAYLOR-SMITH D (1982) The influence of permeability on compressional wave velocity in marine sediments, *Geophysical Prospecting 30* pp 622–640

HARDAGE B A (1987) Blending log date, borehole geophysics and surface seismic measurements into unified geological messages, *SWPLA 28th Logging Symposium* London, Paper INV-AC

HARDIN B O and BLANDFORD G E (1989) Elasticity of particulate materials, *Journal of the Geotechnical Engineering Division, ASCE, 115* (6) pp 788–805

HARDIN B O and DRNVICH V P (1972) Shear modulus and damping in soils: measurement and parameter effects, *Soil Mechanics Foundations Division 98* (SM6)

HASKELL N A (1953) The dispersion of subsurface waves on multilayered media *Bulletin of the Seismological Society of America 43* (1) pp 17–34

HEALTH AND SAFETY COMMISSION (1994) *Managing construction for health and safety, Construction (Design and Management) Regulations. Approved Code of Practice* (HSE Books, Suffolk)

HELLEWELL E G, (1988) The status of old coal mine plans in site investigations in Forde M C (ed) *Proceedings of the Second International Conference on Construction in Areas of Abandoned Mineworkings* 28–30 June, Edinburgh (Engineering Technics Press) pp 9–15

HIGGINBOTTOM I E (1976) The use of geophysical methods in engineering geology, Part 2, electrical resistivity, magnetometer and gravity methods, *Ground Engineering 9* (2) pp 21–23

HIGHT D W, BENNEL J D, CHANA B, DAVIS P D, JARDINE R J and POROVIC E (1997) Wave velocity and stiffness measurements of the Crag and Lower London Tertiaries at Sizewell, *Géotechnique XLVII* (3) pp 451–474

HINZE W J (1990) The role of gravity and magnetic methods in engineering and environmental studies in Ward S H (ed) *Geotechnical and environmental geophysics* (Tulsa Society of Exploration Geophysicists 1 pp 75–126

HOEKSTRA P and BLOHM M W (1990) Case histories of time-domain electromagnetic soundings in environmental geophysics in Ward S H (ed) *Geotechnical and environmental geophysics* (Tulsa, Society of Exploration Geophysicists 2 pp 1–15

HOULISTON D J, LAUTHLIN J and WAUGH G (1982) *Automatic real time event detection for seismic networks,* Global Seismology Research Group, Institute of Geological Sciences, London, Open file report No 159

HUGGENBERGER P, MEIR E and PUGIN A (1994) Ground Probing radar as a tool for heterogeneity estimation in gravel deposits in Geophysics and Environment, *Journal of Applied Geophysics 31* (1–4) pp 171–184

INTERNATIONAL SOCIETY FOR ROCK MECHANICS (1981) *Commission on Standardisation of Laboratory and Field Tests*

IVANSSON S (1985) A study of tomographic velocity estimation in the presence of low velocity zones, *Geophysics 50* pp 969–988

JACKSON P D and McCANN D M (1997) Cross-hole seismic tomography for engineering site investigation in McCann D M, Fenning P J, and Reeves G M (ed) *Modern Geophysics in Engineering Geology* (London, Geological Society Engineering Geology Special Publication No 12) pp 249–266

JACKSON P D, McCANN D M and RUSSELL D L (1987) Geophysical mapping during the planning of new roads: an aid to the detection of mine working in *Planning and Engineering Geology* (Geological Society Special Publication No 4) pp 447–452

JACKSON P D, WILLIAMS G M, WARD R, MELDRUM P and REECE G (1992) Electrical Imaging of Groundwater Problems, *American Nuclear Society, Winter Meeting* (10–14th November, San Francisco No 1) pp 178–179

JOHNSON S T (1994) Rising groundwater levels: engineering and environmental implications, *Groundwater problems in urban areas* (Thomas Telford, London, 1994) pp 285–298

KEYES W S (1990) Borehole Geophysics Applied to Ground-Water Investigations in *Technical Water-Resources Investigations, Book 2,* Chapter E2 (United States Geological Survey) 150 pp

KIM Y S, TATSUOKA F and OCHI (1994) Deformation characteristics at small strains of sedimentary soft rocks by triaxial compression test, *Géotechnique 44* (3) pp 461–478

KING R A (1977) *A review of soil corrosiveness with particular reference to reinforced earth* (TRRL Supplementary Report 316, Transport and Road Research Laboratory, Crowthorne)

KLEIN K and SANTAMARINA J C (1997) Methods for broad-band dielectric permittivity measurements (soil water mixtures, 5 Hz to 1.3 GHz) *Geotechnical Testing Journal 20* pp 179–196

KNIGHT C J and MATTHEWS W L (1976) A landslip study in Tertiary sediments, Northern Tasmania, *Bulletin of the International Association of Engineering Geology 14* pp 7–22

KNIGHT M J, LEONARD J B and WHITELEY R J (1978) Lucas Heights solid waste landfill and downstream leachate transport – a case study in environmental geology, *Bulletin International Association Engineering Geology 18* pp 45–64

KNILL J L (1970) The application of seismic methods in the prediction of grout take in rock, *In-situ investigations in soils and rocks, Proceedings of a Conference* (British Geotechnical Society, London) pp 93–100

KRISHNAMOORTHY K, GOLDSMITH W and SACKMAN J L (1974) Measurements of wave processes in isotropic and transversely isotropic elastic rocks, *International Journal of Rock Mechanics 11* (Mech. Min. Sci. & Geomech. Abstr.) pp 367–378

KUHN S H (1978) Nuclear gauges, *Bulletin of the Association of Engineering Geologists 15* pp 135–144

KUWANO R, CONNOLLY T M and JARDINE R J (2000) Anisotropic stiffness measurements in a stress-path triaxial cell, *Geotechnical testing journal, GTJODJ 23* (2) pp 141–157

LAPENNA V, PERRONE A, PIETRO L, PISCITELLI S, RIZZO E and SDAO F (2000) 2D resistivity and 3D self-potential tomographies in the study of the Giarossa Landslide (Southern Italy), *Proceedings of the 6th Meeting of Environmental and Engineering Geophysics,* Bochum, Germany

LEBRETON F, SARDA J P, TROQUEME F and MORLIER P (1978) Logging tests in porous media to evaluate the influence of their permeability on acoustic wave forms, *Society of Professional Well Log Analysts 19th Annual Symposium,* El Paso, Texas, Q1–26

LEE F T and MYSTKOWSKI W (1978) Loveland Basin Slide, Colorado, U.S.A in Voight B (ed) *Rockslides and Avalanches. 1 Natural Phenomena* (Elsevier, Amsterdam) pp 473–514

LE TIRANT P (1979) *Seabed Reconnaissance and Offshore Soil Mechanics for the Installation of Petroleum Structures* (Technip, Paris)

LO PRESTI D C F, JAMIOLKWSI M B, PALLARA O, CAVALLLARO A and PEDRONI S (1997) Shear modulus and damping of soils, *Géotechnique XLVII* (3) pp 603–618

LOKE M H and BARKER R D (1996a) Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method, *Geophysical Prospecting 44* pp 131–152

LOKE M H and BARKER R D (1996b) Practical techniques for 3D resistivity surveys and data inversion, *Geophysical Prospecting 44* (3) pp 499–523

LOMNITZ C (1994) *Fundamentals of Earthquake Prediction* (John Wiley and Sons) 328 pp

LOMNITZ C (1999) *The Road to Total Earthquake Safety* (Seventh Mallet Milne Lecture, A A Balkema) 89 pp

LUNGU D, ALDEA A, MOLDOVEANU T, CIUGUDEAN V and STEFANICA M (1998) Surface geology and dynamical properties of soil layers in Bucharest in Wenzel F and Lungu D (ed) *Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation* (Kluwer Academic Publishers, Dordrecht)

MACDONALD G J and CHARTRES F R D (1994) Geophysical investigations for the A3 Hindhead Tunnel. Modern Geophysics in Engineering Geology, *Engineering Group of the Geological Society 30th Anniversary Conference* Liege pp 459–484

MAHRER K D (1995) Review of the radio frequency (RIM) method and its utilisation in near-surface investigations, *The Leading Edge 14* (6) pp 249–256

MALAGNINI L (1996) Velocity and attenuation structure of very shallow soils: Evidence for a frequency-dependent Q, *Bulletin of the Seismological Society of America 85* (5) pp 1471–1486

MALLARD D and SKIPP B O (1999) The dynamic properties of the Mercia Mudstone at Oldbury in *The engineering properties of the Mercia Mudstone Group,* Papers presented at a seminar held at Pride Park, Derby, on 25 November 1998 (CIRIA Conference Record 2000/1, CIRIA, London) pp 116–122

MATHIEZ J P and ASTIER J L (1958) SaultùBrenais damsite, refraction seismic survey in *Geophysical surveys in mining, hydrological and engineering projects* (European Association of Exploration Geophysicists, The Hague) pp 232–237

MATTHEWS M C, CLAYTON C R I and OWN Y (2000) The use of field geophysical techniques to determine geotechnical stiffness parameters, *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering, 2000 Vol 143*, January pp 31–42

MATTHEWS M C, HOPE V S and CLAYTON C R I (1997) The use of surface waves in the determination of ground stiffness profiles, *Proceedings of the Institution of Civil Engineers Geotechnical Engineering Vol 119* (2) April pp 84–95

MATTHEWS S L (1998) *Subsurface radar as an investigative technique* (Building Research Establishment Report BR 340, CRC, Garston, Watford)

McCANN D M, CULSHAW M G, and FENNING P J (1997) Setting the standard for geophysical surveys in site investigation in McCann D M, Eddleston M, Fenning P J, and Reeves G M (ed) *Modern Geophysics in Engineering Geology* (Geological Society Engineering Geology Special Publication, No 12) pp 3–34

McCANN D M, CULSHAW M G and NORTHMORE K J (1990) Rock mass assessment from seismic measurements in Bell F G, Culshaw M G Cripps J C and Coffey J R (ed) *Field Testing in Engineering Geology* (Geological Society Engineering Geology Special Publication No 6) pp 257–266

McCANN D M and FORDE M C (in press) *A review of NDT methods in the testing of concrete and masonry structures. Non-destructive Testing and Evaluation* (Elsevier Press)

McCANN D M, and FORSTER A. (1990) Reconnaissance geophysical methods in landslide investigations, *Engineering Geology 29* pp 59–78

McCANN D M and TAYLOR-SMITH D (1973) Geotechnical mapping of sea-floor sediments by use of geophysical techniques, *Transactions of the Institution of Mining and Metallurgy, Section B 82* B155–167

McCANN D M, SUDDABY D L and HALLAM J R (1982) *The use of geophysical methods in the detection of natural cavities, mineshafts and anomalous ground conditions* (Engineering Geology Unit, Institute of Geological Sciences, London, Open file report No EG82/5)

McCAULEY M L (1976) *Microsonic detection of landslides Transportation Research Board, Transportation Research Record 581* pp 25–30

McDOWELL P W (1975) Detection of clay filled sink-holes in the chalk by geophysical methods, *Quarterly Journal of Engineering Geology 8* pp 303–310

McDOWELL P W (1981) Recent developments in geophysical techniques for the rapid location of near-surface anomalous ground conditions by geophysical methods, *Ground Engineering 14* pp 20–23

McDOWELL P W (1986) Seismic refraction surveying in urban areas, *Institution of Mining and Metallurgy conference on rock engineering and excavation in an urban environment,* Hong Kong, 241–247

McDOWELL P W (1990) The determination of the dynamic elastic moduli of rock masses by geophysical methods in Bell F G, CULSHAW M G and CRIPPS A C (ed) *Field testing in Engineering Geology* (Geological Society of London Special Publication, No 6) pp 267–274

McDOWELL P W (1993) Seismic investigation for rock engineering in Hudson J A (ed) *Comprehensive rock engineering Volume 3: Rock testing and site characterisation* (Pergamon Press) pp 619–634

McDOWELL P W, BARLA G and SHARP J C (1992) Investigation of rock mass characteristics by geophysical methods for an underground storage project site in weak jointed chalk, *Proceedings of the ISRM-BGS Symposium EUROCK,* Chester pp 169–173

McDOWELL P W and HOOPER J W (1980) The mapping of chalk pinnacles and clay pockets in gravel by electrical resistivity methods, *Quarry Management and Products 7* pp 304–306

McDOWELL P W and HOPE V (1993) The location and delineation of Karst and solution collapse features by acoustic tomography, *Proc. 4th Multidisciplinary Conf. on Sinkholes and the Engineering and Environmental Impacts of Karst*, Florida, Jan 1993 (Balkema, Rotterdam) pp 123–129

McDOWELL P W and MILLET N (1984) Surface ultrasonic measurement of longitudinal and transverse wave velocities through rock samples, *International Journal of Rock Mechanics, Mining Sciences and Geomechanics Abstracts 21* pp 223–227

MacGREGOR F, FELL R, MOSTYN G R, HOCKING G and McNALLY G (1994) Estimation of rock rippability, *Quarterly Journal of Engineering Geology 27* (2) pp 123–144

McGUFFEY V C, MODEER V A and TURNER A K (1996) Subsurface exploration, in Turner A. K. and Schuster R. L (ed) *Landslides, Investigation and Mitigation* (Transportation Research Special Report No 247, National Research Council) pp 231–277

McMECHAN G A, GAYNOR G C and SZERBIAK R B (1997) Use of ground-penetrating radar for 3-D sedimentological characterisation of clastic reservoir analogues, *Geophysics 62* (3) pp 786–796

McNEIL J D (1997) The application of electromagnetic techniques to environmental geophysical surveys in McCann D M, Eddleston M, Fenning P J and Reeves G M (ed) *Modern Geophysics in Engineering Geology* (The Geological Society, Special Publication No 12, London) 441 pp

McQUILLIN R and ARDUS D A (1977) *Exploring the Geology of Shelf Seas* (Graham and Otman, London)

MEIGH A C and SKIPP B O (1960) Gamma-ray and neutron methods of measuring soil density and moisture, *Géotechnique 10* pp 110–26

MIDTTOMME K, ROALDSET E and AAGAARD P (1997) Thermal conductivities of argillaceous sediments in McCann D M, Eddlestone M, Fenning P J and Reeves G M (ed) *Modern geophysics in Engineering Geology* (Geological Society Special Publication No 12) pp 365–372

MILLER R D and STEEPLES D W, (1994) Application of shallow high-resolution seismic reflection to various environmental problems, *Journal of Applied Geophysics Research 31* pp 65–72

MILLER C H, RAMIREZ A L and BULLARD T F (1980) *Seismic properties of the Springer Ranch Landslide, Powder River Basin, Wyoming* (United States Geological Survey, Professional Paper 1170-C, Washington DC)

MILLER R D, MARKIEWICZ R D, MEREY C, XIA J and MAPLES C G (1995) Improvements in shallow high-resolution seismic reflection through PC-based systems, *Computers & Geosciences 21* (8) pp 957–964

MOHAMMADIOUN B and GARIEL J C (1996) An analysis of on earthquake and bedrock motion: a co-operative NRC/CEA experiment at Garner Valley (California) *Proc. 11th WCEE* (Pergamon. Elsevier Science Ltd, Oxford) Disc 2, paper 903

MOSSMAN R W and HEIM G E (1972) Seismic exploration applied to underground excavation problems, *Proceedings of 1st North American rapid excavation and tunnelling conference*, Chicago (American Society of Civil Engineers and American Institute of Mining, Metallurgical and Petroleum Engineers) pp 169–192

MULLER K (1977) Geophysical methods in the investigation search slope failures, *Bulletin of the International Association of Engineering Geology 16* pp 227–229

MURPHY B J and ROSENBAUM M S (1989) Attenuation from seismic refraction surveying as a ground investigation aid, *Quarterly Journal of Engineering Geology 16* pp 187–195

NEILSON P H (1996) Computation of porosity and water content from geophysical logs, Yucca Mountains, Nevada, *US Geological Survey 64* (Open-File Report, OF 0078)

NEW B M (1971) Ultrasonic wave propagation in discontinuous rock, *TRRL Laboratory Report 720*

NEW B M (1985) An example of tomographic and Fourier microcomputer processing of seismic records, *Quarterly Journal of Engineering Geology 18* pp 335–344

NISHI K, ISHIGRIU T and KUDO K (1989) Dynamic properties of weathered sedimentary soft rocks, *Soils and Foundations 29* (3) pp 67–82

NOBES D C (1996) Troubled waters: environmental applications of electrical and electromagnetic methods, *Surveys in Geophysics 17* (4) pp 393–454

NOVOSAD S, BLAHA P, and KNEIJZLIK J (1977) Geoacoustic methods in slope stability investigations, *Bulletin of the International Association of Engineering Geology* (Krefeld No 16) pp 229–241

OLAYINKA A I and YARAMANCI U (2000) Assessment of the reliability of 2D inversion of apparent resistivity data, *Geophysical Prospecting 48* pp 293–316

OLHOEFT G R (1992) Geophysical detection of hydrocarbon and organic chemical contamination in Bell R S (ed) *Proc. Of the Symposium on the Applications of Geophysics to Engineering and Environmental Problems* (Oakbrook, Illinois) pp 587–595.

ONIONS K R, WHITWORTH K and JACKSON P J (1996) Application of geophysical methods to site investigations of contaminated old collieries, *Quarterly Journal of Engineering Geology 29* pp 219–231

ONODERA T F (1963) Dynamic investigation of foundation rock in-situ, *Proceedings of the 5th Symposium on Rock Mechanics* (University of Minnesota, 1962) pp 517–533

PAILLET FL (1993) Using borehole geophysics and cross-borehole flow testing to define hydraulic connections between fractures zones in bedrock aquifers, *Journal of Applied Geophysics 30* pp 261–279

PARRA J O (1988) Electrical response of a leak in a geomembrane liner, *Geophysics 53* (11) pp 1445–1452

PECKER A (1991) *Garner Valley – Downhole experimentation – Soil profile and mechanical characteristics* (Géodynamique et structure, Project 03-90, Report No 1, Rev A)

PENN S and TUCKER D (1983) The application of geophysics to quarry overburden problems, in *Prospecting and evaluation of non-metallic rocks and minerals* (Institution of Geologists, London) pp 149–156

PENNINGTON D S, NASH D F T and LINGS M L (1997) Anisotropy of G0 shear stiffness in Gault Clay, *Géotechnique 47* (3) pp 391–398

PHILLIPS J D and FITTERMAN D V (1995) Environmental Geophysics, Reviews of Geophysics, *American Geophysical Union Supplement,* July 1995 pp 185–193

PITEAU D R, MYLREA F H and BLOWN I G (1978) Downie Slide, Columbia River, British Columbia, Canada in Voight B (ed) *Rockslides and Avalanches. 1 Natural Phenomena* (Elsevier, Amsterdam) pp 365–392

POSTER C and COPE C (1975) The location of backfilled quarries by high resolution gravimetry, *The Arup Journal 10* pp 7–9

POWELL J H (1998) *A guide to British stratigraphical nomenclature* (Special Publication 149, CIRIA, London)

PRATT R G and CHAPMAN C H (1992) Traveltime tomography in anisotropic media – I. Application, *Geophysical Journal International 109* pp 20–37

PRENTICE J and McDOWELL P W (1976) "Geological and geophysical methods in the location and design of services" Underground Services (No 4) pp 15-8

PRENTICE J and McDOWELL P W (1977) "The investigation of potential bridge sites on the River Torridge at Bideford, Devon" Quarterly Journal of Engineering Geology (No 10) pp 341-342

PRESS W H, TEUKOLSKY S A, VETTERLING W T and FLANNERY B P (1996) Numerical Recipes in FORTRAN, 2nd edition. (Cambridge University Press) 963 pp

RECHTIEN R D, HAMBACKER K L and BALLARD Jr. R F (1993) A high-frequency sparker source for the borehole environment, *Geophysics 58* (5) pp 660–669

REYNOLDS J M (1994) Resolution and differentiation of sub-surface materials using multi-method geophysical surveys in Forde M C (ed) *Proceedings of the Third International Conference on Re-use of Contaminated Land and Landfills*, Brunel University, (London, Engineering Technics Press) pp 63–67

REYNOLDS J M (1997) *An introduction to applied and environmental geophysics* (John Wiley & Sons Ltd, Chichester) 796 pp

REYNOLDS J M and MCCANN D M (1992) Geophysical methods for the assessment of landfill and waste disposal sites in Forde M C (ed) *Proceedings of the Second International Conference on Construction on Polluted and Contaminated Land*, Brunel University (London, Engineering Technics Press) pp 63–71

RICKETTS G A, SMITH J and SKIPP B O (1995) Confidence in seismic characterisation of the ground *Proc. Int. Conf. on Advances in Site Investigation* (London, Thomas Telford)

RICKETTS G A, SMITH J and SKIPP B O (1996) Confidence in seismic characterisation of the ground in Craig C (ed) *Advances in site investigation practice* (Thomas Telford Press)

ROBBINS S L (1980) *Bibliography with abridged abstracts of sub-surface gravimetry (especially borehole) and corresponding in-situ density determinations* (United States Geological Survey, Open File Report) pp 80–710

ROBERTS R L, HINZE W J and LEAP D I (1989) A Multi-Technique Geophysical Approach to Landfill Investigation, *Proceedings of the Third Outdoor Action Conference on Aquifer Restoration, Groundwater and Geophysical Methods 3* Orlando, Florida, 22nd–25th May pp 797–811

ROBERTS R L, HINZE W J and. LEAP D I (1990) Application of the gravity method to the investigation of a landfill in glaciated mid-continent, U.S.A.: a case history in Ward S H (ed) *Geotechnical and environmental geophysics 2* (Tulsa, Society of Exploration Geophysicists) pp 253–259

ROBERY P C and CASSON R B J (1995) Methods of investigation using combined NDT techniques in Forde M C (ed) *Proceeding of the Sixth International Conference on Structural Faults and Repair* 3rd–5th July 1995 (London, Engineering Technics Press) 2 pp 3–15

ROMIG P (1992) Engineering and environmental geophysics get top billing at SAGEEP, *Geophysics: The Leading Edge of Exploration 11* pp 36–37

ROUSE W C, STYLES P, and WILSON S A (1991) Microseismic emissions from flow slide -type movements in South Wales, *Engineering Geology 31* pp 91–110

ROUSSEL J M (1968) Theoretical and experimental study of dynamic modulus of rock masses, *Revue de l'Industrie Minerale 50* pp 573–600

SASAKI Y (1992) Resolution of resistivity tomography inferred from numerical simulation, *Geophysical Prospecting 40* pp 453–463

SASAKI Y (1994) 3-D resistivity inversion using the finite element method *Geophysics 59* (11) pp 453–463

SASS J H, LACHENRUCH A H and MUNROE R J (1971) Thermal conductivity of rocks from measurements on fragments and its application to heat flow determinations, *Journal of Geophysical Research 76* pp 3391–3401

SCHNEIDER B (1967) Contribution it l'etude de massifs de la fondations de barrages, *Transactions du Laboratoire de Geologie de la Faculte de Sciences de Universite de Grenoble,* Monsoir 7

SCHOPPER J R (1966) A theoretical investigation on the formation factor/permeability/porosity relationship using a network model, *Geophysical Prospecting 14* pp 301–341

SIMPSON B, ATKINSON J H and JOVICIC V (1996) The influence of Anisotropy on calculations of ground settlements above tunnels, *Proceedings of Geotechnical Aspects of underground construction in soft ground,* The City University, London pp 591–595

SITE INVESTIGATION STEERING GROUP (1993) *Site investigation in construction Parts 1 to 4* (Thomas Telford, London)

SJOGREN B A, OFSTHUS A and SANDBERG J (1979) Seismic classification of rock mass qualities, *Geophysical Prospecting 27* pp 409–442

SKIPP B O (1995) Acquisition choice and use of ground parameters for soil-structure interaction analysis, *10th European Conference of Earthquake Engineering,* pp 425–440

SLAINE D D, PEHME P E, HUNTER J A, PULLAN S E and GREENHOUSE J P (1990) Mapping overburden stratigraphy at a proposed hazardous waste facility using shallow seismic reflection methods in Ward SH (ed) *Geotechnical and environmental geophysics 2* (Tulsa, Society of Exploration Geophysicists) pp 273–280

STACEY T R and NOBLE G W (1975) Seismic evaluation of soil trenchability, *Proceedings, 6th Regional Conference on African Soil Mechanics and Foundation Engineering 2* pp 185–186

STEEPLES D W and MILLER R D (1990) Seismic reflection methods applied to engineering, environmental, and groundwater problems in Ward S H (ed) *Geotechnical and environmental geophysics 1* (Tulsa, Society of Explor. Geophys.) pp 1–30

STEEPLES D W and NYQYIST J E (1995) What Environmental Geophysics Can Do, *Geotimes,* May 1995 pp 15–17

STEWART I E, WILLIAMS J R and WALKER C S (1997) Seismic refraction in relation to geotechnical information (road) construction contracts in McCann D M, Fenning P and Cripps J (ed) *Modern Geophysics in Engineering Geology* (Papers from the 30th Annual Conference of the Engineering Group of the Geological Society, 1994, Leige, Belgium) pp 337–346

STOLL R D (1985) Sediment Acoustics (Springer –Verlag, Berlin) 153 pp

TATSUOKA F, OCHI K, KOHATA Y and WANG L (1977) Experiments in underground excavation in sedimentary rock at Sagamihara, *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering 125* (6) p 223

TAYLOR S B, WHITE C C and BARKER R D (1999) A comparison of portable and permanent landfill liner leak-detection systems in Durham G N and Marr W A (ed) *Field instrumentation for soil and rock* (ASTM STP 1358 American Society for Testing and Materials, 1999)

TELFORD W S, GELDART L P, and SHERIFF R E (1990) *Applied Geophysics, Second Edition* (Cambridge University Press) 769 pp

TITMAN D J (1994) Aerial thermometry – A cost effective approach to landfill site surveys in Forde M C (ed) *Proceedings of the Third International Conference on Re-use of Contaminated Land and Landfills*, Brunel University (London, Engineering Technics Press) pp 269–271

TRANTINA J A (1962) Investigations of landslides by seismic and electrical resistivity methods, in *Field Testing of Soils* (American Society for Testing Materials Special Publication No 322) pp 120–134

TRRL (1975) *Probing ahead for tunnels: a review of present methods and recommendations for research* (Supplementary Report 171 UC)

TURBERG P, MULLER I and FLURY F (1994) Hydrogeological investigation of porous environments by radio magnetotelluric-resistivity (RMT-R 12-240 kHz), *Journal of Applied Geophysics 31* (1–4) pp 133–143

VAN G P, PARK S K and HAMILTON P (1991) Monitoring leaks from storage ponds using resistivity methods (short note), *Geophysics 56* (8) pp 1267–1270

VENESS K J (1996) *The use of rapid surface geophysical surveys in ground investigations of large development and redevelopment sites* (M.Phil, Thesis Middlesex University) 195 pp

VON HERZEN R P and MAXWELL A E (1959) The measurement of thermal conductivity of deep sea sediments by a needle probe method, *Journal of Geophysical Research 64* pp 15S7–63

VUCETIC M and DOBRY R (1991) Effect of soil plasticity on cyclic response, *ASCE, JGED 117* (1) pp 89–107

WALKER C S and WIN M A (1997) A new standard in the practice of engineering seismic refraction in McCann D M, Fenning P and Cripps J (ed) *Modern Geophysics in Engineering Geology* (Papers from the 30th Annual Conference of the Engineering Group of the Geological Society, 1994, Leige, Belgium) pp 425–434

WARD W H, BURLAND J B and GALLOIS R M (1968) Geotechnical assessment of a site at Mundford, Norfolk, for a proton accelerator, *Géotechnique 18* (4) pp 399–431

WEAVER J M (1975) Geological factors significant in the assessment of rippability, *Civil Engineer in South Africa 17* pp 313–316

WEHR W, STEIN U, CUDAMI R and BOSINGER E (1995) CPT, shear wave propogation and freeze probing to estimate void ratio in loose sands, *International Symposium on Cone Testing* (Sweden, Paper A78) pp 1–6

WHITELEY R J (1995) Environmental Geophysics: Challenges and Perspectives, *Exploration Geophysics 25* pp 189–196

WILLS C J (1998) Differences in shear wave velocity due to measurement methods: A cautionary note, *Seismological Research Letters 69* (3) pp 216–220

WOODLAND A W (1970) The buried tunnel-valleys of East Anglia, *Proceedings of the Yorkshire Geological Society 37* pp 521–578

WORTHINGTON M H (1984) An introduction to geophysical tomography, *First Break 2* pp 20–26

WORTHINGTON P F and BARKER R D (1977) Detection of disused vertical mineshafts at shallow depth by geoelectrical methods, *Geoexploration 15* pp 111–120

WYLLIE M R J, GREGORY A R and GARDNER G H F (1958) An experimental investigation of factors affecting elastic wave velocities in porous media, *Geophysics 23* (3) pp 459–493

YAMAGUCHI S (1977) Determination of the location of drains and assessment of the effect of the work by repeated electrical resistivity surveys, *Bulletin of the International Association of Engineering Geology 16* pp 183–184

YOUNG R P, HILL J J, GREEN A D and MIDDLETON R (1984) Vibration monitoring in assessment of blasting efficiency, a new microcomputer-controlled radio-telemetric instrumentation system, *Transactions of the Institution of Mining and Metallurgy,* Section A, No 93, A202-10

YOUNGER P L, (1994) Minewater pollution: the revenge of Old King Coal, *Geoscientist 4* (5) pp 6–7

ZALASIEWICZ J A, MATHERS S J and CORNWELL J D (1985) The application of ground conductivity measurements to geological mapping, *Quarterly Journal of Engineering Geology 18* pp 139–148

Appendices

A1 INTERNATIONAL PRACTICE

The following is a summary of statements from professional engineering geophysicists of eight other countries. They were asked to report on the methods used in their countries or organisations for procurement, supervision, reporting and interpretation of geophysical investigations and on the attitudes with which their work was viewed by potential clients.

Australia

For general government agency procurement, proposals are usually sought from a number of possible suppliers. Although price is a factor, the lowest quote is not automatically accepted and the quality of the proposal and experience in the area are also considered. Larger jobs are normally let under public tender, frequently sought from pre-qualified tenderers. Once pre-qualified, the lowest price is automatically accepted for the defined scope of work or bill of quantities. This process is governed by legal requirements (anti-corruption legislation). It tends to result in a minimum quality service being supplied, but with pressure on the government agency to vary the contract in the direction of a requirement for more services once the work has commenced. Such variations are achieved usually without a second round of tendering.

For commercial clients, procurement procedures are normally more flexible with greater weight being given to the quality of the results than to the price of the services. Lump sum procurement is becoming more common, although most of the lump sum quotations incorporate within them fees and costs.

Poor procurement procedures often result in poor quality geophysics and leave clients with a perception that geophysics (or a particular technique) at best gives only an approximation of the subsurface or simply does not work.

Austria

Many engineering and environmental studies, which require investigations, are procured by public authorities. In general, they commission geophysical services in the same way as engineering services, through a non-obligatory procedure – the OENORM A2050: *Open tendering, offer, contract for material and labour – Process standard.* The only European norm, which comes close and would be available is EN 45503. This is standard in the public sector and civil engineers often use it in the private sector. Magnetic and geo-electric surveys tend to be paid on the basis of the number of points measured: seismic surveys are paid by line length and configuration; and borehole logging services are paid by log type and metres logged.

Belgium

There is no standard procedure in Belgium for geophysical procurement. A similar situation exists to that in the UK at present. Some administrations or companies issue detailed calls for tenders, with well-defined tasks and quantities. Others simply ask for the solution of a more-or-less well-defined problem, which results in uncertainties about costs and large differences between tenders.

Finland

All surveys are decided on bids requested from, and submitted by, the contractors, which are almost all very small companies or individuals. Almost invariably the cheapest bidder will get the work. Ground-probing radar (GPR) systems have in some cases brought back a "black-box" approach, which is not good for the profession. Customers with minimal budgets and minimal knowledge of geophysical techniques select the cheapest bidder.

France

The Association for Quality in Applied Geophysics (AGAP) has had some influence in reducing the general decline in the health of the engineering geophysics industry in France. Nevertheless, the situation is bad. Prices are low, the market is depressed and clients are applying continual pressure with regard to performance and turn-round of acquisition and reporting. The Code of Practice of the Association issued in March 1992, has provided some protection against the worst excesses.

There does not seem to be a problem with inadequate or misleading specifications. It is usual to seek the cheapest price without regard to technical input. Even when there is an adequate specification, there is little attempt to check adherence to the requirements. When the techniques applied do not achieve the required results, there is usually an enquiry as to why any further work (at further cost) should be undertaken.

Modes of engagement vary, as do the terms (lump sum, day measurement, rate measurement). Strict rules are applied on large contracts using such instruments as *Code de Marché Publique*. This is particularly the case for national companies and major clients. AGAP has considered issuing a standard contract of engagement.

Germany

The most active areas of application are for bridges and roads together with environmental surveys, such as for landfills and hydrogeological studies. The re-unification of Germany provided an opportunity for land regeneration, but the funding is not currently available. There appears to be an inability to consider the overall cost benefit of the front-end ground investigation in relation to total project cost.

No engineering geophysical standards are in place, although the *Handbook for the exploration of the sub-surface of waste dumps, part 3* by Knoedel, Krummel and Lange, published in 1997, covers some of these aspects. As in other countries, it appears that there continues to be a need to inform clients of the benefits of the reconnaissance and non-invasive nature of geophysical investigation.

Geophysics has been utilised in some major studies for possible radioactive waste repository sites and a lot of money has been spent on their investigation.

In a reducing market, six contractors specialising in engineering and environmental land geophysics are believed to remain active.

Italy

No national standards covering engineering uses of geophysics are currently available in Italy, although a code was produced for sonic tomography by the Italian Society of

Rock Mechanics in 1988. A site investigation standard is currently being prepared by the Italian Geotechnical Society, which will include a section on geophysics.

The use of geophysics for engineering projects is subject to the same difficulties as those that apply in the UK, with clients being unaware of the potential benefits and reportedly not understanding the constraints on the techniques. There is thus a corresponding low utilisation of the technology. Nevertheless there appear to be at least six contracting companies specialising in the application of geophysics to the engineering and environmental sectors; most of these companies also provide a consultancy service.

Much of their work appears to be awarded on a nominated basis, possibly as a specific part of a major groundworks or construction project, although there is open tendering in some circumstances.

USA

In the USA, federal and other public organisations are allowed to contract to the private sector any services that can be adequately provided. They may perform their own surveys if they are deemed to be at a research level and cannot be procured from industry. Service contracts tend to specify the work scope and rate items. Small contracts can be from a sole-source contractor, ie the only supplier of a service, or appointment by single-tender action. For large contracts, several bids are requested and the choice of contractor is left to the principal investigator, not necessarily that at the lowest cost.

Many procurement procedures are used in the USA. There are many unqualified geophysicists practising in the environmental and engineering community, which are causing difficulties for the profession. The idea of professional registration is under review.

In the environmental sector in North America, there have been problems associated with the rapid increase in geophysical work, even though the use of the same geophysical techniques across a number of market sectors is well established. Initially, according to Greenhouse (1991) and Whiteley (1995), too many of the geophysics practitioners were poorly trained and inexperienced. Subsequently, prescriptive codes, including individual registration through the US Environmental Protection Agency (USEPA), were developed and applied, to the extent that it has been suggested that more effective self-regulation would have been to the benefit of geophysics practitioners. The market for environmental geophysics in the USA has two components: "geo-contracting" and "geo-consultancy".

A2 RESISTIVITIES OF COMMON SOILS AND ROCKS

Table A2.1 *Electrical resistivities of rocks and sediments (after Telford* et al, *1990)*

Rock type	Resistivity range (Wm)
Igneous rocks	
Andesite	4.5×10^4 (wet) – 1.7×10^2 (dry)
Basalt	$10 - 1.3 \times 10^7$ (dry)
Carbonatised porphyry	2.5×10^3 (wet) – 6×10^4 (dry)
Dacite	2×10^4 (wet)
Diabase (various)	$20 - 5 \times 10^7$
Diorite porphyry	1.9×10^3 (wet) – 2.8×10^4 (dry)
Feldspar porphyry	4×10^3 (wet)
Gabbro	$10^3 - 10^6$
Granite porphyry	4.5×10^3 (wet) – 1.3×10^6 (dry)
Lavas	$10^2 - 5 \times 10^4$
Porhyrite	$10 - 5 \times 10^4$ (wet) – 3.3×10^3 (dry)
Porphyry (various)	$60 - 10^4$
Quartz diorite	$2 \times 10^4 - 2 \times 10^6$ (wet) – 1.8×10^5 (dry)
Svenite	$10^2 - 10^6$
Metamorphic rocks	
Consolidated shales	$20 - 2 \times 10^3$
Graphite schist	$10 - 10^2$
Hornfels	8×10^3 (wet) – 6×10^7 (dry)
Marble	$10^2 - 2.5 \times 10^8$ (dry)
Olivine norite	$10^3 - 6 \times 10^4$ (wet)
Peridotite	3×10^3 (wet) – 6.5×10^3 (dry)
Quartzites (various)	$10 - 2 \times 10^6$
Scarn	2.5×10^2 (wet) – 2.5×10^8 (dry)
Schists (calcareous and mica)	$20 - 10^4$
Slates (various)	$6 \times 10^2 - 4 \times 10^7$
Tuffs	2×10^3 (wet) – 10^6 (dry)
Sediments	
Argillites	$10 - 8 \times 10^2$
Clays	$1 - 10^2$
Conglomerates	$2 \times 10^3 - 10^4$
Dolomite	$3.5 \times 10^2 - 5 \times 10^3$
Limestone	$50 - 10^7$
Marls	3 – 70
Oil sands	$4 - 8 \times 10^8$
Sandstones	$1 - 6.4 \times 10^8$
Limestones	$50 - 10^7$
Unconsolidated wet clay	20

A3 DENISITIES OF ROCKS AND SEDIMENTS

Table A3.1 *Densities of rocks and sediments (after Telford* et al, *1990)*

Rock type	Range (g/cm3)	Average (g/cm3)
Igneous rocks		
Acid igneous	2.30 – 3.11	2.61
Andesite	2.40 – 2.80	2.61
Basalt	2.70 – 3.30	2.99
Basic igneous	2.09 – 3.17	2.79
Diabase	2.50 – 3.20	2.91
Diorite	2.72 – 2.99	2.85
Gabbro	2.70 – 3.50	3.03
Granite	2.50 – 2.81	2.64
Granodiorite	2.67 – 2.79	2.73
Lavas	2.80 – 3.00	2.9
Peridotite	2.78 – 3.37	3.15
Porphyry	2.60 – 2.89	2.74
Quartz diorite	2.62 – 2.96	2.79
Rhyolite	2.35 – 2.70	2.52
Metamorphic rocks		
Amphibolite	2.90 – 3.04	2.96
Eclogite	3.20 – 3.54	3.37
Gneiss	2.59 – 3.00	2.8
Greywacke	2.60 – 2.70	2.65
Marble	2.60 – 2.90	2.75
Metamorphic	2.40 – 3.10	2.74
Quartzite	2.50 – 2.70	2.6
Schists	2.39 – 2.90	2.64
Serpentine	2.40 – 3.10	2.78
Slate	2.70 – 2.90	2.79
Sedimentary rocks (wet)		
Clay	1.63 – 2.60	2.21
Dolomite	2.28 – 2.90	2.7
Gravel	1.70 – 2.40	2
Limestone	1.93 – 2.90	2.55
Sand	1.70 – 2.30	2
Sandstone	1.61 – 2.76	2.35
Sedimentary rocks (average)		2.5
Shale	1.77 – 3.20	2.4
Soil (overburden)	1.20 – 2.40	1.92

A4 MAGNETIC SUSCEPTIBILITIES OF A RANGE OF ROCKS AND SEDIMENTS

Table A4.1 *Magnetic properties of rocks and sediments (after Telford* et al, *1990)*

Type	Susceptibility × 10^3 (SI) Range	Average
Igneous rocks		
Andesite		160
Augite-syenite	30 – 40	
Basalts	0.2 – 175	70
Diabase	1 – 160	55
Diorite	0.6 – 120	85
Dolerite	1 – 35	17
Gabbro	1 – 90	70
Granite	0 – 50	2.5
Olivine-diabase		25
Peridotite	90 – 200	150
Porphyry	0.3 – 200	60
Pyroxenite		125
Rhyolite	0.2 – 35	
Metamorphic		
Amphibolite		0.7
Gneiss	0.1 – 25	
Phyllite		1.5
Quartzite		4
Schist	0.3 – 3	1.4
Serpentine	3 – 17	
Slate	0 – 35	6
Minerals		
Anhydrite, gypsum		-0.01
Arsenopyrite		3
Calcite	-0.001 – -0.01	
Cassiterite		0.9
Chalcopyrite		0.4
Chromite	3 – 110	7
Clays		0.2
Coal		0.02
Franklinite		430
Graphite		0.1

A5 SEISMIC VELOCITIES IN ROCKS AND SOILS

Table A5.1 *Seismic velocities in rocks and soils*

Age	Soil/Rock	Vs (m/s)	Ps (m/s)	Method	Reference	Depth (m)
Holocene (Ca)	Lacustrine clays	185–330		Sea bed acoustics	Stoll, 1985	0–30
Holocene (NY)	Marine sands	100–300		Sea bed acoustics	Stoll, 1985	
Holocene (Ca)	Residual soils	300–440		Suspension log		
Holocene (UK)	Silts and clays	<150		Crosshole seismic	Rickets *et al*, 1995	5–18
Holocene (UK)	Alluvial clay	75–175		Crosshole, downhole seismic and Rayleigh		0–20
Holocene (Spain)	Alluvial sand and silty sand	100–200		Crosshole seismic	Cuellar, 1997 5	
Holocene (UK)	Alluvial silt and clay	160	600	Crosshole seismic	Skipp and Mallard. 1995	
Holocene (UK)	Alluvial sands	200–295	1600–1850	Crosshole seismic		8–36
Holocene (?) (Ca)	Alluvial sands	100–300	1500–2000	Seismic refraction, down hole array, suspension log	Pecker, 1991, Mohammidioun and Gariel, 1996	
Holocene (Ms)	Alluvial sands and gravels	134–142		Seiscone and down hole seismic	Berry and Cook 1995	6–12
Holocene (Ro)	Fluvial gravels and sands	333	1666	Crosshole seismic	Lungu *et al*, 1998	
Holocene (Ro)	Lacustrine clays	236	715	Crosshole seismic	Lungu *et al*, 1998	
Holocene (Ro)	Lacustrine sands	271	1750	Crosshole seismic	Lungu *et al*, 1998	
Holocene (UK)	Beach gravels and sands	100–295	170–2200	Crosshole seismic, Continuous surface wave		0–8
Holocene (UK)	Glacial till	150–400		Crosshole, downhole seismic and Rayleigh		0–25
Pleistocene (UK)	Glacial deposits	300		Crosshole seismic	Ricketts *et al*, 1995	0–18
Pleistocene (UK)	Glacial till	250–350	1400–2000	Crosshole seismic		5–10
Pleistocene (UK)	Glacial sands and gravels	240–450	700–1100	Crosshole seismic		10–15
Neogene (Ro)	Marly clay	348–377	1650–2000	Crosshole seismic	Lungu *et al*, 1998	70
Neogene (UK)	Structured sands (Crag)	200–600		Crosshole and down-hole seismic	Hight *et al*, 1997	10–45
Palaeogene (UK) (Eocene)	London Clay, Lower London Tertiaries	100–500		Crosshole and down hole seismic	Hight *et al*, 1997	40–80
Cretaceous (UK)	Chalk	200–1200	200–2200	Crosshole seismic and Rayleigh	Matthews *et al*, 1997	0–30
Cretaceous (UK)	Gault Clay	100–400		Crosshole, downhole and surface	Butcher and Lord, 1995	
Cretaceous (UK)	Argillites (Hastings Beds)	295–600	1880–2420	Crosshole seismics		40–80
Jurassic (UK)	Limestones	1000–1500		Crosshole seismic, downhole seismic, geolog	Ricketts *et al*, 1995	0–40
Triassic	Argillites	1000-2000		Crosshole and downhole seismic	Ricketts *et al*, 1995	60–120
Triassic	Mercia Mudstone (weathered)	250	1100–1300	Crosshole and downhole seismic	Mallard and Skipp, 1999	9
Triassic	Mercia Mudstone (leached)	350–1000	1650–2500	Crosshole and downhole seismic, geolog	Mallard and Skipp, 1999	9–16
Triassic	Mercia Mudstone	899–1600	2600–3200	Crosshole and downhole seismic, geolog	Mallard and Skipp, 1999	23–32
Triassic	Conglomerate	1500	4500	Crosshole and downhole seismic, geolog	Mallard and Skipp, 1999	

Table A5.1 continued...

Age	Soil/Rock	Vs (m/s)	Ps (m/s)	Method	Reference	Depth (m)
Permo-Triassic (UK)	Sandstone	2500, 2330	4500, 3990	VSP, wave field modelling, geolog	Ricketts *et al*, 1995	300–800
Permian (UK)	Basal breccia	2600, 2740	5000, 4810	VSP and wave field modelling, geolog	Ricketts *et al*, 1995	800–900
Carboniferous	Coal Measure mudstones and sandstones (weathered)	500–700	1500–2500	Crosshole seismic		15–25
Carboniferous (UK)	Coal Measure sandstones and mudstones	1000–2000		Crosshole and downhole seismics	Skipp, 1995	5–50
Carboniferous (UK)	Coal Measure limestone	1800–2000		Crosshole and downhole seismic	Ricketts *et al*, 1995	
Devonian (UK)	Low grade metamorphics	1000–2000		Crosshole and downhole seismics	Ricketts *et al*, 1995	
Devonian (UK)	Argillite	950	2800	Crosshole and downhole seismics	Ricketts *et al*, 1995	>35
Igneous Palaeozoic (UK)	Volcanoclastics	2740–3160	5250–5580	VSP, geolog		>500
Palaeozoic (UK)	Dolerite	3030		Crosshole	Ricketts *et al*, 1995	
	Granite (Ca)	1600	3000	Surface refraction, downhole seismic, suspension log	Pecker 1991, Mohammadioun and Gariel 1996,	
	Granites (US)	2870–3040	5520–5880		Telford, 1990	
	Granodiorite/	3050,	4780–5780		Telford, 1990	
	Diorite (US)	3100				
	Gabbro (US)	3470	6450		Telford, 1990	
	Basalt (Ger)	3200	6400		Telford, 1990	
	Dunite (US)	3790,	7400,		Telford, 1990	
		4370	8600			
Miscellaneous	Compacted sand fill	100–280		Crosshole seismic	Skipp, 1995	5–10
	Compacted	200–290		Crosshole seismic and	Cuellar, 1997	
	Miocene clay embankment			SASW		
	Brick rubble fill, clay fill, compacted fill	70–300		Rayleigh	Butcher and McElmeel, 1993	0–10
	Waste landfill	100–200		SASW	Cuellar, 1997	

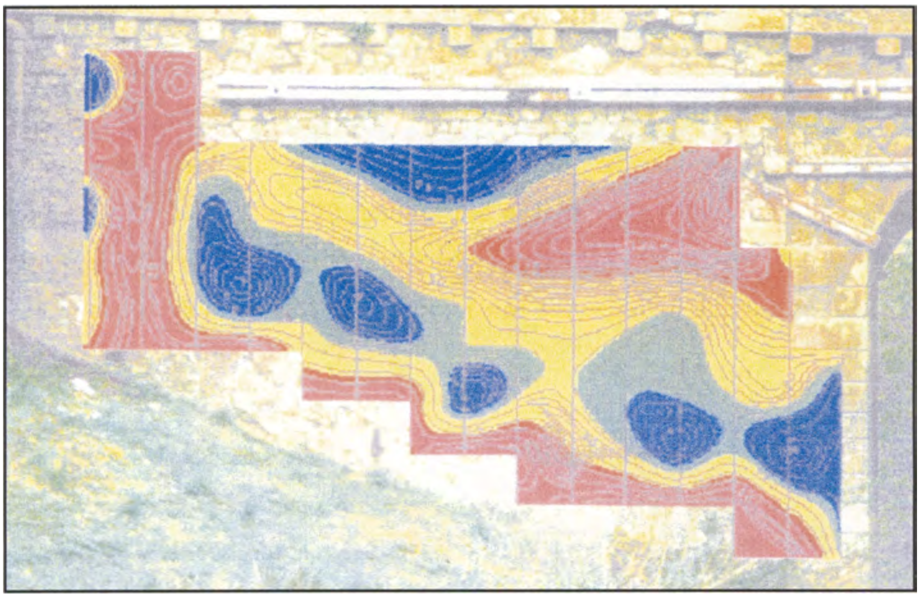
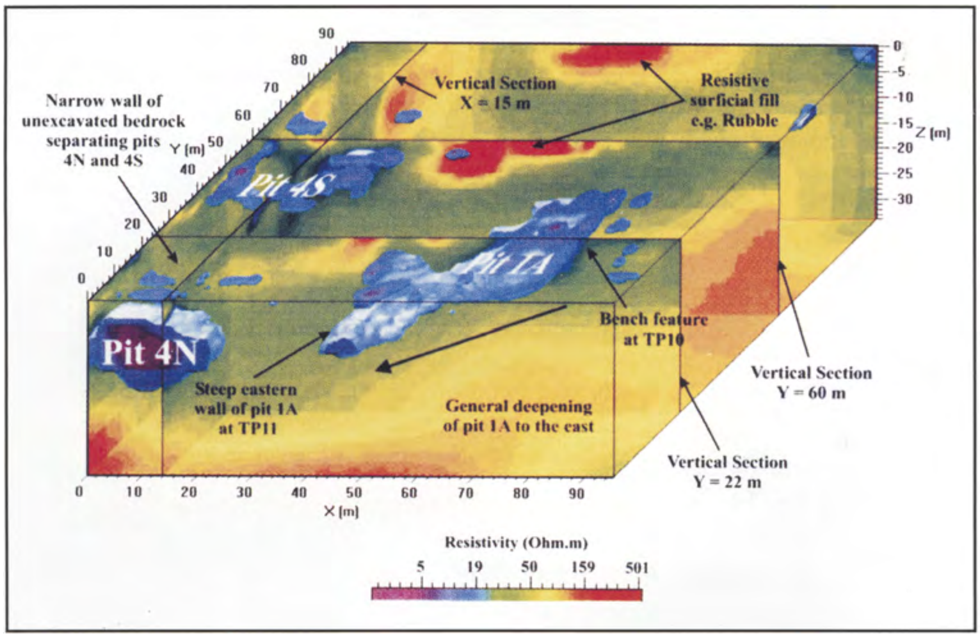


Figure 5.24
from page 103

Figure 6.11(c)
from page 123



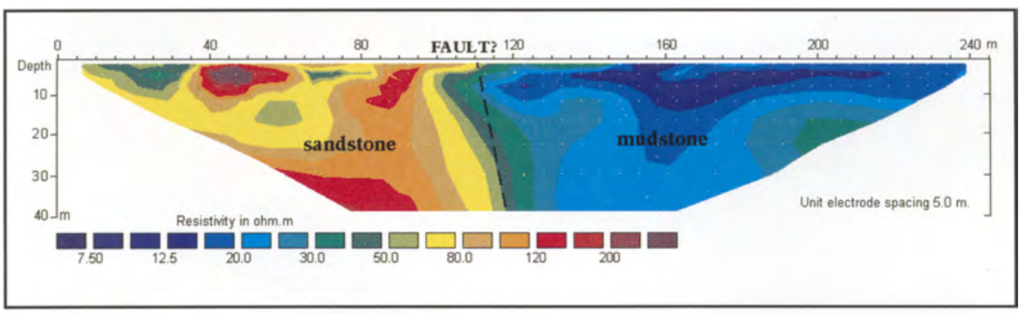
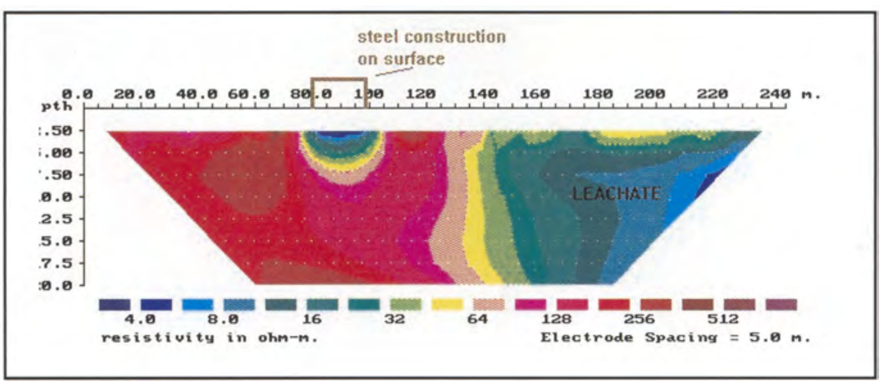


Figure 7.12
from page 139

Figure 9.1
from page 191



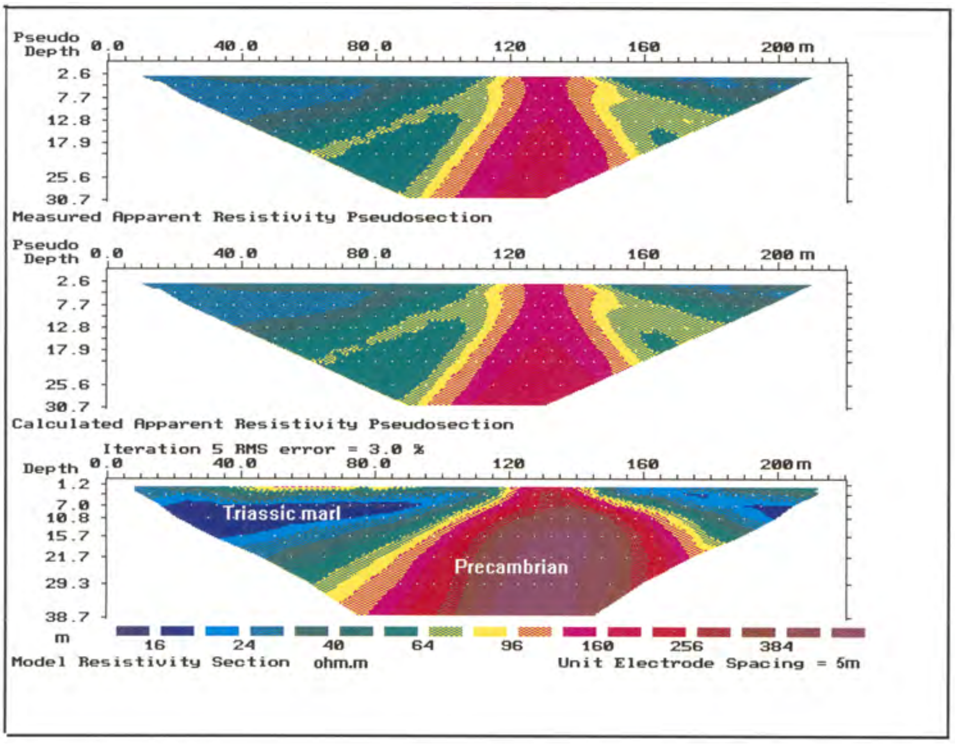


Figure 5.5
from page 65

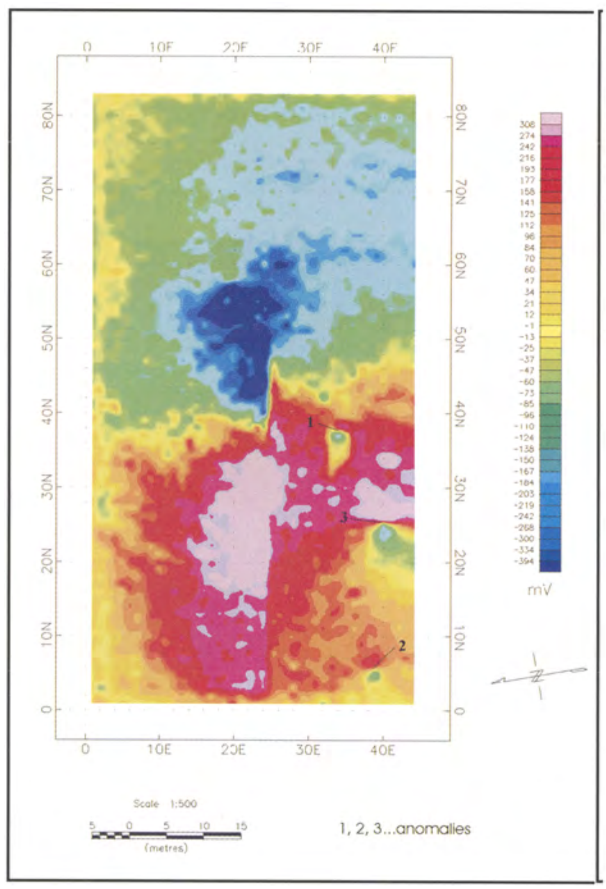


Figure 9.4
from page 199

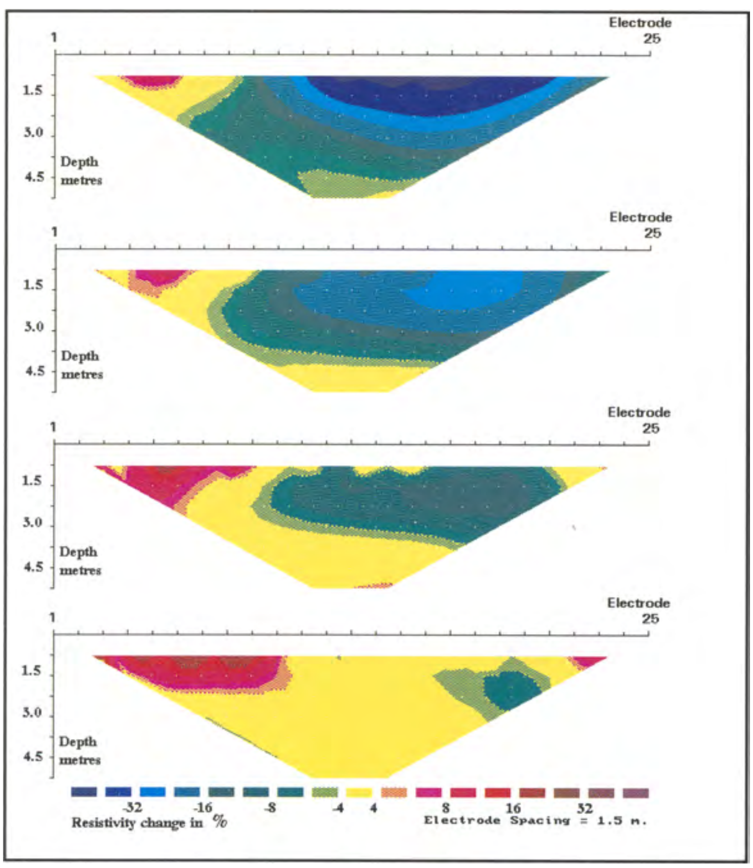


Figure 9.2
from page 192