Monitoring Underground Construction
A best practice guide

British Tunnelling Society

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Chapter 1
Introduction

1.1. The purpose of this guide

1. This document is intended to provide best-practice guidance to assist those who have responsibilities that require the use of monitoring systems to manage risks in underground construction. This includes clients, project managers, designers and contractors who all have duties at different stages of a project. The guidance may also be relevant to other parties such as insurers and adjacent infrastructure owners, who have interests in underground works.
2. This guide focuses on the principles for overall design and control, which must be adopted to ensure that such systems are safe, effective and efficient. The guidance is summarised in the checklists (Appendix B) of the features which would be expected to be present in a best-practice system at each stage in the project.
3. The guidance is based on an idealised timeline of a project and aims to assist users in managing particular monitoring-related risks that occur at each stage.
4. The guidance is not intended to be prescriptive in terms of detail design, which is recognised to change relatively rapidly with advances in technology. Nor is it intended that this guide will address specifically the technology (both hardware and software) of monitoring systems.

1.2. The scope of this guide

1. This guide is aimed principally at geotechnical and structural monitoring associated with underground construction. Underground construction is considered to include new tunnelling works, modification and repair of existing tunnels and other deep excavation processes such as shafts and deep box excavations. These may all give rise to similar monitoring issues.
2. The guide addresses monitoring of parameters relevant to structural behaviour (such as displacement, stress, strain, temperature and groundwater pressure). The guide does not set out to specifically address environmental monitoring (such as contamination, noise and vibration). Nonetheless, it is recognised that many principles of good practice may be common to both types of monitoring. Monitoring principles will also apply to many other construction processes.
3. The guide aims to include monitoring undertaken for a range of different objectives and on behalf of various stakeholders. It is therefore intended to include monitoring of new underground works (for construction verification and control) and of existing infrastructure affected by underground construction (for infrastructure protection). The need to integrate monitoring information with works progress data to facilitate interpretation and construction management is also discussed.
4. Section 2 discusses the range of possible monitoring objectives and highlights which parts may be of particular importance to each user group. The remaining sections discuss, in sequence, the issues arising at the principal stages of a project.
5. Section 3 considers the planning of monitoring, which begins at the inception phase of a project, and deals with actions necessary to discharge the obligations that fall directly on the client. These may include responsibilities such as legal compliance, establishing roles and responsibilities, creating a competent team, ensuring that project insurance is available and addressing the requirements of third parties who may be impacted by the proposed works.
6. Section 3 is principally aimed at clients. It will also be of interest to designers/project managers or others to whom the client delegates responsibility for planning a monitoring system, and to third parties who may require the monitoring system to provide them with information for assurance purposes.

7. Section 4 relates to the project design phase and addresses the specific principles of monitoring system design. This deals primarily with the design phase actions which are the responsibility of those specifying the monitoring. This relates largely to establishing performance requirements for the system which are adequate to ensure that the client's overall requirements are met effectively and efficiently. The principal audience for Section 4 will be the monitoring designer. This section will also be of potential interest to project managers responsible for procuring the works and contractors responsible for implementing the works.
8. Section 5 relates to the implementation phase of the project. It is primarily concerned with actions that should be undertaken by those responsible for installing, commissioning, operating, interpreting and reacting to the monitoring system. These are likely to include the monitoring system suppliers, contractors, designers and, in many cases, third parties.
9. Section 5 addresses the importance of effective management of, and timely response to, all types of monitoring data. It also considers the risks which may arise due to the quantity and complexity of data generated by some modern construction monitoring systems, including tunnelling control systems.
10. A series of appendices have been included that contain a Glossary (Appendix A), Checklists (Appendix B), Common Monitoring problems (Appendix C), example reports (Appendix D), a range of monitoring illustrations (Appendix E) and a bibliography (Appendix F).

1.3. Application

1. The most important principles, guidance and recommendations in this guide are highlighted in the main text by the use of bold text.
2. Most of the key recommendations can be expressed as actions which should be taken during the planning, design and execution of monitoring works. Appendix B contains a checklist which may be used to test the system specification at the main stages of a project to verify that these actions have been appropriately addressed.
3. It is also intended that this document will be relevant not only to major urban tunnelling projects but also to the many smaller projects that are undertaken.

1.4. The British Tunnelling Society interest

1. The British Tunnelling Society (BTS) is a learned society that has recently produced a number of documents that draw together best-practice information on the tunnelling and underground construction industry. These include: *Tunnel Lining Design Guide*; *Closed-face Tunnelling Machines and Ground Stability*; *Hand-arm Vibration Guide to Best Practice*; and *Management of Risk for Underground Construction*.
2. All of these documents have been produced following recognition by the BTS of a need to provide guidance to the tunnelling industry to promote tunnelling excellence and to enable a common approach to be adopted in order to minimise risk in underground construction.
3. Monitoring is an integral part of any construction project and is particularly significant in underground construction. It is commonly a key element in the risk management process. The BTS recognise that there are many publications and papers in the public domain on monitoring for underground construction works, but there is no single document that details all of the principles that should be considered in the development, design, implementation and management of a monitoring system.
4. The BTS was concerned that the industry in the UK might not fully understand and appreciate every aspect of monitoring for underground construction. The BTS has therefore undertaken to review the state-of-the-art for monitoring of underground construction to develop best-practice guidance for those who need to procure monitoring systems in underground construction projects.
5. This guide does not replace existing BTS or third-party publications, but draws together the principles of how the monitoring systems should be designed and implemented to meet the project objectives. The guide is therefore intended to supplement other publications, including the *Tunnel Lining Design Guide*.

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Chapter 2
Objectives of monitoring

1. This section is intended to draw attention to the range of purposes that monitoring of underground works may serve. All parties involved in monitoring processes need to have an understanding of the overall objectives of the undertaking.
2. Monitoring is not normally an end in itself, but is undertaken in support of some other construction or asset management requirement. In many cases, monitoring systems may actually be used to serve multiple objectives. The objective of any monitoring activity should be defined clearly during planning and design in order to avoid later confusion or misinterpretation of data.
3. Some of the most common objectives for monitoring of underground works are described in Table 2.1.
4. These objectives are not mutually exclusive. It is common for the results from one monitoring system to satisfy several objective requirements at the same time, and for these objectives to alter as the work progresses. The relative importance of diverse objectives may also be different for various parties. Figure 2.1 illustrates the likely relationships between the objectives, the interested parties and the project life cycle.

Table 2.1. Monitoring objectives

Objective	Examples
Construction process control	To provide data for making informed decisions as an integral part of construction activities.
Delivery assurance	To provide evidence to confirm that a project is being delivered in accordance with the client's requirements.
Design verification	To provide data to validate assumptions or predictions made during design and verify that the design is appropriate.
Quality assurance	To provide evidence to confirm the quality of materials and workmanship or to demonstrate compliance with due process.
Risk and liability allocation	To provide evidence that may be used to determine which works caused an effect and thereby determine the party accountable for the consequences.
Risk management	To provide data which may be used to trigger preplanned contingency actions to control risks associated with the effect of the works.
Asset protection	To provide data that may be used in connection with contingency plans to protect existing assets or their operation.
Reassurance	Monitoring undertaken to confirm the absence of any adverse influence regardless of predicted effect.
Legislative compliance	To provide evidence in support of a safe system of work for the work force and third parties (Health and Safety); to meet designers' requirements or to provide information needed for future management of the structures or systems affected (Construction Design & Management).
Research	To provide data to fulfil predefined research objectives.

Figure 2.1. The objectives of monitoring for underground construction projects (SCL: sprayed concrete lining; EPB: Earth pressure balance; CDM: Construction Design and Management Regulations; EPP: emergency preparedness plan; TBM: Tunnel Boring Machine)

The progression of responsibility and interest relating to the objectives of monitoring during an idealised underground construction project.

Project phase: *Inception* | *Scope* | *Design* | *Implemention* | *Fitting-out* | *Commissioning* | *Operation*

Responsible or interested party	*Objectives*	*Explanatory notes/examples*
CLIENT inc. project manager	Legislative compliance (CDM)	For fulfilment of legal obligations
	Delivery assurance	Maintaining project programme requirements
	Risk allocation	Legal/contractual framework – management and revision processes
	Quality assurance	Legal/contractual framework – materials and workmanship
DESIGNER	Legislative compliance (CDM)	For fulfilment of legal obligations
	Delivery assurance	Maintaining project programme/design expectations
	Risk allocation	Protection of indemnity, contractual specifications
	Risk management	Control of risk mitigation
	Design verification (e.g. permanent works)	Verification of design expectations
	Construction process control (SCL, EPB, etc.)	Ensure that contractor's working methods meet design expectations
	Quality assurance	Ensure that materials and methods meet design expectations
	Research	Interface between research and design
CONTRACTOR	Legislative compliance (H&S, CDM)	Fulfilment of legal obligations
	Delivery assurance	Ensuring the construction programme is met
	Risk allocation	Ensuring contractual compliance, refute false damage claims
	Risk management (e.g. EPP)	Timely identification and mitigation of adverse effects
	Design verification (e.g. temporary works)	Verification of design expectations
	Construction process control (SCL, EPB, etc.)	Monitoring integral to work method SCL, TBM operations, etc.
	Quality assurance	Procedural compliance
	Research	Interface between monitoring and construction activities
THIRD PARTIES	Asset protection	Protection of plant, equipment and operations influenced by the works
	Reassurance	Verification of site monitoring, application of specialist knowledge
RESEARCHERS	Research	Purpose of research self-defined, tailored to suit site/project conditions
OPERATOR	Legislative compliance (CDM & safety case)	Long-term impact of construction upon operations (as below)
	Risk allocation	Asset and contractual protection from long-term consolidation
	Delivery assurance	Programme risks from effects of dewatering shutdown
INSURERS	Legislative compliance (contractual)	Breach of conditions of cover arising from failure in legal compliance
	Risk management	Auditing of processes – management processes and competency
	Risk allocation	Auditing of processes – contractual and legal compliance
	Quality assurance	Auditing of processes – materials and workmanship
STATUTORY AUTHORITIES	Legislative compliance	Interest arising from legal investigation of a site incident
	Risk allocation	Interest arising from legal investigation of a site incident

For definitions of the above objectives, refer to Appendix A

Key to bar symbols
- (dotted) Passive interest or residual/secondary involvement or responsibility
- (dark dashed) Probable active interest or potential involvement or responsibility
- (grey dashed) Active interest or probable involvement and responsibility
- (solid) Responsible for monitoring activities/planning/procurement

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Chapter 3
Principles for planning effective monitoring systems

3.1. Client obligations

1. It is essential that the objectives of a monitoring system are clearly understood early in the life of a project. This section addresses the main actions, which are necessary to discharge the obligations of the client. These responsibilities are driven by factors such as:
   - clients' requirements
   - legal compliance
   - the need to establish roles, responsibilities and a competent team
   - meeting insurance requirements
   - addressing the requirements of third parties who may be impacted by the proposed works.
2. In order for a monitoring system to be of full value, there must be early appreciation and recognition of the nature and extent of these requirements.
3. Most of what is covered by this section relates to decisions that must be addressed early in the project life, probably in the inception phase. These decisions form the basis for establishing the requirements for the system specification which must be communicated to the monitoring system designer.
4. In many cases the client may elect to manage these obligations through the procurement of appropriate competent professional services. The client must ensure that the way this is done satisfies fully the requirements of the Construction (Design and Management) (CDM) Regulations.
5. **In planning a monitoring system, a full list of requirements that the monitoring system can fulfil and restrictions should be compiled. Failure to produce such a list that is agreed by all stakeholders introduces risks and has often resulted in last-minute changes to requirements. Such last-minute changes can lead to increased costs, delays and mistakes.**

3.2. Engaging stakeholders

1. It is important to recognise the full range of stakeholders with an interest in the project as this may be much wider than just the parties contractually associated with the work. In addition to the client, contractors, designers, supervisors and project managers, it may also be necessary to engage other parties including third-party asset owners such as building owners, utility companies and transport infrastructure owners. In some cases, project insurers and planning authorities may also need to be engaged to agree on the monitoring coverage and other requirements.
2. Identifying the parties with an interest in a monitoring system at an early stage is important. Different stakeholders may have specific interests and requirements for data collection and reporting; stakeholder confidence in the project can be improved if these parties are engaged at an early stage.
3. It is important to recognise that affected external parties may require time to procure advice and expertise to allow them to review proposals and participate in the monitoring process, especially where they may need to provide site-specific contingency measures. These stakeholders may need time to implement appropriate resources, develop and train their staff and undertake enabling works as required.
4. For underground construction projects in rural locations, the list of stakeholders and issues affecting planning may be smaller and thus potentially easier to reconcile in contrast to projects in an urban setting, where the list of stakeholders can be

extensive and the work involved in planning to reconcile all of their interests may be complex, time consuming and expensive.

5. **In planning a monitoring system, a full list of all potential stakeholders should be made which details their specific monitoring requirements and any programming and resource restrictions that arise from their involvement.**

3.3. Constraints

1. **In the planning and subsequent design of a monitoring system, there will inevitably be constraints which affect the way the work can be undertaken. These need to be identified and explicitly considered at an early stage in the planning process, as they may affect the feasibility of the work**.
2. In most cases it will be necessary to undertake some monitoring in advance of the actual project works, in order to identify seasonal and other trends. This may mean that monitoring needs to be one of the earliest site activities in a project in order to establish a baseline prior to the start of construction. It is also often one of the last activities to be completed.
3. Access and space restrictions may materially affect the choice of monitoring system. For example, restrictions on man access around railways or other secure areas may lead to a need for more automation of monitoring. Similarly, a lack of continuous access may require remote data capture, using cabled or wireless equipment.
4. The need to obtain planning consents or other third-party agreements may mean that external parties have some influence over the choice of monitoring system and equipment, particularly where measurement is needed on assets. Allowance needs to be made early in the system planning for consideration of appropriate third-party interests.
5. Consideration should be given to the likely availability of appropriately skilled staff and specialist equipment. These issues may pose a significant project risk in certain situations.
6. As in any works, commercial factors and the need for cost control will also be significant.
7. Monitoring systems may also pose particular questions about the procurement model. In principle, the best monitoring system performance is likely to be achieved where each task is assigned to those with the greatest motivation for attaining high-quality results. While this is desirable, it needs to be recognised that project procurement models may not always enable this.
8. For example, design outputs may be prepared by different parties in some cases. Often it is likely that the designer of the main works may prepare the specification, while the specialist contractor may prepare the detailed design of the system with documents relating to contingency plans and emergency response developed in collaboration with third parties.
9. The common procurement issue of the need to start monitoring early in a project sometimes results in a requirement to procure the monitoring prior to engaging a main works contractor. This may lead to a situation in which the client later wishes to novate the monitoring contract to the main contractor. This scenario needs to be recognised and planned for at an early stage.

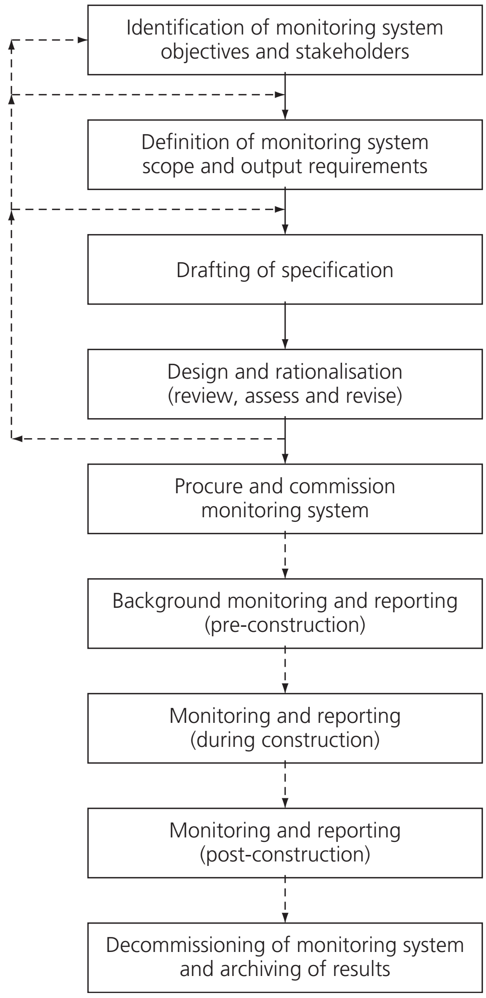
3.4. Process and deliverables

1. It is important that the required monitoring process and deliverables are identified early in the planning of the work. Figure 3.1 illustrates the generic process that is applicable to most monitoring systems associated with underground construction works.
2. It is good practice to undertake an inspection process for the works where there is access available. It is expected that the selected monitoring system will complement this process.
3. Defining the deliverables is an important part of determining the scope of a monitoring system. In the past, problems have been experienced where a narrow focus on the construction phase has resulted in a lack of consideration of other aspects, such as project archiving.
4. It is likely that the monitoring requirements will include the supply, installation, testing, commissioning, operation, maintenance and, ultimately, removal of the system. There may also be a requirement for the monitoring contractor to contribute

to wider design and construction management processes through provision of data and advice. These outputs need to be clearly defined; project requirements may therefore include the following deliverables:

- key documents (e.g. method statements, programme, as-built drawings, witness diagrams, etc.)
- baseline data reports
- periodic data reports during the works
- monitoring database (including maintenance)
- final close-out report including the database archived in a predefined format
- ongoing risk assessment and management.

Figure 3.1. Generic process for monitoring activities



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Chapter 4
Considerations for designing effective monitoring systems

1. This section deals primarily with the main actions, which are the responsibility of the monitoring designer. The principles set out are those that will help ensure that the system is capable of effectively and efficiently addressing the effect of the proposed works. The checklist provided in Appendix B is directly related to this section and is frequently cross-referenced.
2. The principal target audience for this section comprises those who specify and design monitoring systems. This section may also be of interest to project managers responsible for procuring the works and to contractors responsible for implementing the works.

4.1. Design basis

1. **Prior to undertaking detailed design of a monitoring system, the fundamental objectives of the system should be defined and communicated clearly. This may be achieved through a statement of the design basis which should briefly describe the following points:**
   - why the monitoring is required, with reference to the works being undertaken that may cause change and what the potential effect is
   - what needs to be monitored, including consideration of whether any existing assets are particularly susceptible to change and the nature of any changes to be identified
   - who the monitoring is intended to inform
   - when the monitoring is required to be active
   - what monitoring technique is anticipated and how this will relate to the inspection regime for the works
   - how the monitoring data may be expected to be used, including whether it may be required to trigger any form of contingency response.
2. **This statement of the design basis will inform the detailed design of the scheme and will serve to assist others, who may become involved at later stages, to understand the purpose and development of the monitoring regime.**

4.2. Monitoring system functional requirements

1. The design of all monitoring systems should include consideration of a number of generic functional requirements. It is particularly important that these are considered in the design process in order to enable comparison of the suitability of different monitoring options that may be based on different technologies and experience. These functional requirements should be stated explicitly and should include
   - extent of the area to be monitored
   - frequency of monitoring
   - accuracy
   - precision
   - density of monitoring
   - the range of measurements to be undertaken
   - system robustness and reliability
   - requirements for system verification
   - requirements for system recovery after a failure
   - requirements for data processing and usage.

4.3. Distribution of monitoring

1. **The monitoring system must have sufficient spatial coverage of the area of interest. Good practice commonly includes monitoring across the whole area predicted to be subject to significant change due to underground works. Monitoring should additionally extend to areas where no change is expected in order to provide a stable reference and protect the project from spurious claims. If the monitoring system relies on collection of data at discrete survey points then the survey points should be more concentrated where greater differential movements are expected.**
2. Consideration should be given to the relationship of the monitoring points to both the works and the existing infrastructure. Systems should generally align with these where practical. Ideally, the ground above tunnels should be monitored in sections parallel and perpendicular to the tunnel axis. Sensitive buildings will commonly need monitoring along facades. Monitoring arranged in other ways, such as an arbitrary grid, will result in more complex back analysis to relate measured change to the works.
3. Where possible, the location of maximum change should be monitored directly. For example, it is good practice to install monitoring points above a tunnel centreline where practicable and at locations that are subjected to the compound effects of multiple settlement events during construction.
4. Consideration should also be given to the spatial reference system to be used for monitoring. Commonly, this will either be a project-wide coordinate grid or a local system of reference relative to the works. A common reference frame simplifies comparisons of changes measured by different types of monitoring.
5. During the installation of the monitoring system, due consideration should be given to the setting out of the system with respect to the works. This is particularly important for tunnel works, where the position of the works relative to existing assets is not visually obvious.
6. **In cases where the primary objective of monitoring is to determine the effects of tunnelling works on existing infrastructure, it is important that the scope of the monitoring also includes direct monitoring of the adjacent ground.** This will provide a control for determination of the actual volume loss induced by tunnelling without the complicating effect of the ground–structure interaction.
7. Where other adjacent works are being undertaken, there may be a need for monitoring to specifically distinguish between the effects of different works. This may protect the project from claims not attributable to its works.
8. Surface or subsurface ground monitoring may also be used to provide advance indication of likely changes due to tunnelling at the location of vulnerable infrastructure. If a tunnel is being driven towards a utility, for example, it may be helpful to determine what changes are actually occurring at the same depth as the utility in an earlier section of the tunnel drive.

4.4. Accuracy, precision and range

1. **The accuracy and precision of measurement required will depend on the usage to be made of the data. Many modern measurement systems offer very high degrees of precision; it is sometimes tempting to over-specify the project requirement simply because of the available measurement technology, but with no real benefit.**
2. **The designer should assess critically the amount of change that is of practical significance to the project and specify the system accordingly.** It may be that relatively simple low-precision systems will be sufficient for many purposes and will provide the most efficient solutions. Conversely, it is important that the system accuracy is sufficient to reliably distinguish between different trigger levels for contingency plans.
3. The monitoring system specification will also need to include an indication of the anticipated range of measurements, as this may influence the choice of system. The designer will need to consider both the maximum predicted variation in the measured parameters and the appropriate margin to allow for unexpected behaviour. There may be a relationship between instrument range and accuracy in some systems, which must be considered. It may be appropriate to specify systems which are capable of being re-baselined if the measurements fall outwith a particular range.

4.5. Frequency of monitoring

1. The monitoring frequency may depend on a number of factors. These include:
   - the rate at which change is expected to develop
   - feedback requirements for practical control of a construction process

- the requirements of any contingency or emergency plan
- the stage of the works (e.g. it is common practice to have reduced frequencies during background monitoring and close-out monitoring compared to the main construction phase)
- undertakings given to satisfy third parties.

2. In some situations it may be appropriate to use activity-based data gathering as an alternative to monitoring at a defined frequency. Consideration should be given to taking measurements at specific stages of construction, modification or repair processes.
3. **The monitoring frequency should be sufficient to allow an effective response to observations. However, very high monitoring frequencies are not always beneficial because the quantity of data may result in problems with data management and difficulties in the identification of significant results.**
4. Many types of monitoring systems have practical upper limits on the frequency at which measurements can be obtained, and this needs to be considered in the system specification.
5. Frequencies of data collection and routine reporting will not necessarily match. There will commonly be regular reviews of data collected over a period of time. As a result, systems that may be used to trigger a contingency plan will require some form of alarm-raising functionality independent of the regular review process.
6. **It should be noted that the cost of monitoring is not normally directly proportional to the frequency of monitoring for all systems. Increasing the frequency for some systems, such as those involving manual measurements, will however carry a significant cost penalty. In such cases it may be reasonable and efficient to target particular areas for higher frequency monitoring at critical stages of the works while the remainder of the site is monitored at a lower frequency.**
7. The term 'real-time' is commonly used in relation to monitoring underground works but is problematic as there have been, and still are, differing interpretations of its meaning. If the term is used in design it should be carefully defined. A true real-time system would ensure that readings are available for review immediately after collection. This is achievable with a number of monitoring instrument types but may be considerably more expensive than, say, a system giving hourly readings. The enhanced frequency for certain operations may be warranted, but perhaps not cost effective for all.

4.6. Baseline measurements

1. **Baseline measurements are needed to establish the stability of any monitoring system prior to the works.** The data from baseline measurements are commonly used as a reference against which subsequent change is measured. Good-quality baseline measurements are therefore essential for subsequent interpretation.
2. **The baseline measurements should also be used to determine any existing movements which could otherwise be attributed to the works**. For example, some structures are sensitive to temperature changes and may move in daily or seasonal cycles. These changes may have been occurring for many years and may be completely benign. If they are not properly understood, however, they may become a concern when they are measured. It is important that the effects of changes from other sources are not incorrectly attributed to construction projects.
3. **It is important to determine an appropriate baseline monitoring duration. A long period of baseline monitoring will increase confidence, but this may need to be balanced against other factors such as the risk of delay to the works.** There is no prescriptive answer to what is necessary. The designer will need to identify likely environmental trends which may affect monitoring. Engineering judgement must be used in determining the period of baseline monitoring which will establish, with reasonable confidence, the ambient behaviour of the asset being monitored. Factors to consider in reaching this decision may include natural daily, seasonal and tidal movements and also artificial influences such as traffic disturbance and the effect of adjacent works. In many cases the processes in question will be temperature related; it is usually advisable to log temperature change and correlate this data with other results to aid interpretation. There may also be specific third-party requirements that affect the baseline monitoring duration.

4.7. System reliability and redundancy

1. **System reliability is important as a lack of monitoring results may result in limitations on works or even suspension of construction operations**. The cost of a stoppage to a project may considerably exceed any cost savings from a lower specification monitoring system.
2. **Where the consequences of a monitoring system failure are unacceptable to a project, there should be sufficient redundancy built into the system so that losses of discrete elements do not cause loss of the entire monitoring system**. In these cases it is good practice to provide a secondary monitoring system capable of allowing checks to be carried out on the primary system, or of providing key information in the event of loss of the main system. Both systems should be able to operate independently. There is further benefit in the two systems being of different types, as this will reduce the likelihood of systematic errors.
3. Certain types of monitoring system are liable to interruptions due to obstructed lines of sight or other predictable external interferences. The likely impact of external factors needs to be considered in design.
4. A monitoring system needs to operate in a fail-safe fashion. System malfunctions and failures need to be notified where possible and remedial actions initiated. The system must be designed such that each section can be verified as operating correctly. Consideration also needs to be given to how the checking function is verified.
5. Where designers have specified monitoring systems that rely upon survey networks (e.g. the use of Robotic Total Station (RTS) or RTS-based solutions), they should give significant consideration to the robustness of the survey network. The designer must carefully consider the geometry of the survey network, the locations for RTSs and where reference prisms can be sighted from. Additionally, it may be necessary to have clear lines of sight to other RTS locations in the survey network. There may be other constraints to consider in urban settings, such as listed buildings (which require consent to attach monitoring equipment to), vibration from traffic/trains and obstructed lines of sight due to foliage.
6. A monitoring system suffering from power loss should be capable of notifying this situation. For example, if a system is connected to an uninterruptible power supply (UPS), the power supply can be monitored and an email or other message sent when the power supply fails and the UPS is activated. Voltages of batteries in logger boxes can be monitored and alarms sent when an unacceptable level is approached.
7. Consideration should be given to specification of spare parts requirements and maintenance agreements for monitoring systems. A maintenance or technical support agreement with a response time appropriate to the system objectives should be specified.
8. In addition to the reliability and redundancy of instrumentation hardware, consideration needs to be given to providing redundancy in the data management system itself. Error trapping systems are commonly needed to prevent minor data-handling issues causing the whole system to fail. It is also important to consider recovery planning in the event of system loss. This requires consideration of each stage in the process from data collection to reporting systems.
9. System clock settings may be an issue in some applications. In the UK, it may be prudent to stay on Greenwich Mean Time rather than follow British Summer Time changes (which result in the system identifying missing readings in the spring and apparent duplications in time readings in the autumn). The downside of this may be a need to highlight the time system employed to the end users of the data.

4.8. System verification

1. **It is important to have confidence in the monitoring systems installed. The monitoring designer must consider how the behaviour of the system can be verified and any false alarms trapped**.
2. Effective systems of calibration are required for most types of monitoring equipment and these requirements should be specified in the design of the system.
3. A common error with certain types of monitoring systems is that the response of the instrumentation and software is not tested before the actual effect of the works is detected. This can result in erroneous readings and a need for corrective action. For example, more than one settlement monitoring system has initially reported heave

instead of settlement simply because the instruments had been connected the wrong way round or an incorrect sign convention has been programmed into the software.

4. The monitoring designer should consider specifying a system of testing to verify that the monitoring system (including the data processing) correctly reports the nature of changes before critical works commence.
5. A good form of system testing is a whole system check. This involves artificially inducing a known change to an instrument and testing whether the expected result is reported. For example, in an electrolevel beam tilt sensor system it may be possible to displace a beam with a shim of known thickness and determine whether the entire monitoring system (including loggers, transmission elements and reporting software) correctly reports both the magnitude and direction of the change. This is different to a laboratory calibration test and may not achieve the same accuracy, but the test does provide a practical check that the electrolevels are correctly wired to the multiplexer/data logger, the data are correctly referenced and processed and the correct calibration factors have been used. Similar checks can be designed for most instrumentation types.

4.9. Monitoring system maintenance requirements

1. Most monitoring systems require some access for maintenance. The monitoring designer must consider how this can best be achieved. In some cases, individual components may need to be easily accessible in order to be serviced or replaced without compromising the rest of the system. The level of redundancy in a system may need to be raised to enable continuous monitoring while maintenance activities are undertaken.
2. Most construction-related monitoring systems are operated for a period of between a few days and a few years. Where longer-term monitoring is established, for example to record structural behaviour over the whole design life of an asset, particular consideration should be given to future-proofing of the system. In particular, future availability of components may be a significant limitation for electronic systems where the typical component lifecycle may be relatively short.
3. The long-term stability of electronic systems may be uncertain in some environments to which they may be exposed. For this reason relatively simple instruments, such as vibrating wire strain gauges, are often favoured for certain longer-term applications in underground structures.
4. Maintenance requirements may also be influenced by how close to its maximum capacity a system operates. Some instruments, and in particular those with motorised components, may be more susceptible to overheating and mechanical degradation if they are consistently used at close to their maximum possible rate.
5. **Monitoring systems require routine checks and maintenance. A maintenance plan which schedules these activities is recommended and should include details of the necessary maintenance personnel and their training requirements.**
6. A log of maintenance undertaken on the system is recommended. This log should record the date, the nature of the work and who undertook it. This is useful for error tracing and a change in control procedures.
7. Any restrictions arising from excessive use of the monitoring system should be highlighted, particularly for those where increased maintenance is required as a result.

4.10. Other factors influencing the choice of technology

1. **Apart from the capability to monitor the required parameters, other factors will affect the choice of instrumentation technology. These may also influence the system specification and need to be stated clearly in the design basis and reflected in the maintenance plan.** Examples include:
   - ease of access during monitoring: e.g. if monitoring is required in an area without safe access, such as a live railway tunnel, an automated system may be required, regardless of other constraints
   - space available for monitoring equipment installation, which may require consideration of gauge clearance and lines of sight in transportation tunnels
   - restrictions on appearance and fixings, for example on the facades of heritage buildings
   - compatibility with other existing or planned future systems
   - induced current effects on instrumentation from adjacent power cables

- induced current effects on adjacent sensitive equipment (such as railway signalling) from instrumentation
- protection from theft or vandalism.

2. Commercial factors may also be significant. There is a limited pool of specialist monitoring suppliers, many of whom have expertise in particular types of system. As a result, it is possible for the monitoring system specification to inadvertently exclude certain suppliers if the specification is unduly prescriptive rather than performance based.
3. Cost may influence system design. There is to some extent opportunity to trade off capital cost against operating cost in many civil engineering monitoring systems. For example, a conventional manual survey system may have a small installation cost but relatively high operating costs when compared to the use of automated systems. The length of time needed or the number of monitoring cycles may therefore be a major influence on the choice of system type.

4.11. Requirements for data processing

1. The data processing system must be designed to accommodate the impacts of foreseeable system changes and maintenance, such as the replacement of defective or uncalibrated sensors, re-baselining of the system or routine amendments of datum values, etc. Such accommodation should be controlled by clear protocols with full recording and reporting of where and when such changes were applied to the system.
2. Raw data will generally need some form of processing to convert them into useful information for review. It is desirable that the data can be exported to a commonly accessible format such as a spreadsheet. Data processing is increasingly automated and some degree of verification will be required (whether the process is manual or automatic) to ensure that errors are not introduced. The system supplier may largely determine the detail of this process, as it is likely to include bespoke software. This is further reason for verifying the performance of the system as a whole, including the processing part, once it has been installed. The requirement for such testing should be specified.

4.12. Requirements for data interpretation and review

1. **Processed monitoring data needs to be assimilated and reviewed. For underground construction works, this process will typically involve daily or weekly monitoring review meetings with representatives of the client and contractor who are familiar with the scope and progress of the works.**
2. Review meetings provide an important forum where decisions on the works can be made based on the data received and the knowledge of ongoing site operations. The monitoring system designer needs to indicate what would be an appropriate regime for routine review of data, taking account of actions which may follow from monitoring observations. This may include the specification of key outputs, such as summary graphs of key parameters which are to be produced on a regular basis. The contractor implementing the work is likely to organise the reviews and should ensure that the process addresses the design basis requirements. The review also needs to consider any fluctuations in results arising from system maintenance. These are a potential source of false alarms and inappropriate responses. Early involvement of third-party asset owners will assist in understanding the resource requirements for monitoring the assets and the required frequency of review meetings.
3. The review meetings should inform all parties of any planned maintenance or changes to the monitoring systems in order to avoid the risk of false alarms or the triggering of inappropriate responses.

4.13. Requirements for data presentation to stakeholders

1. Monitoring data from underground works is increasingly used to satisfy not only the project requirements but also the needs of third parties and other stakeholders.
2. In considering information generated from row data for review purposes, consideration should be given to how magnitude is presented. For example, where small movements are recorded, these may appear unduly significant if automatic scaling is used in graphics software. It may be preferable to generate all graphs for a project on a common scale to allow direct comparison.
3. The system specification should include precise requirements for reporting, including any bespoke reports to be generated to service third-party needs. Increasing use is

being made of email as a means of disseminating such reports, an example of which is presented in Appendix D.

4.14. Requirements for data back-up and archiving

1. The specification should include detailed data back-up requirements; all data should be backed up to safe storage. The number and frequency of back-ups may vary according to the project requirements. It is prudent to consider secure, remote storage of back-up data.
2. While hard copies of data remain readable providing its original form is unchanged, the same may not be true for the various digital formats. The rate of change of common storage media over recent years (e.g. 8″ floppy disk, 5.25″ floppy disk, 3.5″ floppy disk, zip disk, CD, DVD+R, DVD-R, solid state 'flash drives') is unlikely to slow; important data will therefore need to be transferred to more recent storage media before use of the older media ceases. The longevity of the physical storage media itself also needs to be considered.
3. The data file format itself must be capable of being read and used in the future. Proprietary specialist software formats are of particular concern. Even if the data can be read, the original software used to process and visualise it may not work correctly on the latest operating systems. While it might be considered that the need for the data ends after construction has been completed and changes have demonstrably ceased, it may be necessary to defend against long-term damage claims. The data may also have a commercial or research value for others wishing to construct in similar conditions in future.

4.15. Requirements for responses to monitoring

1. **Monitoring design and operation are only part of the construction process. Contingency plans for a response to monitoring are typically required and must be developed through the design and risk assessment process on a project-specific basis.**
2. **Changes tend to be progressive in many underground construction works; evidence of structure or ground behaviour become progressively apparent before failure occurs. In this type of situation it is likely that a system of hierarchical trigger levels is appropriate, which allows a proportionate response to adverse indications from monitoring. Work will generally be planned to avoid the occurrence of trigger events but appropriate pre-planned actions should be instigated in the event that trigger levels are breached.**
3. Trigger values and the actions associated with them are normally project specific and relate to safety and serviceability considerations. Trigger values will normally be based on the result of assessment of at-risk infrastructure. If the assessment indicates that the at-risk infrastructure is unlikely to be able to tolerate the change due to the works, then trigger levels will be set based on the levels of tolerable change. The general principle is to control the works such that unacceptable levels are not breached and a warning of trends which may approach unacceptable levels is provided.
4. In many cases, assessment will indicate that the at-risk infrastructure will be able to tolerate the change expected to be produced by the works. In this scenario, good practice is to set the triggers at a level reflecting the change expected to be caused by the works. This means that triggers will be breached (and typically the works reviewed) if unexpected results occur even if there is no immediate threat to other infrastructure.
5. It is helpful to describe triggers in terms of colours. Green is typically used to indicate a normal safe operating condition; red is used to indicate a level at which significant disruption occurs either to the works or to the infrastructure being monitored. The number of trigger bands may vary according to the project needs. In many cases a green/amber/red system may suffice. In some recent complex tunnelling works (particularly around railways) a system of clear/green/amber/red/black has been used. A system of greater complexity has the benefit of allowing more detailed planning of escalating contingency responses. For example, providing more levels may allow a distinction to be made between the point at which construction works are suspended and the point at which third-party railway operations are suspended. Table 4.1 illustrates a possible system of triggers.
6. In determining trigger levels, consideration should be given to the time needed to instigate any pre-planned response to a developing trend.

Table 4.1. An example of a system of trigger levels for a monitoring system. Note that the use of green, amber and red is more common; many systems do not require as many stages as in this illustration and so the black and clear conditions may not always be used

Monitoring result	Trigger condition or band	Examples of possible response actions
Below green trigger level	Clear	Maintain normal monitoring regime.
Below amber trigger level but above green	Green	Maintain normal monitoring regime. More frequent engineering review of observations.
Below red trigger level but above amber	Amber	Enhanced monitoring, urgent engineering review of observations, amended methods of working, notification of affected third parties.
Below black trigger level but above red	Red	Controlled cessation of works, enhanced monitoring, engineering review of observations, redesign and notification of affected third parties, limitation or cessation of third-party activities.
Above black trigger	Black	Full emergency response, cessation of all third-party operations, evacuation of affected third-party infrastructure, installation of emergency support systems.

7. There are some situations where change is less progressive and monitoring may simply be required to give a yes/no response. Clearly, in these cases reporting is simple and systems of triggers are not appropriate.

4.16. Design outputs

1. The specification or design output for the monitoring system consists of a number of elements. Typically these include:
   - statement of design basis (including the purpose of the monitoring and what change is expected to be observed and when)
   - monitoring system functional specification (including parameters to be measured, locations, frequencies and redundancy requirements)
   - as-built drawings
   - designer's risk assessment
   - contingency plans incorporating trigger levels and agreed actions
   - the frequency of review meetings
   - the controls necessary to accommodate maintenance or changes to the system during the course of the project
   - requirements for decommissioning and long-term data storage.

   Programmes for such outputs are naturally dependent on the nature of the works and what is affected by the works.
2. **It is important that a change control process is established for a monitoring system.** This is particularly significant in cases where trigger values are used, as there is inevitably a possibility that events or observations during the works may require that trigger values be modified. Such events may occur where a contractor proposes a variation in the design; the designer should be asked to endorse the change to confirm that the modified design remains compatible with the design intent. Similarly, where late design changes are applied during construction, the designer must consult with the contractor regarding the impact this has on the sequencing and methods of construction and the associated monitoring requirements.

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Chapter 5
Considerations for operation and management

1. This section addresses the implementation phase of the works. It is primarily concerned with the installation, commissioning and operation of the monitoring system and the interpretation of, and response to, the data produced.
2. **It is recommended that a monitoring plan is prepared which includes details of the roles and responsibilities of the various parties to the system, trigger levels and contingency plans.** Such a plan provides any third parties with confidence in the process of data review and interpretation.

5.1. Operational basis

1. The operation and management phase of the life of the monitoring system will typically involve a number of parties including the monitoring contractor, the main works contractor, the designer and those with an interest in assets being monitored (including the project manager and third parties).
2. In many cases specialist monitoring contractors provide a service which is limited to the system installation and maintenance, but does not extend to interpretation of the data. The detailed design of the monitoring system hardware and data-handling systems is also likely to be performed by a specialist monitoring contractor.
3. **Interpretation of the monitoring data is fundamentally linked to the design of the works or performance of various other systems. People with knowledge and understanding of these works or systems therefore need to be involved in the interpretation of monitoring data. This will often mean collaboration with many different parties.**

5.2. Personnel, resourcing and competency

1. Obtaining and retaining adequate competent personnel is a generic concern for many aspects of underground works; monitoring work is not different in this respect. The work is project based and so demand within individual organisations is variable, meaning that few can afford to maintain a permanent staff resource; subcontracting is therefore the norm.
2. There are no globally recognised formal personnel qualifications specific to monitoring. Competency will often be demonstrated by having performed a similar monitoring function satisfactorily in the past. This is a factor to consider in both recruitment of individuals and employment of subcontracting specialist suppliers.
3. One consequence of the general difficulty in procuring adequate skilled staff is a tendency towards greater use of automated systems. There are significant differences between manual and automated systems for similar tasks, described as follows.
   - Manual data collection tends to be characterised by low instrumentation cost, high data collection cost, relatively low data collection frequency rates and a greater potential for inconsistency of data between different surveys. It also tends to be a very flexible and adaptable system with integral observation of the site activities at the time of monitoring.
   - Automated data collection tends to be characterised by higher instrumentation cost, lower data collection cost, higher data collection frequency rates and a lower potential for inconsistency of data between different surveys. It also tends to be inflexible and not easily adaptable, as data are often recorded without accompanying observations of the site activities (which must be retrospectively gleaned from site records).
4. The advantages of automated systems are significant in delivering consistent performance, but they still require proper design and set-up. The traditional land and engineering surveyor's skills are still highly relevant in achieving this end.

5. **There should ideally be continuity of personnel through the design and implementation phases. As a minimum, the monitoring designer's intent needs to be communicated clearly to those who implement the system and utilise the data generated; the interpretation of monitoring data may be greatly aided by an understanding of the monitoring designer's intent.**

5.3. Demonstration of compliance with requirements

1. The monitoring system is no different to other parts of the works in terms of normal management processes. The contractor undertaking the monitoring work will need to prepare method statements, inspection and testing plans and risk assessments as for any other element of the works.
2. There will commonly be a need to prepare as-built drawings of the monitoring system for use during the works. It is particularly important to ensure that those responsible for receiving monitoring data and acting upon it can quickly and accurately identify where the measurements were taken.
3. **There may be specific requirements to demonstrate compliance with the monitoring designer's intent. In particular, any system verification requirements need to be thoroughly dealt with. The monitoring contractor has a responsibility to satisfy himself that the monitoring system is correctly reporting what it is intended to report, and that all processes necessary to facilitate any planned responses to monitoring data are functioning as expected.**
4. There is also a need to provide training to those who will be in receipt of the data in order to ensure that they can interpret the results correctly.
5. Prior to the commencement of the works, checks on the stability of the survey network supporting the monitoring system and the validity of the software (and/or spreadsheets) should be undertaken to ensure that the systems, processes and procedures are robust and can tolerate scrutiny.
6. In situations where monitoring has to be installed as the work progresses, particular attention must be given to ensuring that it works correctly first time. Examples include establishing reliable convergence monitoring as a tunnel heading advances.

5.4. Data processing and management

1. **Rapid processing and delivery of processed data in appropriate formats are fundamental to managing risks to projects. The quality of all data (validated before use) should be such that it can be used for interpretation. All data need to be checked for correct format and rogue values, as a minimum.**
2. Most monitoring systems require some degree of data 'post-processing' before information is presented for use. There is benefit in minimising this requirement wherever possible and automating the process to minimise errors. Even manually operated systems such as precise levelling can have largely automated post-processing. Nonetheless, it remains important that the personnel involved have a full understanding of the process. Periodic manual spot checks of results are valuable in this regard.
3. Reduced (and adjusted) data can then be exported to spreadsheet format to produce time–history graphs or to other software packages to be added to, for example, mimics depicting change of an observed structure.

5.5. Integration of monitoring data with works

1. **It is important to link what is observed happening to the assets being monitored to the progress of the works**. The designer may need to know for back-analysis purposes that the structure is performing as designed. The client may need to know if the works are progressing as predicted. The contractor may need to know that his contingency measures are effective and third parties need to be kept abreast of construction progress and the effects on their assets.
2. **In practice, linking monitoring observations to the progress of the works can sometimes be problematic. This may be a particular issue if the monitoring is undertaken by a party other than the main contractor. There will be a need for a collaborative review process, involving all the parties that have an interest in either the main works or the monitoring system.**
3. Consideration should be given to requiring formal integration of monitoring data and works progress data. For example, it can be beneficial to ensure up-to-date drawings are maintained showing both the monitoring point locations and the

progress of the works. Works progress data should ideally be included as a time-stamped data stream in the monitoring database. For example, a database of settlement measurements over a tunnel heading should include information on the position of the tunnel face at different points in time.

5.6. Data interpretation and review

1. A formal, regular and recorded review process is required for all monitoring data. The frequency of such reviews should reflect the risks associated with the works and should be defined prior to commencement of the main works. In many projects, it may be appropriate to have meetings at relatively high frequencies for those closely involved in the works and less regular summary meetings for third parties and others.
2. The review process should involve scrutiny of any unexpected trends or results from monitoring. These should be investigated even where they do not lead to a breach of a trigger value.
3. The review process may be used to seek agreement between all interested parties that work can continue with/without amendments to construction processes. In many cases, the monitoring data from underground construction will be utilised in a review meeting with the aim of issuing a 'permit to dig' for the next shift.

5.7. Contingency plans

1. **Separately from the review process, a contingency plan must be established for dealing with exceptional monitoring results and trigger events. This plan is likely to involve ad hoc meetings of on-call representatives of interested parties in response to trigger events. These meetings will review the data and determine further actions.**

5.8. Data presentation to stakeholders

1. Most projects will have a requirement to distribute key data to various stakeholders during or after the works. Modern monitoring systems lend themselves to the production of automated reports to meet these needs. Such reports can be used in conjunction with conventional community relations activities to maintain a dialogue with third parties, and can help to reduce the number of ad hoc enquiries which may be received about progress of the works and results to date. The benefit of doing this is increased if the report is produced in a set format at regular intervals.
2. There may be particular information which will be of value to incident management and consideration should be given to preparing report formats which may be used for this purpose. An example of this might be a pre-programmed facility to produce a graphical report of all data trends in an area over the previous 24 hours.
3. There are various means of disseminating monitoring results. Appropriate formats need to be identified and implemented. Commonly used methods include
   - hard copy reports
   - email
   - web access
   - SMS text messages
   - regular meetings.
4. Mimic diagrams and other graphical forms of presentations may be considered for these purposes, as they often provide information in an easy-to-assimilate form. Presentation of tables of numbers alone is unlikely to be well received. It is also helpful to include illustrations of the works progress at the time of the measurements, particularly in the case of monitoring of assets with a tunnel drive passing beneath. Appendix D includes an illustration of such a report from a recent project.
5. Particular consideration needs to be given to whether remote access to the monitoring data is required by the client or others. This can be achieved using web access, possibly using only a web browser rather than dedicated software. For such a system, the number of simultaneous accesses to the data needs to be assessed and the system scaled to meet that peak. The time when the system is most heavily loaded will be the time of greatest scrutiny. Security may also be a significant consideration and may be addressed through measures such as read-only access and password protection.

5.9. Close-out/completion process

1. In most cases, monitoring data will have shown changes arising due to the works. It is good practice to continue monitoring, possibly at a reduced frequency, until either the change has been demonstrated to have ceased or until change due to the works is

indistinguishable from background noise. There may also be additional third-party or contractual requirements to consider.

2. Many clients will require some form of completion statement to ensure records are kept and that construction processes, including any agreed changes, have been documented. There will usually be a need to include some monitoring-related information in the project health and safety file.
3. In some situations, for example when monitoring the effects of dewatering or settlement over tunnels in stiff clays, monitoring for a considerable period after completion of the remainder of the works should be undertaken. In cases where monitoring is part of the main works contract, consideration should be given to whether any form of longer-term monitoring arrangement needs to be procured (as an ongoing monitoring requirement may prevent completion of a main contract).
4. Once the monitoring equipment is no longer required, the system will need to be decommissioned and removed. Depending on the nature of the system and where it is installed, the residual monitoring equipment may be viewed as assets or liabilities. It is important that the criteria to trigger decommissioning, the responsibility for decommissioning and the ownership of residual assets are clearly established at the outset to avoid disputes at this stage.
5. **To ensure that best practice has been carried through to the end of the completion phase of a project, it is recommended that a comprehensive monitoring close-out report be prepared. This is prudent even where the monitoring has not shown any unexpected behaviour. It will demonstrate that movements have been recorded throughout the works and that these have now ceased. The report should also include details of inspection/condition surveys, a record of any changes noted during the works and details of any monitoring points that have not been removed and are available for future monitoring.**

5.10. Archiving process

1. **Following completion of the project, it is important that all of the monitoring data are archived in a secure manner that will be accessible in the future if required.**
2. Electronic data should be stored on a server which is connected to a network that has adequate security protocols installed and is backed up on a daily basis. The backed up data should be in a format that is readily usable once loaded back onto the server.
3. The process of creating back-ups needs careful consideration. In most cases it will be done electronically, but this can lead to various difficulties. For example, when the data is being backed up does this disable the system for the timescale involved? Backing up and archiving activities will read data and may 'lock' database files, thus preventing other operations on those data. If this is considered unacceptable, then databases may need to be mirrored to another location which is then used for back-up purposes.
4. Paper-based data should be copied and filed in an auditable filing system. In most modern systems it will be beneficial to scan paper-based data and store a copy digitally, commonly as a portable document format (*.pdf) or similar.
5. Where the information from a monitoring system is kept in more than one format, it is important that there is adequate cross-referencing in the archive to be able to identify and locate all associated material. This applies not only to the monitoring data itself but also to any associated construction records, which may be required to put any future data interpretation in context.

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Chapter 6
Conclusions and recommendations

1. This guide aims to document advice on what constitutes good industry practice in the planning and execution of monitoring works for underground construction projects. The information presented here is advisory in nature. It is suggested that the guidance given should be considered for future schemes.
2. One of the most important observations is that monitoring work may require inputs from all the main parties to a project. It is also a subject that requires early consideration in the project life and can therefore be something that a client needs to give particular attention to before all the other parties are established.
3. It is hoped that following the guidance given here will help projects achieve the maximum benefits from their investment in monitoring and avoid the most common pitfalls of past projects.
4. This guide is structured to follow the generalised project life cycle. The most important principles at each stage are emboldened as recommendations in the main text. It is further recommended that the checklist presented in Appendix B is used as a tool to determine whether planned monitoring systems meet with industry guidelines. Where it is decided that it is appropriate to adopt different practices to those described here, consideration should be given to documenting the reasons.

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Appendix A
Glossary

The suggested definitions in this glossary apply when the terms are used in the context of monitoring underground works.

Term	Definition
Absolute change	A change in the value of a monitored parameter expressed in absolute measurement units relative to a recognised datum value.
Absolute data	Monitoring results described in terms of absolute engineering units (e.g. pressure, time).
Accuracy	A measure of how close the measured value of the parameter is to the true value. Related terms include: ■ Derived accuracy: accuracy derived by data manipulation through the application of corrections or weightings from other complementary monitoring equipment. ■ Relative accuracy: refers to monitoring methods or equipment that does not necessarily reflect accurate absolute values but accurately reflects relative changes in the monitored variable (e.g. settlement versus relative settlement of a building).
Analogue systems	Monitoring equipment that uses non-digital signals to relay results (e.g. Hertz, Voltage). Typical of older monitoring equipment (parallels can be drawn with terrestrial TV and radio).
Asynchronous monitoring	This refers to the majority of monitoring systems which are installed well in advance of the engineering event that they are intended to monitor (e.g. settlement monitoring, groundwater monitoring).
Automated monitoring	A monitoring system that, once installed, is not reliant on personnel to acquire, process or report the monitoring data. Monitoring undertaken using automatically operated measurement instruments.
Background monitoring	Refers to monitoring of asynchronous systems undertaken in advance of tunnelling-induced events to detect and identify external or background influences on the monitoring equipment or system (e.g. tidal loading on tunnel linings, thermal effects on structures or atmospheric effects such as humidity). This process is vital for critical systems where false alarms arising from such effects could lead to major disruption.
Background noise	Variation, which occurs in monitoring data due to factors other than the process that the monitoring system is intended to monitor. For successful measurement, the amplitude of the background noise after any appropriate corrections have been applied should be lower than that which the monitoring is intended to identify.
Back up	A process for arranging the safe and independent storage of a duplicate set of data from a monitoring system. Related terms include: ■ Back-up provision: this describes the process for a specific monitoring system by which the data obtained to date will be safely stored for recovery in the event of a system failure which removes the system and the data it contains, e.g. theft, computer virus, hard drive failure, etc.
Back-up monitoring system	A duplicate monitoring system which is independent of the primary monitoring system for a particular installation and which provides redundancy. The back-up monitoring system provides a means of ensuring continuity of monitoring in the event of any malfunction of the primary monitoring system.

Term	**Definition**
Base readings	Measurements taken to establish the stability of a monitoring system and to provide a reference against which future data can be compared to identify changes.
Baselining	The process of obtaining base readings from a monitoring system prior to the start of the main works for which the monitoring system is to be used.
Benchmark	A reference monitoring point established at a stable location outside the potential area of influence of the works. The benchmark provides a reference against which measurements of change due to the works may be compared.
Calibration	The process of adjusting a monitoring system to ensure that it produces the correct value when applied to a test sample of known value. Related terms include: ■ Manufacturer calibration: to ensure instruments are traceable to National Accreditation of Measurement and Sampling (NAMAS) standards they are usually supplied with a manufacturer's calibration certificate as a part of the system ITP along with a specified frequency for manufacturer's recommended calibration checking of system critical sensor elements (e.g. survey theodolites and levels). ■ Calibration range: many instrument sensors have limited ranges over which they work (e.g. pressure sensors, electrolevels, accelerometers). If the sensor in question measures outside the stated calibration range the sensor may cease to work or give inaccurate or imprecise results. It is worth noting that the precision of such sensors is usually related to the calibration range; the smaller the calibration range the higher is the sensor precision. ■ Site calibration: in addition to the manufacturer's calibration and checks, equipment in routine use should be subject to planned site calibration checks to ensure it has not 'drifted' out of calibration, reporting false results.
Contingency plans	Planned actions identified prior to the works and implemented immediately when a trigger level is exceeded.
Correction	A deliberate and controlled adjustment made to the recorded value of a parameter in a monitoring system to compensate for a known effect which is not directly attributable to the process which the system is intended to monitor. Correction should be made through a change control process which ensures that the change is recorded and is reported with the subsequent data to ensure misconceptions or false alarms do not result.
Data formats	Examples include: ■ DIGGS (Data Interchange for Geotechnical and Geoenvironmental Specialists): the latest internationally recognised electronic data format for monitoring data based on the XML (Extensible Markup Language) used for web-based programming systems. ■ CSV (Comma Separated Variable): an older electronic data format commonly used to store and transmit monitoring data using simple alphanumeric text files. ■ AGS (Association of Geotechnical and Geoenvironmental Specialists): an electronic data format for monitoring devised and promoted by the AGS for recording monitoring data based on a formulaic CSV format. It is planned that this format will be superseded by DIGGS AGS format in the future to give international compatibility.
Data management	The process of collating, storing, analysing and reacting to data from monitoring.
Data retrieval	Refers to the ability to interrogate the results of a monitoring system. With high-frequency monitoring systems and systems which undergo frequent revision (e.g. track monitoring systems) this can be an onerous and expensive option since large volumes of data are involved and have to be correlated to temporal changes to the monitoring systems.
Derived data	The results of monitoring derived from the numerical processing of raw sensor data (e.g. easting, level, convergence, etc.).
Designer	CDM definition.

Term	Definition
Digital systems	Monitoring systems that use digital signals to relay results, typical of many forms of modern monitoring equipment (parallels can be drawn with digital TV and radio).
Drift	An inherent tendency for the value returned by a repeated measurement to vary systematically over time when there is no real variation in the parameter being measured.
Effective real-time monitoring	Where the frequencies of data acquisition, processing and reporting are the same and are sufficiently frequent for the control of engineering processes (electrolevel readings or automated theodolite monitoring (ATM) target readings during compensation grouting). In strict terms there are few truly real-time monitoring systems. The process of taking a sweep or measurements across a range of sensors and targets, gathering and processing the data and then reporting it leads to a lag in the reporting of results. The term is often erroneously used to describe high-frequency monitoring and reporting systems, which report at a frequency sufficient for monitoring and controlling engineering processes. See 'Pseudo real-time monitoring'.
Emergency response monitoring	Any monitoring system that is installed in response to an unforeseen engineering event, hopefully as a pre-planned action defined in the EPP utilising suitable equipment and staff trained in synchronous monitoring requirements.
Emergency preparedness plan (EPP)	A site-specific document that details the actions of site management, utility companies and the emergency services in response to critical monitoring systems exceeding specified critical values (trigger criteria). Can form part of a contingency plan and can also be known under different names: emergency response plan, incident plan, etc.
Emergency power supply (EPS)	A system of batteries or standby generators used to ensure that critical monitoring systems are not affected in the event of a failure of the normal power supplies.
Environmental trends	Natural variations in the value of a measured parameter that may occur over time. In general these will be distinct from the variations in the parameter due to the process which the monitoring system is primarily intended to monitor. Examples of environmental trends may include seasonal, diurnal and tidal variations.
Frequency (sometimes referred to as monitoring frequency, data collection frequency or acquisition frequency)	The rate at which readings are taken by a monitoring system. Related terms include: ■ Staged monitoring frequency: describes a variable monitoring frequency that is typically controlled by proximity of the monitoring to construction activities or as a reaction to an unexpected detected change in the monitoring results. It is commonly recommended to avoid data overload and wastage of monitoring resources. ■ Processing frequency: the rate at which acquired monitoring data is processed by a monitoring system. ■ Reporting frequency: the rate at which the raw or processed data from a monitoring system is reported. The above three terms can be best clarified by considering a data-logger-based system covering a range of sensors – it can gather data at a programmed frequency and keep it in memory (e.g. 1 reading per minute), a separate programme can undertake data processing (e.g. rolling average and variance of the gathered data at a different frequency, such as once per hour, storing the derived results in memory), another programme can undertake to report the derived results at another frequency (e.g. once per day). Thus in one data-logger the acquisition, processing and reporting frequencies can differ. ■ Low-frequency monitoring: undertaken at a low frequency relative to the rate of expected change. Typically, low-frequency monitoring may be specified where the main purpose is to collect data for back-analysis and design verification purposes. The actual frequency may vary according to the context and hence the distinction between high-frequency and low-frequency monitoring is to some extent subjective. ■ High-frequency monitoring: monitoring which is not real-time but which is undertaken at a high frequency relative to the rate of expected change. Typically high-frequency monitoring may be specified where there is a requirement to implement contingency plans if trigger values are exceeded.

Term	Definition
Ground monitoring	Monitoring of changes in the ground itself (i.e. the profile of the ground surface as a tunnelling process is carried out beneath) as opposed to measurements of the behaviour of infrastructure. Monitoring of the ground for tunnelling applications will be the only consistent way to acquire data to verify volume losses.
Holiday cover	Refers to the provision of alternative personnel to cover the holiday arrangements of key monitoring personnel to ensure monitoring systems are not jeopardised.
Illness cover	The provision of arrangements to ensure that any illness or other unforeseen absence of key monitoring personnel does not jeopardise monitoring provisions.
Independent system	A monitoring system which is completely separate from another system but which produces duplicate (or near-duplicate) information.
Inspection and test plan (ITP)	A standard quality assurance system requirement, which requires that monitoring systems are supplied with calibration certificates, calibration checking arrangements and specific frequencies and protocols for such checks including any integral processing and reporting software.
Instrumentation	Equipment for detecting and recording change in specific parameters.
Instrumentation manufacturer	An organisation that manufactures or fabricates monitoring equipment and its related software and hardware for interrogation and display of monitoring results.
Instrumentation supplier	An organisation that commissions the manufacture of monitoring equipment to order or holds stocks of monitoring equipment for purchase. Such organisations may undertake the installation of equipment but do not provide ongoing monitoring thereafter.
Intelligent systems	Describes any monitoring system that includes facilities to undertake predetermined actions in response to the results of monitoring as described below. ■ Intelligent acquisition systems: systems that undertake predetermined actions in response to the results of monitoring (e.g. increase the frequency of the monitoring activity if specific monitored criteria are exceeded). ■ Intelligent processing systems: systems that undertake different processing actions in response to the results of monitoring (e.g. undertake trend analyses for data to predict rates of change and/or time until certain monitored criteria are breached). ■ Intelligent reporting systems: systems that undertake different reporting actions in response to the results of monitoring (e.g. reporting to different ranges of staff if specific raw or derived monitoring criteria are exceeded).
Manual monitoring	A monitoring system that is reliant on the use of personnel to acquire, process and report the monitoring data. Monitoring undertaken by an operative using manually operated measurement instruments. This will include conventional manual surveying processes. Related terms include: ■ Manual acquisition: where monitoring results are acquired by personnel (e.g. traditional surveying). ■ Manual processing: where monitoring results are processed by personnel (e.g. by traditional survey reduction calculations). ■ Manual reporting: the process of reporting is undertaken by site personnel (e.g. the reporting of manually observed measurements).
Monitoring	The process of taking measurements of changes caused by construction activities. Monitoring is taken to include collection of data by a wide range of means including conventional survey methods and various automated systems. In some situations monitoring may also include systematic inspections.
Monitoring coverage	Describes the extent of monitoring provisions in terms of area and/or density.
Monitoring service provider	An organisation which undertakes to provide ongoing monitoring services which may additionally include any or all of the following: design, purchase, supply, installation, commissioning and decommissioning of equipment. Typically such organisations have

Term	Definition
	bespoke software developed to fulfil monitoring objectives that can often be adapted to suit specification requirements.
Monitoring specifier	An organisation or individual that defines the objectives and requirements of a monitoring system that has yet to be designed.
Monitoring system	An integrated system for collecting and managing measurement data. Monitoring in this context is envisaged to be primarily the monitoring of the effect of underground construction works on the adjacent ground and existing infrastructure, although it is recognised that there is an inevitable overlap and interest in monitoring systems in the new works under construction.
Monitoring system risk assessment	A specific assessment of risks relating to a monitoring system covering all aspects of the installation, acquisition, processing, reporting and decommissioning of the system.
NAMAS standards	Monitoring systems that report in absolute units should be 'traceable' to NAMAS (National Accreditation of Measurement and Sampling) standards; these are the international standards for the base engineering units (e.g. metre, kilogram, second).
Planned preventative maintenance (PPM)	This describes the process devised for a specific monitoring system by which foreseeable maintenance issues, as identified by the monitoring system risk assessment for the system will be addressed (e.g. theodolite replacement or target cleaning on automated optical monitoring systems).
Precision	The repeatability of a measurement when there is no real change in the parameter being measured. Related terms include: ■ Derived precision: precision derived by mathematical manipulation of data (e.g. rolling averages, data corrected for thermal effects).
Pseudo real-time monitoring	Where the frequency of data acquisition, processing and reporting is the same and is sufficiently recurrent for the control of engineering processes (e.g. electrolevel readings or automated theodolite monitoring target readings during compensation grouting). In strict terms there are few truly real-time monitoring systems. The process of taking a sweep or measurements across a range of sensors and targets, gathering and processing the data and then reporting it leads to a lag in the reporting of results. The term is often erroneously used to describe high-frequency monitoring and reporting systems, which report at a frequency sufficient for monitoring and controlling engineering processes.
Qualitative data	Monitoring data that are not described in numerical terms (e.g. the absence of data, weather).
Quantitative data	Raw or derived monitoring data reported numerically, preferably in meaningful engineering units.
Raw data	The basic data derived from a sensor system prior to any numerical processing (e.g. Voltage, Hertz).
Record format	Refers to the physical media on which monitoring results are recorded and reported (e.g. graphical paper printout, tabular paper printout, electronic transmission by DVD, CD and floppy disk).
Recovery period	This is the specified time by which a monitoring system should be fully reinstated following a catastrophic failure.
Recovery plan	This is a documented process for a specific monitoring system that described the means by which the system can be reinstated following a loss, damage or component failure.
Redundancy	This is the provision of more instrumentation than the minimum necessary to meet the specified monitoring objective. Providing redundancy ensures that loss of some instrumentation or even failure of part of a monitoring system would not result in a loss of all the required information for a project.

Term	Definition
Relative change	A change in the value of a monitored parameter expressed as a proportion of the value of another parameter measured by the same monitoring system. Related terms include: ■ Relative data: monitoring results described in terms of change from an arbitrary datum value (e.g. strain, tilt).
Repeatability (of measurements)	The extent to which a measurement process produces the same value each time the measurement is made when there is no change in the true value of the parameter being measured (see 'Precision').
Response level	This refers to the level in the monitoring system at which a response may be triggered. A low-level response is a reaction by the monitoring site staff (e.g. repeating a reading or checking calculations). A high-level response is one involving the actions of senior management (e.g. notification of emergency services). An alternative term for 'trigger level'.
Robotic monitoring	Automatic monitoring using a system with robotic instruments which are capable of moving to take a repeating sequence of different measurements.
Semi-automated monitoring	A monitoring system that, once installed, is only partially reliant on personnel to acquire, process or report the monitoring data. Surveying is an example of this, where manually acquired data is now routinely processed by automated systems.
Semi-qualitative data	Monitoring data that is described in numerical terms which have no meaningful engineering units.
Semi-real-time	Sometimes used to describe high-frequency monitoring. Not a preferred term.
Site shutdown	A planned or unplanned closure of the construction site which may result in suspension of routine site activities that could impact on monitoring (e.g. access to instrumentation without special provisions). These need to be planned for in the EPP and any site holiday arrangements.
Stability	The characteristic of not being susceptible to drift.
Synchronous monitoring	This refers to monitoring systems that are installed and commissioned at the same time as the engineering event that they are intended to monitor (e.g. sprayed concrete lined (SCL) lining monitoring, emergency response monitoring installed during unforeseen events).
The works	The underground construction works which cause the effects that are being monitored.
Trigger level	As defined by Construction Industry Research and Information Association (CIRIA) Report 185, the specific values that apply to a prescribed monitoring system which trigger a response or management action. Typically it is a three-level system described in terms of red, amber and green levels but it can have more or fewer levels. A predetermined value of a measured parameter. If monitoring indicates that the parameter exceeds the trigger level, a predetermined response will be initiated. Red trigger levels may be used to initiate a cessation of works. Black trigger levels may be used to indicate the level at which structural failure of affected infrastructure may be expected. See 'Response level'.
True real-time monitoring	Monitoring which provides a continuously updated value of a parameter. The data are available for use as soon as the measurement is made.
Underground construction	Includes construction of bored tunnels and other deep excavations, such as shafts and deep boxes, that may give rise to similar monitoring issues.
Uninterruptible power supply (UPS)	A facility that allows for constant operation of a monitoring system in a situation where mains power has been lost. Power can be supplied by, for example, a standby generator or batteries.
Validation	A process for ensuring that the value obtained for a measurement is a true reflection of the actual change in the parameter being monitored. The process should be detailed in the ITP.

Term	Definition
Visual monitoring	The most basic form of qualitative monitoring and first resort of any EPP. A defined process for observing and recording visual information by staff competent to understand, describe and make logical deductions from what they observe. See ‘Qualitative data’.
Zero reading	This is the value assigned for a sensor against which all subsequent readings are compared (i.e. baseline value).
Zone of influence	The area that is bounded by movement contours that have been generated by the designer during his assessment of ground movements due to the works. The zone of influence shall be defined to enable the designer to estimate the likelihood of potential damage to adjacent structures/infrastructure and design an appropriate monitoring system to measure ground movements generated by the works. The zone of influence shall also determine where stable reference targets and benchmarks can be sited/located.

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Appendix B
Monitoring system specification checklists

These checklists are intended for use as an *aide-memoire* by those responsible for specifying, designing and operating a monitoring system. They are intended to provide a means of verifying that the main issues highlighted in this guide have received appropriate consideration. The items in the checklists are grouped into logically related issues.

The checklists are

1. Design Basis
2. Required Outputs
3. Commissioning
4. Maintainability
5. Operations and Management

1. DESIGN BASIS CHECKLIST		
Item to be checked	**Applicability**	**Reference clause**
Objectives		
Are objectives of monitoring defined?	Yes/No/NA	4.1.1
Do the objectives change during the course of the works?	Yes/No/NA	4.1.1
Are the functional requirements for the monitoring system defined?	Yes/No/NA	4.2.1
Distribution of monitoring		
Does the system cover the whole area at risk from the works?	Yes/No/NA	4.3.1
Does the system adapt to the progress of the works over time?	Yes/No/NA	
Does the system include controlled reference points outside the zone of influence?	Yes/No/NA	4.3.1
Is the location where maximum change is expected directly monitored?	Yes/No/NA	4.3.2
Is there planned redundancy of coverage at the maximum change location and does it address the location varying over time?	Yes/No/NA	
Has the system setting out been checked?	Yes/No/NA	4.3.5
Does the monitoring system use a logical referencing system that can be related to the main works?	Yes/No/NA	4.3.4
Is ground movement measured directly?	Yes/No/NA	4.3.6, 4.3.8
Has the design of the monitoring system taken account of any planned or recently completed adjacent construction works by other parties?	Yes/No/NA	4.3.12
Can the movements caused by planned or recent adjacent construction activity be distinguished?	Yes/No/NA	
Accuracy, precision and range		
Are precision and accuracy requirements proportionate to the need at all times during the project?	Yes/No/NA	4.4.1, 4.4.2
Has an appropriate period of background monitoring been specified or achieved?	Yes/No/NA	
Does the system have adequate measurement range?	Yes/No/NA	4.4.3
Can the user re-baseline the system?	Yes/No/NA	4.4.3
Does it allow for any future system adaptations such as increased coverage, monitoring frequency or equipment replacement?	Yes/No/NA	
Frequency of monitoring		
Is observation frequency adequate to trigger planned response?	Yes/No/NA	4.5.3
Has an economic or appropriate balance been achieved between automated and manual systems?	Yes/No/NA	4.5.6
System reliability and redundancy		
Does the monitoring system have known reliability?	Yes/No/NA	4.7.1
Does the monitoring system have redundancy for component failures?	Yes/No/NA	4.7.2, 4.8.4
Does the monitoring system raise fail-safe alarms?	Yes/No/NA	4.7.4
Does the monitoring system have uninterruptible power supply (UPS)?	Yes/No/NA	4.7.6
Are adequate spares and consumable stocks specified?	Yes/No/NA	4.7.7
Is there a recovery plan for system failure?	Yes/No/NA	4.7.8
Has a strategy been specified for dealing with time changes (BST/GMT)?	Yes/No/NA	4.7.9
Has a robust change control process been established on the project?	Yes/No/NA	4.16.2
Have third-party stakeholders been engaged in relation to setting of trigger levels and contingency planning?	Yes/No/NA	3.2.2

2. REQUIRED OUTPUTS CHECKLIST		
Item to be checked	**Applicability**	**Reference clause**
Design outputs		
Has a statement of the design basis for the monitoring system been produced?	Yes/No/NA	4.16.1
Have drawings been prepared to describe the monitoring distribution?	Yes/No/NA	4.16.1
Has a designer's risk assessment been prepared?	Yes/No/NA	4.16.1
Are all risk aspects of the monitoring system, including those arising from processing and reporting, addressed (see Appendices D, E)	Yes/No/NA	
Has a contingency plan, including trigger values, been prepared for the monitoring system?	Yes/No/NA	4.16.1
Have the decommissioning requirements been specified?	Yes/No/NA	4.16.1

3. COMMISSIONING CHECKLIST		
Item to be checked	**Applicability**	**Reference clause**
Baseline measurements		
Are sufficient baseline measurements specified?	Yes/No/NA	4.6.1
Does baselining allow for environmental variables including temperature, seasons, vibration and tides?	Yes/No/NA	4.6.2, 4.6.3
System verification		
Is the system fully calibrated?	Yes/No/NA	4.8.2, 4.8.3
Has a whole system check been undertaken?	Yes/No/NA	4.8.3, 4.8.5
System maintenance		
Is a maintenance schedule specified?	Yes/No/NA	4.9.5
Is the requirement for a maintenance log specified?	Yes/No/NA	4.9.6
Are the contractual and control systems governing changes to the monitoring system clear?	Yes/No/NA	
Change control		
Is the process governing change control specified?	Yes/No/NA	4.16.2

4. MAINTAINABILITY CHECKLIST		
Item to be checked	**Applicability**	**Reference clause**
Maintenance requirements		
Has consideration been given to access for maintenance?	Yes/No/NA	4.9.1
Has consideration been given to future-proofing the monitoring system?	Yes/No/NA	4.9.2
Are there any longer-term stability issues with the specified system?	Yes/No/NA	4.9.3
Has the designer/monitoring contractor formulated a maintenance regime?	Yes/No/NA	4.9.1–4.9.4
Are there any particular agreements or restrictions on fixing monitoring equipment to existing infrastructure or building facades?	Yes/No/NA	4.10.1
Is the design of the monitoring system over-prescriptive in the specification (i.e. has the specification potentially excluded certain suppliers by being over-prescriptive)?	Yes/No/NA	4.10.2
Has a review of the capital cost against the whole life operating cost been considered for the monitoring system?	Yes/No/NA	4.10.3
Is there an inspection and test plan covering the system to check on maintenance schedule and logs?	Yes/No/NA	4.9.5
Are the maintenance implications of over-use clearly specified?	Yes/No/NA	4.9.7
Is there an active risk register concerning maintenance which reflects the changing site conditions?	Yes/No/NA	
Are the key staff for the system identified and do they have up-to-date access permits and training? Do they have understudies who can fulfil their role when absent (e.g. the software programmer)?	Yes/No/NA	

5. OPERATIONS AND DATA MANAGEMENT CHECKLIST		
Item to be checked	**Applicability**	**Reference clause**
Data processing, review and presentation		
Has the specification stipulated that the processed data is available for review and interpretation?	Yes/No/NA	
Has the specification stipulated that the processed data is readily available in formats appropriate to the needs of the project?	Yes/No/NA	4.10.3
Is there a requirement in the specification for the monitoring contractor to provide verification of the calculation process?	Yes/No/NA	4.11.2
Data interpretation and review		
Has the designer specified a review regime for monitoring data and site operations (daily/weekly)?	Yes/No/NA	4.12.1
Is there a procedure in place whereby this frequency can be amended?	Yes/No/NA	4.12.2
Data presentation to stakeholders		
Is there an agreed plan of action to accommodate stakeholders?	Yes/No/NA	4.13.1
Data back-up, system recovery and archiving		
Has the specification included requirements for the routine back up of all observed data?	Yes/No/NA	4.14.1
Is the monitoring system designed in such a way that back-up operations do not compromise its normal function?	Yes/No/NA	4.14.1
Has the back-up storage media been specified?	Yes/No/NA	4.14.2, 4.14.3
Is the back-up procedure integrated with the system recovery process?	Yes/No/NA	4.14.1
Are there any data degradation issues on particular storage media?	Yes/No/NA	4.14.2
Does the raw data require bespoke software to read it?	Yes/No/NA	4.14.3
Can the data be readily exported to commercially available formats?	Yes/No/NA	
Does the system recovery procedure cover computer hardware as well as the monitoring data?	Yes/No/NA	
Is the speed of the recovery procedure acceptable and has it been verified?	Yes/No/NA	4.2.1
Responses to monitoring		
Have contingency plans been formulated to respond to breached trigger levels?	Yes/No/NA	4.15.1
Have trigger levels been pre-determined?	Yes/No/NA	4.15.2
Has sufficient time to implement pre-planned interventions been considered?	Yes/No/NA	4.15.6

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Appendix C
Common monitoring problems

A wide range of problems can affect the successful delivery and operation of a monitoring system. This guide aims to provide advice to help to minimise such difficulties. In the course of preparing the guide, the authors compared experiences of what can go wrong and produced a list based on their actual experiences from a wide range of projects. This list is tabulated below to illustrate the potential hazards arising from undertaking monitoring for deep excavations and tunnels. The list is not exhaustive and should not be used to replace a specific project monitoring risk assessment. Nonetheless, it is hoped that it may be helpful to consider during the planning of future monitoring works.

The table comprises the list of potential problems with short descriptions and a subjective assessment of the likely nature of the root cause according to the following classification.

- Specification: inadequate requirements definition and/or specification.
- Design: errors or inadequacies in monitoring system design.
- Procurement: the procurement arrangements.
- Management: difficulties in managing the monitoring system, the data or the various parties influencing the works.
- Operation: inappropriate operation of the monitoring system.
- Human factors: human error or lack of adequately skilled human input.
- Equipment: breakage or failure of equipment.

In most cases, there is more than one possible contributory factor, although it is notable that a large proportion of the issues can be traced back to the original specification for the work.

Issue	Problems experienced on previous projects	Likely root causes						
		Specification	Design	Procurement	Management	Operation	Human factors	Equipment
Parameters measured	Failure to define objectives leads to measurement of inappropriate parameters. This may result in failure to detect critical changes (e.g. monitoring deformation rather than stress in a tunnel lining may not give adequate warning of brittle failure). Failure to appreciate failure mechanisms may result in the correct sensors/monitoring being used but wrongly located or inadequate monitoring coverage, resulting in important changes being missed.	✓	✓	✓				
Back-up systems and redundancy	Failure of one element in the monitoring system may result in failure to obtain the required information. The problem can be failure of personnel, training, hardware or software so redundancy is required in all these areas.	✓	✓	✓	✓			
Monitoring frequency	An unduly low measurement frequency may result in short-term changes such as peak loading under traffic being missed. Low measurement frequencies may also result in change being detected too late for contingency responses to be activated. Excessively high measurement frequency may result in data overload problems if data is acquired faster than it can be processed and interpreted. There have been instances of tunnel collapse for which subsequent investigation revealed that the signs of imminent failure had been detected, but not interpreted and acted upon in adequate time. Excessive monitoring frequencies may also lead to wear issues in some systems. Worn equipment may be less reliable and also less accurate (e.g. wear of robotic theodolites and overheating of sensors such as vibrating wire instruments).		✓		✓			✓
Calibration	Calibration is critical to most monitoring systems. Unfortunately, errors are common in a site environment where equipment may be prone to accidental damage and where cleaning and maintenance is not always rigorous. On many sites, monitoring work may only be a small part of the personnel responsibilities. This means it may not be considered a high priority by the staff involved in taking measurements, with a resulting adverse impact on quality of work.	✓			✓	✓	✓	✓
Instrument range	Problems may occur if changes are larger than expected and measurements are taken outside the calibrated ranges of instruments. The calibrated range may be inadequately specified because of an error in the assessment of expected change on which the specification is based. The calibrated range may also be inadequate as a result of an excessive specification for precision. There is often a tendency to specify the maximum possible precision for an instrument even if this results in an ability to detect changes of a magnitude of no practical civil engineering significance. In many instruments, precision is inversely proportional to measurement range so a high precision specification will limit the range of reliable measurement. The project objectives may actually be best served by specifying a larger range but lower precision for a given measurement.	✓	✓			✓		✓

Issue	Problems experienced on previous projects	Likely root causes						
		Specification	Design	Procurement	Management	Operation	Human factors	Equipment
Background monitoring and baselines	Failures of process to determine and correct external influences on monitoring results (e.g. temperature, tides, rainfall, atmospheric pressure, traffic, dewatering) can lead to errors in reported data. Additionally, failures to check and correct for changes in site benchmarks will also lead to errors. Failure to allow time or resources to set up background monitoring (i.e. installation and commissioning of equipment) will lead to inadequate baselining and validation of monitoring data.	✓	✓		✓	✓		
System validation	Omission or failure to specify or undertake checks on the monitoring system (i.e. equipment, functions and results) before or during construction (e.g. lack of independent manual checks of calculations, reporting and measurements) will lead to inaccurate monitoring results.	✓	✓		✓	✓		
Data interpretation	Problems can arise from some of the following points: a lack of knowledge, experience or adequate training among staff; lack of time/resources to make the appropriate assessments; oversimplification of data interpretation; failure to consult past results to permit trends in data to be assessed.	✓		✓	✓	✓		
Reporting	Difficulties in data reporting, such as the following, often arise: reporting of results with incorrect scales (graphs) or in the wrong units; over-complex reporting methods; missing context data (e.g. weather conditions, site activities) that were concurrent with the reported monitoring results; absence of contractual mechanisms to correct reporting failings.	✓		✓	✓	✓		
Planned responses to monitoring and emergency preparedness	Examples of an absence of contractual mechanisms to ensure planning for emergency situations (EPP) include: failure to anticipate worst-case and intermediate-case emergency situations during construction activities (e.g. provision of safe shutdown and site evacuation measures); neglect to liaise and agree actions with all potentially affected third parties (e.g. utility companies, rail operators, emergency services); failure to anticipate the urgent need to supply equipment and personnel for increased monitoring frequency or coverage; failure to anticipate access requirements at all times during construction.	✓	✓	✓	✓			
Novel/ unproven technologies	Problems can arise from: the implicit lack of past experience with the techniques; the shortage of appropriately skilled staff (single supplier); shortages of equipment leading to late supply; increased reliance on validation of results and background monitoring; erroneous results or unforeseen responses in use; potential for non-acceptance of system by third parties (i.e. reassurance failure and resultant late deployment of conventional systems).	✓	✓	✓	✓	✓	✓	✓
Incompatible tenders for monitoring	Often, a characteristic of the monitoring industry is that specialist suppliers have preferred technologies and offer a variety of bespoke instrumentation systems. If tender specifications are prescriptive, there is a risk of a poor response with only those comfortable with the prescribed approach	✓		✓				

Issue	Problems experienced on previous projects	Likely root causes						
		Specification	Design	Procurement	Management	Operation	Human factors	Equipment
Incompatible tenders for monitoring – continued	being willing to tender. There may be a likelihood of non-conforming bids that may often be cheaper but may not address all the intended designer requirements. Diverse approaches from suppliers may mean it is preferable to present a performance specification and allow each tenderer to offer their best ideas.	✓		✓				
Isolation of monitoring design from main works design	This often arises from factors such as: the failure to anticipate the need for monitoring during design; no identification of risks in design phase (i.e. no risk assessment or workshops) that could identify what needs to be monitored during construction; poor or hurried design planning for the project; the late development of a procurement strategy for the project; the delegation of monitoring to the main (principal) contractor.	✓	✓	✓				
Resources	A common problem arising from failures to appreciate the complexity of monitoring systems and site-dependent activities. With a lack of resources, difficulties with other site activities or the extent of reporting for the monitoring systems are often magnified. Monitoring contractors are rarely large organisations and tend to only have a few key staff, limiting their ability to undertake large monitoring installations over short durations.	✓	✓	✓	✓		✓	
Resources for processing and/or response	Examples of this have arisen in the past from poor process specification, complex procedures, poor management, lack of training and lack of holiday/sickness cover. Finding staff with the requisite skills and experience is often fraught.	✓		✓	✓			
Inappropriate allocation of risks to monitoring contractor	This arises from badly chosen procurement methods, such as seeking to place inappropriate risks (e.g. consequences of ground and structure failure) with a monitoring (sub-) contractor who does not have the expertise to cover it. Senior project management should always be aware of inappropriate risk allocation.	✓		✓	✓			
Access and audit of raw data	Similar to the above, problems in this respect arise from calculation or processing errors that are embedded in monitoring systems and software. Monitoring calculations and software should be easily auditable.	✓	✓		✓	✓		
Contractual dislocation – monitoring not under control of client/main contractor	This arises from multiple contractual layers (e.g. monitoring is undertaken by a subcontractors) and the objectives and control measures for the monitoring have become confused and diluted in the process. Often results in multiple contract representatives attending monitoring meetings to argue points of contract rather than address pertinent monitoring issues.	✓		✓	✓			
'Self specification'	Delegation of monitoring system design to a monitoring contractor can import risks to a project arising from a 'design and build' approach to the design. Monitoring contractors rarely have the capacity (technically or commercially) to manage significant project risks. They are unlikely to be engineers so won't have the necessary skills to carry out complex assessment calculations that drive monitoring design.	✓	✓	✓				

Issue	Problems experienced on previous projects	Likely root causes						
		Specification	Design	Procurement	Management	Operation	Human factors	Equipment
Training	Applies at all levels in the monitoring process from using the instrumentation to recording data, processing data, interpreting data, etc. Lack of programming time for training of operatives, for example to familiarise them with some third-party infrastructure, will require minimum training (e.g. access permit training for London Underground, track awareness training for Network Rail, confined space training for sewers).	✓		✓	✓			
Access	Monitoring often requires access to restricted locations (e.g. live railways, working at heights or in confined spaces). Delays can occur when awaiting safe access periods or the granting of access permits to specific staff. Such restrictions may make certain monitoring techniques unfeasible, resulting in late changes to designed methods. When 'whole life' access to monitoring equipment and its location is not considered during concept/design stages, this can impact the programme later on and have knock-on cost implications. A common hazard arises from the failure to plan for monitoring provisions during a site closure, typically resulting in problems such as lack of keys/power to gain access, lack of ventilation, lack of emergency provisions, lack of senior staff to undertake data review or the absence of personnel to undertake the appropriate emergency actions. Where monitoring is to be undertaken during site shutdowns (i.e. Easter or Christmas), provision for site access is often overlooked; similarly, supervisory cover can sometimes be neglected – this can be a failing of site emergency plans.	✓	✓	✓	✓			
Third party engagement	The late involvement of affected third parties can result in: specific reassurance requirements not being addressed in the scope of work thus introducing late changes to the programme; lack of appropriate resources for the third parties to be properly represented in reacting to the monitoring (i.e. should be embedded in any emergency plan); insufficient time to design and implement appropriate emergency response procedures that are appropriate to the monitoring; potential for the third party to fail to correctly appreciate the hazards and respond appropriately. The above can arise from late involvement but can also be due to poor management, lack of resources or a failure to appreciate potential hazards.		✓		✓	✓		
Change control	Change control processes should be specified as contractual requirements but can arise as a result of later management instructions. In either situation they can prove to be inadequate or inappropriate (e.g. for revision of trigger values, application of corrections to results, etc.).	✓		✓	✓			
Trigger level criteria	Problems which commonly occur with trigger level criteria are: trigger criteria have been specified on the basis of specific design criteria and then failed to anticipate external influences (e.g. temperature fluctuations, rainfall); late (possibly ill-informed) management changes are applied to the criteria (e.g. 'halving the trigger criteria makes it twice as safe'); corrections applied for		✓		✓	✓		

Issue	Problems experienced on previous projects	Likely root causes						
		Specification	Design	Procurement	Management	Operation	Human factors	Equipment
Trigger level criteria – continued	external influences are applied to monitoring with insufficient background readings, resulting in the trigger criteria being based on incorrect data; in automated systems, failure to check that the correct trigger alarm data has been set.		✓		✓	✓		
Equipment protection	Monitoring equipment is often installed in advance of the main project construction activities and can be easily overlooked, resulting in equipment damage and loss; this should be mitigated by appropriate protective measures and proactive site management.			✓	✓			
Reporting	In the past some projects have specified the reporting of monitoring requirements based on the quantity of data generated rather than the significance of the results observed. This can result in excessive resources being deployed on producing voluminous reports, having a detrimental effect on available resources for installation, maintenance and interpretation.	✓			✓			
Review meeting overload	Specification of meetings at a frequency, timing and/or duration that result in resources being spent on these activities to the detriment of installation, maintenance and interpretation. Review meetings should be pertinent to the works being undertaken as well as looking at the broader picture around the works. The basis for monitoring review meetings should be technical in nature, be attended by key staff involved in the works and as brief as the matters to be covered will allow. Meetings should be recorded (e.g. minutes) and the output from the meetings should be that all parties agree on the reported results, identify trends that imply continuing movements and the appropriate excavation (for tunnelling/shaft sinking/box excavation) 'parameters' for the next shift (i.e. a sign-off sheet should form part of the record).	✓			✓			
Data overload	A frequent criticism with monitoring data is that too much data is generated and reported. Where this is the case, it is vitally important to concentrate efforts on reviewing data that is relevant to the works being currently undertaken. Project engineers/managers should ensure that efforts are directed at these aspects of the works and that the coverage, resources and frequencies of the monitoring system are appropriate to the site tasks and third-party infrastructure affected by the works. There should be a seamless change control process on site to ensure that the coverage, resources and frequencies of the monitoring system can be refocused as required.	✓	✓	✓	✓			
Mis-information	This relates to the hazards arising from interpreting and responding to monitoring results that are based on either incorrect context information or where the wrong results have been reported. This commonly occurs where there is a lack of checking in the systems or a lack of training or continuity in the staff undertaking the interpretation and management. Third-party representatives may try to override the established procedures.				✓	✓	✓	

Issue	Problems experienced on previous projects	Likely root causes						
		Specification	Design	Procurement	Management	Operation	Human factors	Equipment
Data archiving	A number of projects have suffered from late specification of the need to store and archive monitoring data in specific formats. This has resulted in late changes to the monitoring data processing systems and significant reworking of data. The problem usually occurs on projects involving multiple contracts, each containing monitoring work and where the client wishes to obtain a single database containing all the information. In this situation it is important that the client specifies the required data output format early so that all the contractors set up compatible systems. In general, all that will be necessary is specification of the production of data in a standard digital format (typically the AGS format).	✓	✓	✓	✓			
Access 24/7 to relevant external expertise	Emergency Preparedness Plans, agreed trigger level responses (internal to a project), agreed protocols for when to notify external (stakeholders) bodies. Notification of a breach in system trigger criteria must be made to the appropriate staff in many organisations, especially where they are responsible for safety critical responses, and they need to be available at all times and in a position to instigate their actions. This consideration must be addressed by the management of the monitoring systems.	✓		✓				
Datum errors or instability	The datum measurements used by a monitoring system need to regularly reviewed to ensure that they remain stable. Failure to do so may result in generation of anomalous data and false alarms. Many automated alarm systems may have difficulty interpreting the results of a datum point movement as the processing assumes by default that such changes cannot happen. In the event that changes in datum values are detected, it may be decided to artificially correct the data for this change. Such adjustments are often performed manually and may be prone to error. A rigorous change control process will be needed and this should include recording an account of why the change was considered appropriate. This may require checking processes to be specified and/or undertaken as part of the monitoring site management (e.g. the specification of planned maintenance regimes for equipment, the routine management of a schedule of manual checks on survey datum points, etc.).	✓		✓	✓		✓	
Unit conversion	Errors have arisen from the incorrect conversion of results from one unit to another. This may be an issue for contractors who have been working in different cultures and are used to other units. It may also be an issue with software developed in another country. The main defence is good-quality control coupled with awareness of the risk.				✓	✓	✓	
Convention errors	A common error is failure to confirm that a reporting convention is being applied correctly. This risk particularly applies to automated systems with computerised data processing. More than one tunnel				✓	✓	✓	

Issue	Problems experienced on previous projects	Likely root causes						
		Specification	Design	Procurement	Management	Operation	Human factors	Equipment
Convention errors – continued	settlement monitoring system has been found to report a heave when the ground first started to subside. The operators are often then inclined to start trying to explain why the apparent behaviour is counterintuitive rather than beginning by critically challenging the data. These problems can generally be avoided by effective whole-system testing during commissioning of the monitoring.				✓	✓	✓	
Sensor disturbance or replacement	Some monitoring systems will require routine 're-setting' during the life of the project. Examples include survey of railway track which may require re-baselining following rail replacement, ballast tamping or adjustment of displacement transducers once they have attained their maximum extent of travel. In past projects, such events have resulted in false alarms or prolonged periods of downtime in the monitoring system while corrections were made. Events of this nature should be considered during design and provision made for rapid adjustments in the data-handling system. Where such events result in a need for artificial changes to the data, a rigorous change control process is required, which must include recording the reason for the change.		✓	✓	✓			
Fail-safes	The manner in which a monitoring system responds to a failure of any of its components must be appropriate and proven to be so before it is critical. Assuming failure will not occur is not a viable alternative to planning the response to a failure. In addition to spontaneous instrument failure, monitoring systems have been known to fail for a variety of reasons including loss of power supply, loss of contact with a sensor, loss of internet/SMS signal, obscured lines of sight, data corruption, vandalism and loss of equipment due to fire or theft. In the failure to acquire data, there should be a response to each event and traceability of action arising from it. The response must ensure that the appropriate level of safety is maintained.	✓	✓	✓	✓			
Key personnel absence	Increasingly, projects rely on highly automated systems. These systems are often inherently complex and require specialist knowledge not always found on a construction site. If the system programming is understood by only a single member of staff who obviously requires sleep/weekends/holidays or who may fall ill and cannot then be raised at critical times, the system is deficient.				✓		✓	

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Appendix D
Monitoring report example

Figure D.1 provides an illustration of a weekly monitoring report from a project. It provides basic information about works progress and settlement monitoring results in a graphical format intended to be suitable for electronic distribution to interested parties.

Underground construction projects will often have some requirement to provide regular update reports on progress of the works and monitoring observations. These reports may be of use both to the project team and to third parties who may be affected by the work. A single report format may be adequate for both groups.

A good report will have a number of characteristics. The report should be issued at a regular frequency so that interested parties know when they will receive the update. Ideally, the report will be sufficiently frequent and detailed to minimise the number of ad hoc enquiries with which those undertaking the monitoring have to deal. A weekly report in a consistent format issued on the same day each week has been found to be appropriate in many cases. Most such reports will be issued by email to a predetermined list of recipients. As an alternative, some projects may make available internet access to allow interested parties a read-only view of summary information from the system.

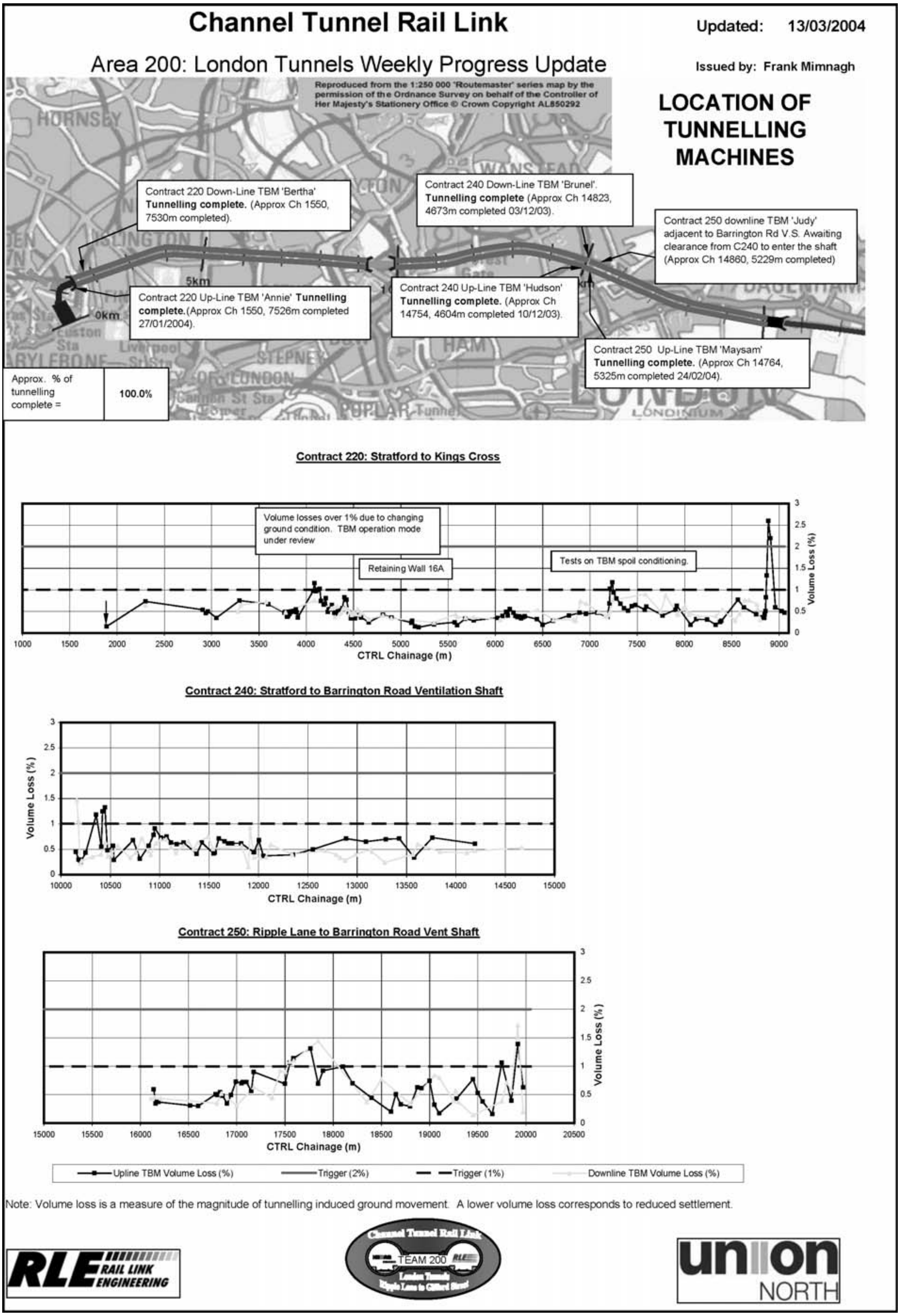
The report format should be clear and concise. It is often best to filter data down to key results which can be displayed on a single page and which are in a layout which can be readily printed by the recipient. Reports consisting of multiple pages of tabulated numbers may convey less than a few simple trend graphs.

The content of the report may typically include

- the name of the project
- the date/time of the report
- a summary of works undertaken in the period covered
- key monitoring observations, including measurements with stated units
- any trigger values that have been exceeded
- the name of the person and organisation responsible for preparing the report.

An example (Figure D.1) is provided of a weekly monitoring report from the Channel Tunnel Rail Link project in London. It was found that once this report was developed and adopted, the number of enquiries to the project engineering team from third parties was substantially reduced.

Figure D.1. An example of a weekly monitoring report from the Channel Tunnel Rail Link project in London



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Appendix E
Case studies

E1. Monitoring case study 1

This appendix contains a series of case studies to demonstrate the diversity of monitoring undertaken in underground construction.

Description

As part of a 9.5 km long new metro line, a 3.8 km underground twin-bore railway with three large cut-and-cover stations is being constructed beneath a busy, historic inner city environment (see Figure E.1).

Affected parties

- Building owners/residents.
- Utilities: gas, electricity, potable water, foul and storm water, telecoms (including fibre optic).
- Railway operations.
- Municipality: tram and bus operations.

Monitoring solutions

Sensitive conditions placed high demands on settlement control and monitoring of structures potentially affected by the works, requiring a number of primary and secondary monitoring systems.

- Remote data capture (RDC) instrumentation including robotic total stations (RTS), in-place inclinometers (IPI), rod extensometers and piezometers.

Figure E.1. RTS being used to monitor movements in an urban environment

- Manual data capture (MDC) instrumentation including precise levelling, inclinometers and piezometers.

Data handling

- RDC with radio network to monitoring contractor's office.
- MDC downloaded from instrumentation storage media at monitoring contractor's office.
- RDC and MDC data checked, validated and processed; processed and raw data uploaded to client's geographic information system (GIS).
- Web access to monitoring data in GIS by authorised parties (designers, contractors).

Notable features

- Scale and programme of the project allows reuse of IPIs and extensometer heads. Initially installed to cut-and-cover station sites, recycled to bored tunnel drives and reused as tunnelling progresses. Recycling of reflector-less RTS along trace.
  - 80 RTS installed on key building facades, taking readings from over 6300 prisms installed to over 1200 buildings, bridges, rail tracks and quay walls plus over 2800 reflector-less readings.
  - Precise levelling to over 2400 building points and over 2000 ground monitoring points.
  - Remotely monitored sub-surface instruments (IPIs, extensometers and piezometers) installed to over 6 km of boreholes.
- Public interface makes monitoring data available to affected parties via independent municipality organisation set up to assess damage claims by affected parties.
- Monitoring contractor and monitoring team (client) independent of main construction works contractor.

E2. Monitoring case study 2

Description

Tunnel boring machine (TBM) bored tunnel crossing under newly constructed Channel Tunnel Rail Link (CTRL) segmental running tunnels (see Figure E.2). Cover between tunnels c. 17 m with angle of crossing at 75°.

Affected parties

Railway operations in CTRL.

Monitoring solutions

Combination of methods used to monitor the running tunnels include

- comparison of before and after 'wriggle' surveys undertaken using manual observations
- surface settlement monitoring using manual observations
- real-time monitoring of track distortions in CTRL tunnels using electrolevels.

Data handling consisted of manual input from the two manual survey methods and automatic data capture from the electrolevels. Data was sent to a web-based handling system via a radio link on surface in vent shaft. A back-up system consisting of a modem was installed in case of radio link failure.

Features and outturns

Notable features of this monitoring system include

- access not available 24/7; installation and maintenance times were limited to night-time access during non-operational hours
- coordination of manual and automatic data from different sources
- CTRL traffic unaffected and real-time data enabled the asset owner to have confidence in the tunnelling process.

Figure E.2. Installing monitoring in CTRL tunnel during maintenance period

E3. Monitoring case study 3

Description

TBM-bored tunnel crossing under brick-lined waterway tunnel (Figure E.3). Approximately 34 m cover between tunnels with a perpendicular crossing.

Affected parties

British Waterways boating operations.

Monitoring solutions

The monitoring solution employed was manual trigonometric levelling. A series of prism mounting points were established within the tunnel and surveyed using a total station mounted on the tunnel wall. Data capture was by data-card in theodolite then downloaded to PC in office. A simple spreadsheet reporting system was emailed to stakeholders for review.

Features and outturns

Notable features of this monitoring system include the following.

- Monitoring system had to account for presence of protected species of bats within tunnel.
- All monitoring system components had to be demountable (including targets) due to clearance for passing traffic.
- Access problematical; all readings were undertaken from a boat; tunnel closures had to be managed by survey party.
- Predicted damage of less consequence than overall movements.
- Canal traffic unaffected by working closely with the asset owner.

Figure E.3. Surveyor using Theodolite in a canal tunnel

E4. Monitoring case study 4

Description

Open-cut works impacting on brick-lined underground reservoir. The wall of the reservoir needed to be monitored to ensure the integrity of the brick structure.

Affected parties

Utilities: potable water supply from reservoir.

Monitoring solutions

The solution employed was to monitor the embankment of the reservoir. An automated system was employed to monitor survey targets embedded in the embankment. Data capture was automated and fed by radio link to office-based PC with data-handling facilities. PC was available to all stakeholders.

Features and outturns

Notable features of this monitoring system include the following.

- Monitoring system eliminated H&S risk of working continually on embankment slope, as would have been the case with manual levelling techniques.
- Coverage of monitoring was also increased by automated means.
- System was programmed by site surveyor, so maintenance/repair function was not onerous with resource readily available in case of problems.

H&S risk of working on steep slopes was mitigated by this method of monitoring. The coverage and frequency of the system was increased by the use of automatic means and by utilising an office-based PC to receive the information. Confidence in the stability of the asset was maintained throughout the works.

E5. Monitoring case study 5

Description

Use of hand-excavated timber headings to form connection between newly constructed and existing London Underground (LU) assets. Initial guidance on support measures resulted in apparently excessive support requirements, so the support was sized on realistic design assumptions which were backed up by monitoring of excavation as the work proceeded.

Figure E.4 shows the installation of a hydraulic flat-jack installed between the crown bar and a purpose-built concrete plinth within timber heading. Curvature of the Spheroidal Graphite Iron (SGI) lining of the existing asset can be seen.

Affected parties

LU Operational Assets; Network Rail Operational Assets.

Monitoring solutions

The solution employed was to monitor the ground loads on the timber-lined excavation and how they developed with time. Flat-jacks were installed beneath the crown bars within the crown of the excavation and manual readings were taken on a twice-daily basis. Data handling was undertaken by the site team who submitted the results to the designer on a daily basis.

Features and outturns

Notable features of this monitoring system include the following.

- Lengthy approval period not only from asset owner but also from owners of overlying assets (Network Rail).
- Monitoring was in crown of ongoing excavation, so access had to be planned by the construction team.
- This monitoring system enabled the design input parameters to be verified and these were then used across the project with the end result of rationalising timber support member sizes.

Figure E.4. Typical example of where monitoring could be used in a heading

E6. Monitoring case study 6

Description

Cross-passage construction between running tunnels on large TBM-driven tunnels in London; focus on temporary works (see Figure E.5(a) and (b)).

Affected parties

Stakeholders include utility companies, Network Rail and London Underground.

Monitoring solutions

Several methods were utilised, including the following:

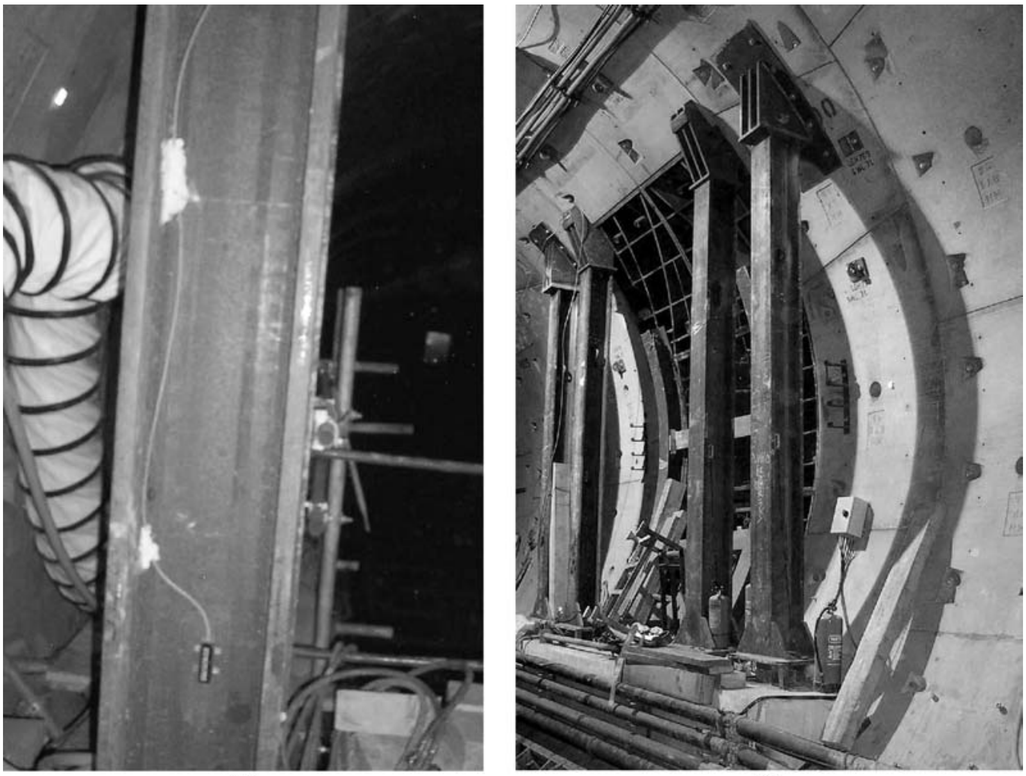
- strain monitoring was used on temporary props to measure any changes in loading to running tunnel linings
- diametric measurements across the running tunnels using tape extensometer were made
- visual observations of the works were made twice daily
- trigger levels were set to define action levels to alert changes in loading around the new opening during construction. An amber response indicated that the face area of the excavation should be reduced and the frequency of the monitoring increased. A red response indicated that the excavation should be secured and work stopped. A watch was to be maintained on the running tunnel and cross passage while monitoring frequency was again increased.

Features and outturns

Notable features of this monitoring system include the following:

- diametric measurements were timed to avoid segment and grout trains
- concerns with temperature effects on strain measurements
- works successfully completed (all 29 cross passages)
- measured load was demonstrated to be much less than capacity of propping system provided
- relatively constant temperature in the running tunnels negated any concerns with temperature effects
- no amber trigger level was exceeded on any of the 29 cross passages.

Figure E.5. Temporary propping of an opening in a tunnel lining. Strain gauges attached to steel columns



(a) (b)

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Appendix F
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Page locators in *italics* refer to figures separate from the corresponding text.