Client Guide

Instrumentation and Monitoring

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RICS

THE SURVEY ASSOCIATION

Definition of terms

Activity
The construction, development or aggravating operation.

Asset
The item or feature to be measured, such as a wall, bridge, railway or building.

Global Navigation Satellite Systems (GNSS)
GNSS is the overall term for positioning satellite systems such as GPS, GLONASS, Galileo and BeiDou.

Impact assessment (IA)
A report that covers geotechnical analysis and live and dead loading effects. It covers the existing capacity arrangements and how they affect structures. Predicted movements are quantified to help define associated trigger and action levels. The report will commonly be referred to as a 'structural IA' or 'settlement IA'.

Instrument and monitoring (I&M)
I&M is a commonly used abbreviation for the particular instruments and monitoring systems to be used.

Instrument and monitoring plan (I&M plan)
A report produced for the client by the designers involving the structural assessment team, geotechnical and I&M specialists covering the recommended instruments and monitoring methods to be used.

Movement
This can refer to x, y, z, angle, rotation heave, settlement and displacement.

Zone of influence (ZOI)
The identified area that will be affected by the activity. Specialist structural engineers and geologists would need to be consulted to determine the ZOI.

References and sources of information

Measured surveys of land, buildings and utilities: Client requirements guidance note and specification
RICS 3rd Edition, ISBN 0 85406 539 3

Geotechnical investigation and testing: Geotechnical monitoring by field instrumentation
General rules
ISO 18674-1: 2015

Geotechnical investigation and testing: Geotechnical monitoring by field instrumentation
Part 2: Measurement of displacements along a line: Extensometers
ISO 18674-2: 2016

Geotechnical investigation and testing: Geotechnical monitoring by field instrumentation
Part 3: Measurement of displacements across a line: Inclinometers
ISO 18674-3: 2017

Contents

1. Preface

This first edition of the Client Guide to Instrumentation and Monitoring has been prepared to assist those associated with the inception, design, management and undertaking of monitoring projects. It has been compiled by public and private industry experts along with instrument and software manufacturers.

The aim of the guide is to consider the common questions posed by clients, designers and contractors during a monitoring scheme – from the initial inception through to installation. As with all projects, it is important that a solution is right first time; is cost-effective; sets out to achieve objectives; and adds value to a project.

In a fast-moving world, technological enhancements and innovations offer various solutions for monitoring, but what remains paramount is the fundamental understanding of what you are monitoring and why. Various questions will be posed within this guide that provoke thought, debate and solutions, as well as raising an industry awareness of the equipment and monitoring systems on offer.

It is hoped that this best practice reference guide will contribute to transparency as well as enhanced collaboration between all parties involved on a project. Individual professionals shall have the responsibility of deciding upon the appropriate final choices and criteria to meet project requirements.

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Thanks are expressed to the equipment suppliers, manufacturers and monitoring companies for supplying images and equipment data information; Trimble, Leica Geosystems, Topcon, RST Instruments, Imetrum, Telespazio, Gete and Geotechnical Observations.

2. Introduction

This document is a guide for clients to select the most appropriate monitoring scheme and allows them to formulate both general and specific project requirements. This initial information will then allow a monitoring specialist to propose, design and implement an optimum solution with the advantage of being aware of the technical systems as well as advances in technology.

It will be important that the project team understands the scale of movement predicted (usually through an impact assessment, including the zone of influence) and the size of movements to be detected. An understanding of the capability and capacity of an asset is required to determine if any movement is likely to cause a detrimental effect that could interrupt operations.

3. Terms of reference

Monitoring can take many forms; environmental, geospatial or geophysical. All are important in gaining a full understanding of the factors at play in a given location. The focus of this document will be geospatial monitoring, concentrating on settlement monitoring and the movement of assets.

4. Purpose

Why do we monitor?
Protecting our national heritage is of paramount importance, especially the history that it represents. The regeneration and restoration of assets using innovative and challenging design and build processes needs different solutions as technology and techniques advance. Linked to this is protecting the assets we already have, such as listed and heritage buildings. Any new works must not have a detrimental effect on their structural integrity.

It will be important to observe movements that the client and designers deem to be of critical importance. This can be controlled by a previously known asset identification list and the operational working tolerances that apply. Escalators and railway tracks are examples of operational assets that would have key safety movement band tolerances pre-identified.

Providing accurate and precise monitoring systems that deliver data representation, analysis and interpretation of results is important so that we can understand the relationship between construction activities and any potential deformation movement. The information collected allows:

- Lifecycle planning and preventative maintenance of an asset.
- Movement trend analysis to confirm behaviour and design model predictions.
- Recording for the operations manual and project archive purposes.
- Statutory duties to be performed.
- Preparation of safety cases.
- Safeguarding of existing buildings and other adjacent facilities.
- Assurance to relevant stakeholders.
- Value for money while delivering added value.

5. Scope of monitoring

When considering the scope of monitoring, the client and monitoring specialist should ask:

- What are the site extents and the zone of influence (ZOI)?
- What accuracy is required and at what intervals or frequency are measurements and readings required?
- What is the rate of predicted change and movement?
- What is the expected duration of the monitoring activity?
- How long does the baseline monitoring period need to be before activities start?
- Is there a monitoring and risk mitigation plan for during and after activities?
- Is there a long term monitoring plan accounting for residual movement?
- What measurement techniques and equipment will be used?
- Is there an absolute or relative monitoring requirement?
- What software and data formats will be used?
- What kind of interface will display the report? Will it need to be available on a web portal?
- What are the trigger thresholds? Keep in mind that a factor of safety may be required to protect against instrument error.
- What reporting systems and actions need to be in place?

Safety
Consider risk reduction for any unplanned additional time for delays; increased costs mitigation/avoidance; and health and safety guidance to the workforce and public.

Risk planning
Allow for risk management and forward planning to mitigate delays and avoid increased costs. Consider what liabilities could or would be associated with the works and any potential movement detected.

Asset management
Review the asset in relation to its long term structural health monitoring, beyond any associated works deemed to have any movement influence. This could be in relation to the design life of an asset which is extended; long term environmental effects which may increase fatigue in a structure, such as a bridge, or safety critical assets, such as a steep railway embankment or cutting, which could have a greater risk of failure.

6. Information required to establish an initial assessment

6.1 Identifying the asset

Location
The asset location should be provided in a detailed description using aligned referencing consistent with the asset owner's numbering or reference system. Plans, photographs and maps are key to identifying the asset location in relation to its environment and physicality.

The asset and its condition
A detailed description of the asset type should be provided that is sufficient enough to identify what features require monitoring along with their current condition.

Note: The accuracy band table in Appendix A (Table 5) should be reviewed before completing Table 1. Further consultation with other experts to attain anticipated movements of geological features and structures should be undertaken.

Asset	Required	Accuracy band required	Comments
Buildings			
Earthworks (cuttings/embankments)			
Walls (inc retaining walls)			
Railways			
Roads and highways			
Bridges			
Tunnels and subways			
Underground utilities and services			
Dams and embankments			
Coastal erosion and beaches			
Archaeology abstracts			
Other (specify)			

Table 1: Assets to be monitored.

Interested parties
All interested parties and stakeholders should be described, be they the immediate asset owner, companies/persons involved with works or changes to the asset or a third party.

6.2 What type of movement are you interested in?

The interested party should provide a brief outline of the type of movement expected. For example, vertical movement, horizontal movement or a combination of both; or movement parallel or perpendicular to site gridlines or in relation to a particular asset or structure, such as a railway line, retaining wall or river. This aids the interpolation of the data.

Furthermore, for data analysis purposes, it is common practice to quantify these movements as displacements, be they longitudinal (perpendicular), lateral/transversal (parallel) or, in the case of tunnel monitoring, described as sectional change.

Movement type	Required	Compliant equipment	Comments
Horizontal		Extensometers; global navigation satellite systems (GNSS); interconnected tilt sensors; shape accel arrays (SAA); tape measures (offset markers); terrestrial laser scanners; total stations (manual and automated)	
Vertical (settlement/heave)		Extensometers; global navigation satellite systems (GNSS); interconnected tilt sensors; interferometry; laser alignment systems; precise levels; shape accel arrays (SAA); total stations	
Rotational (about the Z axis/twist)		Accelerometers; gyroscopic devices; photogrammetry (camera and image-based); total stations; video monitoring	
Tilt (about the X or Y axis/ inclination)		Inclinometers; plumb lines; tiltmeters	
Vibration		Accelerometers; geophones; velocimeters	
Crack/joint expansion		Calibrated digital images; crackmeters; digital calipers; laser scanners (manual and automated); non-invasive systems; tell-tales; total stations	
Strain		Calibrated digital images; fiber optics; potentiometer; strain gauges	
Convergence		Shape accel arrays (SAA); tape extensometers; tilt sensors	
Combination of any of the above to provide validation		Calibrated digital images	
Other (specify)		Environmental monitors; noise and vibration monitors; weather stations	

Table 2: Movement type and compliant equipment.

7. Commencement and lifespan

7.1 Influences on the asset to be considered

Unmanageable influences

Weather factors, such as rain, wind, temperature and sun, will affect the movement of the asset. Movement can also come from other external factors, such as tidal river loads, the ground water table and peak hour traffic. The combination of these can be termed seasonal effects and/or environmental trends for which the implicated baseline monitoring period should be undertaken over a sufficient time period to establish background information. Evaluation of this information will aid understanding of movement trends over time. 'Acts of God', such as natural disasters (flooding, storms, droughts, tectonic activity and so on), may have significant effects on any system – both in displacement and function. These normally cannot be accounted for in the predictions, however, a pre and post-event analysis could be undertaken to quantify their effect.

Manageable influences

Passive and dynamic loads could affect the asset.

- A passive (dead) load such as a stockpile adjacent to another part of the asset could cause influence.
- A dynamic (live) load such as differing amounts of traffic on a bridge at different times of the day or days of the week would cause a dynamic influence.

Development and construction activities

Construction, refurbishment or demolition of another asset or buildings within the zone of influence can affect movement. This needs to be considered relative to the project lifecycle, designs for works and the monitoring specification.

Change to existing conditions

When the use of an asset or an adjacent asset alters, this can have an influence on the asset's movements and needs to be considered and accounted for. For example, this could be moving road or rail traffic on another part of a bridge, the closure or opening of an office floor, or the removal of bridge structural components for refurbishment.

7.2 Why is the asset being monitored?

Various scenarios may be considered in answer to this question. However, some possible explanations are:

- Is the asset identified as being 'safety critical' and being monitored to ensure it is not operationally affected during the activity period? (An example of this would be railway track movements and clearances).
- Is the change to the asset affecting a third-party asset in the activity period? (This could be related to managing risks associated with the asset or a third-party asset that are covered by an insurance policy. By installing a monitoring system, it may allow the negotiation of better insurance premiums for risk liabilities.)
- Is it to provide assurance and confirm movements do not exceed predictions?
- Is it to give confidence that the asset is complete during and after adverse weather?
- Is it to keep an infrastructure route open?
- Is it to understand the rate of change of an asset?

Note: Where a new third-party asset is identified, it is necessary to re-appraise the asset from the beginning again.

7.3 What elements of the asset should be measured?

Specific points of interest

Any critical points or points of interest should be identified so that the designs for monitoring schemes incorporate these.

Size of the asset

To ensure the extent of the asset is fully identified, the original foundation design drawings should be reviewed.

Amount of change in the asset

Is the measurement area going to be the same at the beginning through to the end? Demolition, refurbishment and construction nearby can remove or introduce new areas where the asset will have a requirement to be monitored. How will phases of works affect the asset as they progress? Will any monitoring be viable for the lifecycle of the project?

Zone of influence or item to be monitored

The zone of influence (ZOI) and features to be monitored should be identified clearly before planning any scheme. It is critical to identify any overlapping ZOI or monitored items. In addition, an impact assessment report may identify 'hot-spots' within a ZOI, for which the largest movements are predicted. In these situations, there may be opportunities to maximise operational efficiency and design the instrumentation and monitoring (I&M) plan so that the proposed monitoring focuses on these key areas in a different way. The continuous review of the collected monitoring data may enable analysis of actual data versus the predicted data, and so change the ZOI as the activity progresses. This enables a lean and proactive scheme relative to the ongoing activity. This may increase or decrease the requirements in particular areas with the agreement of the client, asset owners or third party.

8. Requirements of the scheme

8.1 Duration

The duration of the scheme must be linked to the proposed activity. Consider whether unmanageable and manageable influences are going to be contributory factors to the duration. Pre and post-activity monitoring should be considered, and allow for the design, procurement, installation, commissioning and decommissioning of the monitoring scheme. The duration may be impacted by the scheme design and whether it is automated or manually measured and processed.

8.2 Frequency

The frequency of measurement must be directly linked to the works activity or expected rate of change of geotechnical movement. Measurements should be at the highest frequency for the baseline readings or when the likely influence from the activity is at its greatest. The frequency rates are subject to change due to actual and anticipated movement rates. The rate of predicted change may also govern the monitoring data collection method between real-time automated and manual.

Table 3 concerns typical frequency requirements.

Frequency	Relevant activity	Required	Comments
Constant			
Hourly			
Daily			
Weekly			
Monthly			
Quarterly/seasonally			
Annually			
Other (specify)			

Table 3: Monitoring frequency.

8.3 Units and type of change to be measured

The units of measurement and their display should be identified to assist in interpreting the data (such as millimetre, angle, a combination of millimetre per metre, or even unitless like microstrain).

Note: Movement parallel or perpendicular to a particular asset such as a railway line or river aids with interpolation of resultant data.

Relative change

Relative change is change to an object or to assets relative to each other within the zone of influence (ZOI). Measurable points can be established on the structures in question but do not necessarily have to be referenced to stable monuments outside the ZOI (although this may be helpful in background corroboration that genuine and real movement has happened at a point in time within the ZOI). Relative movement is then reported. (An example of this would be the amount of sag of a steel beam from its initially monitored position.)

Absolute change

The absolute position requires geospatially referenced x, y, z, θ, ψ, φ (east, north, height, yaw, pitch, roll) values related to a defined grid and/or height datum. In these situations, stable permanent ground markers (PGM) may be established or keyed into solid rock so that they are independent of any on-site structural movement within the ZOI. Alternatively, a fixed reference frame outside the ZOI that could be used to determine change would be of use. (For example, GNSS-based for coordinates, particulate PPM calibrated sensors for environmental, or beam calculations where both ends are out of the ZOI.) There should be sufficient quantity to allow determination of whether the reference frame or the asset is changing. Such a dataset may also be used for other tasks across the duration of the project and after.

Note: Coordinate-based monitoring system surveys should be connected to a local project grid, such as Snakegrid or a national grid system. (For example, the squat in a tunnel that requires the true position to compare with the activities or assets above ground and relates to an off-site fixed datum.)

Geospatial monitoring data will be collected in a homogeneous coordinate system to facilitate the comparison of results and to provide a dataset that can be used for different tasks across the duration of the project and after. This will ensure the possibility of comparing results and set alarms and alerts on multiple sensor results to provide redundancy and the maximum level of reliability.

8.4 Reporting interval

The reporting interval may differ from the measurement frequency and can be at such an interval as to ensure that any trends are identified, rather than individual data spikes (outliers) causing immediate alarms. For example, reporting change may be required every 24 hours yet the measurement frequency may be every four hours to measure more than the minimum required data. However, in different phases of the activity, the measurement frequency may change relative to the risk or likelihood of movement due to different activities on the asset. These should be planned at the scheme design stage.

8.5 Triggers, alerts and limits of predicted or acceptable movement

It is imperative to understand the limits of movement of each asset. The client should ensure that its specialist consultants and design team advise on the predicted and acceptable movement of each individual asset.

The designer, contractor and monitoring specialist should prepare action plans and/or emergency preparedness plans (EPP) in association with the impact assessment and baseline monitoring data. These shall be produced for each asset owner or stakeholder (such as Network Rail, Transport for London, utility company or building owner). The designer will specify the trigger values for each movement type and the actions that will be undertaken in the event of a breach being triggered. These will be agreed with any affected stakeholder. An example trigger level and action flow diagram is provided in Appendix F.

9. Data management system

9.1 Objective

The data management system may be required to have capabilities to include data from geospatial (such as total stations and precise levels), geotechnical (such as piezometers, extensometers and earth pressure cells), environmental (such as air, dust, noise and vibration monitors) and construction instruments and sensors (such as tunnel boring machines, graders and roadheader drills) within one platform. It should also include progress and commentary on works activities. The platform should allow the user to track cause, effect and magnitude.

It may also require information about the surroundings (such as factual details for hazards, sensitive structures, borings, samples and tests). Predictions from ground modelling or calculations to allow movements to be compared with expectations may also be needed.

The system should reduce the time spent on data processing following data collection and increase the time spent on data analysis.

9.2 Key requirements

The identified data management system may be required to have the following capabilities:

- Fully web-based using technologies with proven future proofing.
- Dedicated database storage servers (local project based and web-based via FTP).
- Flexible data transfer options via LAN, FTP and Wi-Fi.
- Accessible over all devices on 3G or better connections.
- Secure and allow local mirroring to reduce reliance on web connection and back-up of data.
- Designed and proven for the data volumes required and Internet speeds envisaged.
- Accept raw data and independently process data to provide complete data transparency.
- Interoperable: Accept data from a variety of data sources and formats covering the majority of all instrument, construction, investigation and design output types.
- Store original files provided and track all changes to data values and settings and reasons for changes.
- Allow configuration by the end user, without reliance on the system supplier for any data type, configuration, calibration, calculation, graph or report.
- Allow distributed pre-processing, if required, to handle high volume data.
- Have built-in audit, quality control and filter functions to ensure high quality of data release to the wider project.
- Flexible and efficient alarm notification and close-out system.
- Hierarchy of permissions to control access to and security of data.
- Map-based with viewing of data in a variety of coordinate systems, such as Snakegrid, local or chainage, level and so on.
- Configurable graph and map plotting and reporting, allowing multiple types of data to be combined in one display.
- Allow ready communication (data extraction from databases) with other software in use on the project, such as programming, building information modelling (BIM), geographical information systems (GIS) and document management, using custom queries and API.
- Automation of common tasks and general reporting.
- Metadata functionality with the collection and recording of information, such as construction history events and photographs tagged to monitoring data.

10. Operational phasing

The operational phasing of a monitoring scheme follows key steps. These are related to the asset and activities. They should be acknowledged and addressed before procurement and used as stage gate testing points to ensure the relevance of the monitoring to the activity on the asset. Appendix B gives an operation phasing process flow diagram and Appendix C details a typical geotechnical and monitoring system design process.

10.1 Selection of monitoring system and method

Selection of a system and method will be based on the previously identified parameters relative to the requirements. It may include creation of an impact assessment plan, design mitigation review and assessment, monitoring plan and supporting documentation, such as method statements and qualitative load assessment of fixtures and fittings.

10.2 Installation

All affected parties shall agree the installation or at least have an approval in principle in place. Practicality of the installation and any lifecycle operation or maintenance should be considered during the planning. Planning can take significantly longer than actual installation time – sometimes in the region of 75% planning, to 25% installation – and would be linked to the complexity of the asset and conformance to client standards. Restrictions and constraints regarding access to assets must be noted, such as railways and highways, during the installation stage and beyond into operation and decommissioning.

10.3 Commissioning

Commissioning requires a quality control process specific to each scheme. Commissioning should include the capture, initialisation and visualisation of data within the report reviewer's deliverable, and any other subsequent databases and datasets.

10.4 Baseline data

The scope and requirement for baseline data capture shall be related specifically to the activity and the specific asset or element within the asset and not copied generically from another scheme.

10.5 Reporting

Reporting of monitoring movements should alert the authorised people in a comprehensive manner providing specific information in relation to the construction timeline and activities. However, a manual check of alert triggers is a wise precaution to avoid unnecessary alerts being sent to authorised people. Typical outputs of a monitoring project are identified in Table 4. Note: Deliverable format types would range from spreadsheets, graphical representations, database, reports (Word, pdf and so on), image files, CAD model files or any combination of these.

Output	Required	Digital deliverable format (if required)	Comments
Supply of monitoring system			
Plan of monitoring points			
Survey report detailing methodology			
Baseline data and historical background movement analysis			
Survey report detailing monitoring point movement			
Tabular/graphical survey results			
Website based results			
Critical tolerance alerts via email/SMS text message			
Installation, decommission and close-out reports			
Other (specify)			

Table 4: Possible monitoring outputs.

10.6 Maintenance and service interventions

Monitoring equipment will require periodic calibration, maintenance and visits for potential unforeseen equipment failure. Accessibility restrictions should be reviewed and if possible mitigated during the initial planning, design and installation stage within a project risk register.

10.7 Decommissioning and reinstatement

Following the cessation of the requirements for monitoring, any installed equipment, unless being left for legacy or long-term referencing, will have to be removed and the original conditions of the environment prior to the initial installation reinstated. The reinstatement works (making good) process should be fully understood – particularly in relation to heritage buildings which may stipulate certain conditions and caveats that could have unforeseen costs.

10.8 Archiving

Data retention must be understood. Data should be readily available and presented in a common data format which is easily accessible beyond the project lifetime and remains potentially usable as background information for future schemes.

11. Equipment and accuracies

11.1 How do we monitor?

Various geospatial and geotechnical techniques and equipment are available to capture millimetric and sub-millimetric measurements. Each is tailored to a specific requirement, condition or environment. A monitoring specialist can advise, supply and install to a project's requirements. Details of typical geospatial and geotechnical monitoring equipment and systems are supplied in Tables 6 and 7 within Appendices D and E.

Integrated systems, with different technologies and sensors, such as total stations, laser scanning, precise levelling, global navigation satellite systems (GNSS) or tiltmeters can improve the reliability and global accuracy of the monitoring solution, providing redundancy and cross checking of measurements from different sources. These are referred to as primary and/or secondary geospatial monitoring systems, and can capture data manually or automatically. Selection of the data capture technique and equipment can be stipulated and controlled by criteria such as project budget, duration, frequency, accuracy, function and accessibility.

All instruments must be checked when they arrive from the manufacturer or supplier, before they are installed and when they are removed for damage or defects (especially if they are going to be used again). Equipment should be stored so that it is not adversely affected by weather conditions.

Various instrumentation data storage and transfer techniques exist and selection of the most appropriate should be advised by a monitoring specialist. In some cases this may be controlled by the environment and location, such as for underground projects. Typical methods of data transfer and storage include:

- On-site data loggers.
- Solar powered GSM gateways.
- Portable readout.
- On-site communication enclosure boxes for remote control or access. (Options include containing cellular modems/routers, industrial PCs, Wi-Fi, ADSL broadband radios, hardwired cable and Bluetooth data transfer methods.)

11.2 System accuracies

For deformation monitoring surveys, the accuracy and precision requirement should be relative to the movement threshold the designer, engineer or consultant analysing the data needs to detect. Table 5 in Appendix A gives an indication of the accuracy bands that can be specified. Only accuracy bands applicable to a monitoring project are provided.
Note: The project team, consultants and client should have a clear understanding of the instrumentation and component accuracies and precision, along with error factors, which when combined result in an overall survey system accuracy. Consultation with a monitoring specialist should be sought during the design assessment review stage for an understanding of the achievable accuracies in real situations, in addition to data stability and repeatability without any filtering or post processing or compensation. This is particularly relevant for environmental or inherent system/sensor performance related factors. This should then be set alongside the cost and quality implications related to the intended survey data use.

11.3 What errors could occur in a monitoring system?

Gross errors
Gross errors are often called mistakes or blunders and are most commonly associated with human error. Company assurance procedures and processes should detect and mitigate this.

Systematic errors
Systematic errors will generally have the same magnitude and sign in a series of measurements and are linked to a constant within the measurement device or related to other physical factors. For example, a wrong prism constant applied to a range of electronic distance measurement (EDM) or an un-calibrated instrument introducing an erroneous distance adjustment. Physical factors such as temperature and pressure, if not accounted for, will introduce further systematic errors. Some lower quality sensors and systems may need data to be compensated for normal external factors such as temperature and humidity swings. These are all repeatable errors in the defined measurement system that may occur due to a method or component part of the system being incorrect or of lesser quality or performance.

Random errors
Random errors remain after the elimination of both gross and systematic errors, and are inherent in all measurements. They are beyond the control of the observer and result from the human inability of an observer to make exact measurements. A good measurement system with adequate redundancy of measurement will minimise the occurrence of these.

Constant errors
Constant errors are independent of the measurement being taken and are made up of internal sources within instruments' accuracies that are normally beyond the control of the user. It is an estimate of the individual errors caused by such phenomena as unwanted phase shifts in electronic components and errors in phase and transit time measurements.

Appendix A. Accuracy bands

Plan accuracy (X, Y)			Height accuracy (Z)			Survey types/uses	Legacy plot scale output required to achieve accuracy band (approx)	Compliant equipment/methods
Band	1 Sigma	2 Sigma	Band	Hard detail	Soft detail			
A	±2mm	±4mm	A	±2mm	n/a	Fabrication surveys; high accuracy engineering; monitoring; setting out;	1:5	Accelerometer; crack sensor; extensometer; hydrostatic levelling cell; precise level; strain gauge; tape measure; tiltmeter; total station
B	±4mm	±8mm	B	±4mm	n/a	High accuracy engineering; measured building surveys; monitoring; setting out	1:10	Accelerometer; crack sensor; extensometer; hydrostatic levelling cell; precise level; strain gauge; tape measure; tiltmeter; total station
C	±5mm	±10mm	C	±5mm	n/a	Engineering surveying and setting out; heritage recording; high accuracy measured building surveying	1:20	Accelerometer; crack sensor; extensometer; GNSS static network; hydrostatic levelling cell; precise level; strain gauge; tape measure; tiltmeter; total station
D	±10mm	±20mm	D	±10mm	±25mm	Area registration; boundary determination; engineering surveying and setting out; high accuracy topographic surveys; measured building surveys	1:50	Accelerometer; crack sensor; extensometer; GNSS network RTK; hydrostatic levelling cell; precise level; strain gauge; tape measure; tiltmeter; total station

Table 5: Accuracy bands from Measured Surveys of Land, Buildings and Utilities, Royal Institution of Chartered Surveyors.

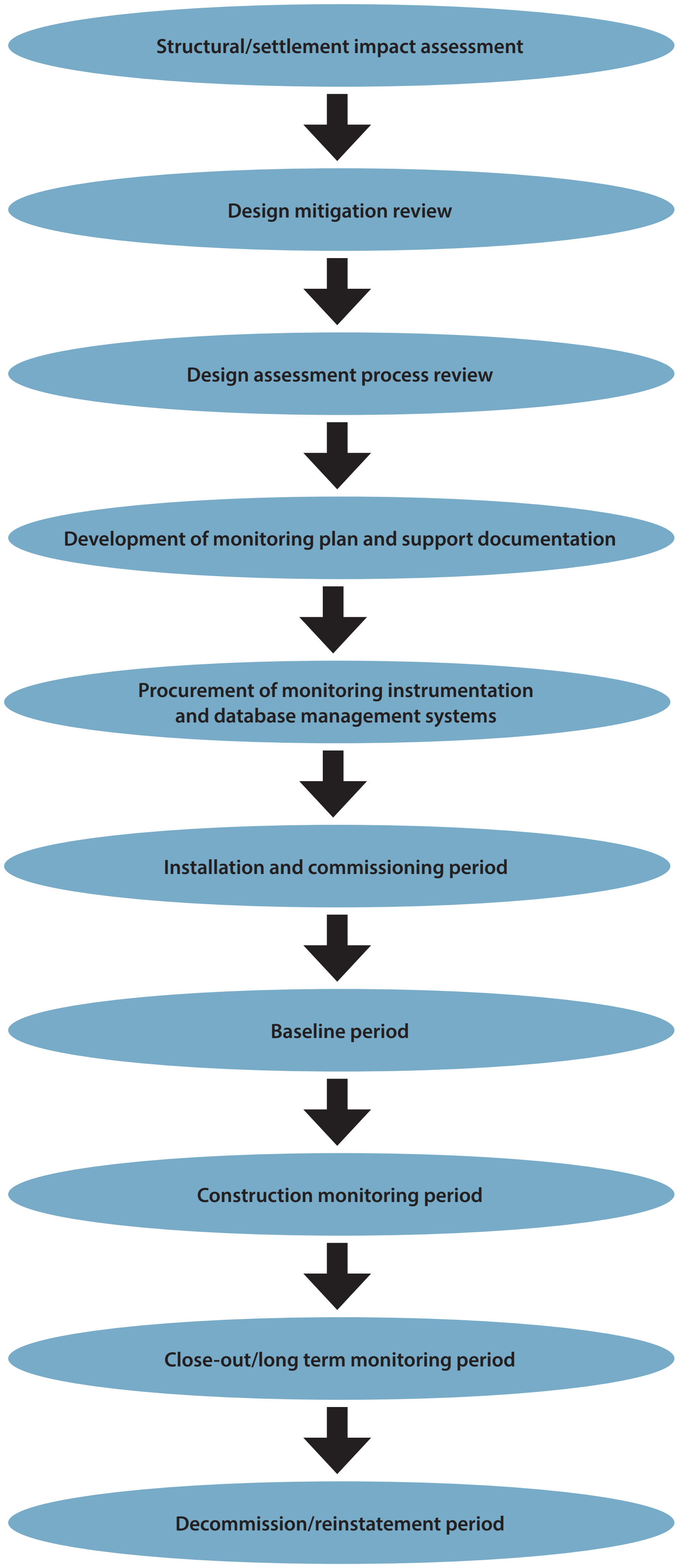
Note:
Bands A and B are generally considered to involve additional work and may incur additional costs.

To create a customised band, select the band letter required and add as a prefix to X, Y or Z (i.e. ±10mm plan = C-XY)

Survey accuracies need to account for the accuracy of the system and not of the individual component. For example, a survey system accuracy of an ATS (automated total station) would consist of the total station angular and distance accuracy; the distance at which the asset is being monitored from; centring accuracy if a forced centring solution is not adopted; and prism constant variation. Each part of the system has an accuracy or standard error associated with it, which as a combination will result in a bespoke accuracy for individual projects.

The accuracy values stated in Table 5 show both 1 Sigma (standard deviation/error) and 2 Sigma values. 1 Sigma accuracy means that 68% of normally distributed observation residuals will fall within the band value shown for 1 Sigma with 95% falling within the 2 Sigma value. Using Sigma accuracy it can be noted that 99.7% of observations will fall within three times the 1 Sigma value.

Appendix B. Operational phasing process



Appendix C. Geotechnical monitoring system design

Structural/settlement impact assessment

- Provision of as-built construction records
- Provision of geological information
- Ground investigation - Trial pits
- Tunnelling trial analysis with surface monitoring
- Pre-construction condition survey with review of category of damage inherent for asset
- Determination of construction works methodology

Geotechnical design and analysis stage

Design mitigation review

- Review process for mitigation measures to reduce possible impacts to assets. Options include:
  1. Reduce movements at source
  2. Carry out non-intrusive adjustment/strengthening
  3. Intrusive strengthening/modification
  4. Replacement of asset

Design assessment process review

- Identification of assets
- Review process of assets to quantify assessment criteria
- Phase 1, 2, 3 assessment identification
- Quantification of movement types

Development of monitoring plan

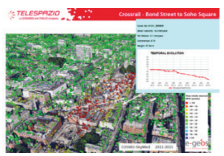
- Design of primary and secondary monitoring systems (automated/manual)
- Selection of monitoring instrumentation
- Selection of monitoring data management system

Monitoring system design

Support documentation

- Instrumentation and monitoring statement
- Action/emergency preparedness plan
- Instrumentation and monitoring team organagram
- Design review and qualitative safe load assessment
- Inspection test plans
- Data capture, storage and display plan
- WPP, TBS, SSOW, permits, applications, permit to load (power) etc

Appendix D. Geospatial/geodetic monitoring equipment

Survey equipment	Outline	Advantages	Disadvantages	Expected accuracy/range, resolution, repeatability
Global navigation satellite system (OSNet/network RTK or static GNSS) 	Tripod, bracket or 'pogo stick' mounted receiver and logger unit. Measures microwave signals transmitted from satellites, and GPRS data sent from OSNet control. Used to observe relative coordinates and elevations. Specific monitoring applications exist (including the VADASE autonomous monitoring system).	Provides global 3D coordinates. Multiple satellites and observations taken over time – provides redundancy. Permanent or semi-permanent stations can be installed with 360° prisms to generate active control points for total station networks. Monitoring GNSS networks can be realised without software/hardware infrastructure investment using SaaS cloud computations. Autonomous and manual method.	Satellite signals can be obstructed or 'dithered'. Will only measure 'snapshot' of points at moment of survey. Data requires post-processing.	Static accuracy Horizontal: 3mm +0.5ppm Vertical: 5mm +0.5ppm RTK accuracy Horizontal: 8mm +1.0ppm Vertical: 15mm +1.0ppm Network RTK accuracy Horizontal: 8mm +0.5ppm Vertical: 15mm +0.5ppm RMSE ±10-20mm VADASE accuracy threshold 8mm/s (E), 12mm/s (N) & 20mm/s (Ht) Accuracy band: C-D
Hydrostatic levelling system (HLC) 	Settlement system consisting of cells connected by hose pipe lines; one for water, the other for air. The airline is left open to allow cells to have the same air pressure. If the cell location moves, the difference in water pressure is recorded and compared to the reference cell.	High accuracy. Automated real-time system. Can be aligned with tiltmeters. Suitable for accessing restricted areas.	Relative change measured only. Vertical movement only. Can be effected by temperature variations.	Accuracy: ±0.3mm Resolution: ± 0.02mm Repeatability/stability ±0.02mm/a Range: 200-500m Accuracy band: A-D
InSAR interferometry 	Active remote sensing technique using radar satellite images to measure surface movement with millimetric precision.	Provides historical surface movement (structures and ground). Optimum for baseline studies in most locations in Europe. Covers very large areas. Optimum for linear infrastructure monitoring and underground construction. All remotely measured, no need to visit the site, particularly in urban environments. Broad measurement scale from large movements (cm) to small movements (mm) with centimetric to millimetric precision. Not light or weather affected. Measurements used to clarify liabilities. Long term monitoring solution after in-situ instrumentation has been removed. Used for selection of benchmark locations for in-situ instrumentation.	Not a real-time monitoring system. The maximum period is four days (COSMO-SkyMed). Depends on radar reflectivity of targets. No changes should occur on targets, difficult to measure with vegetation and surface changes on manmade structures. Corner reflectors (CR) can be installed to improve radar reflection from satellite on the site. Dependent on at least 30 images in the archives to proceed with baseline studies. Commercial satellites need to be tasked if none archived.	Precision vertical Typically ±2mm (±1mm can be achieved depending on quality of target, type of movement and large number of radar images processed (more than 30 and continuous close acquisition dates)) Position horizontal Half of the pixel size Accuracy band: A-D

Appendix D. Geospatial/geodetic monitoring equipment cont.

Survey equipment	Outline	Advantages	Disadvantages	Expected accuracy/range, resolution, repeatability
Laser distance meter 	Handheld laser distance unit. Measures reflectorless distances between points of detail (e.g. reference points, structure).	Fairly accurate distances between points. Easy to use.	Requires operator to hold meter on point to be measured. Will only measure distance between two points. Manual system (can be automated).	Accuracy = ±1mm Resolution = ± 1mm Range = <200m Accuracy band: B-D
Precise levelling 	Traditional technique using digital or precise levels. Digital levels use a special bar-coded levelling staff. Precise levels have a parallel plate micrometer in front of the object lens. Predominately used for 1D (Z) elevation.	Cheap methodology. Very high accuracy (0.2mm) on standard invar staff.	Can be labour intensive. Subject to human error. Pure manual human interactive method. Generally requires two operatives. Dependant on access to monitoring points.	**Digital level** Accuracy ±0.2mm (invar staff) ±1.0mm (standard staff) Per 1km of double levelling Resolution = ±0.0001mm Measurement Range 1.8m to 180m **Precise level** Accuracy = ±0.7mm ±0.3mm (with parallel-plate micrometer) Per 1km of double levelling Accuracy band: A-D
Steel tape measure, Survey rod 	Handheld steel calibrated band or rod. Measures distances between points of detail (e.g. reference points, structure). Best practice use of spring balance to apply loaded tension.	Fairly accurate distances between points. Easy to use.	Requires operator to hold tape/rod on point to be measured. Will only measure distance between two points. Application of corrections for slope, temperature and sag (catenary taping) have to be applied.	Relative accuracy = ±2mm Accuracy band: A-D
Video monitoring 	Video camera technique which can undertake measurements similar to total station, tiltmeter or strain gauge from a remote position. Can measure strain, displacement and rotation.	Remote dynamic system. Non-contact. Real time monitoring option. Ability to amend measurements in post-process mode. Up to 200 measurement points per image in real time, more in post process. Measurement tools include LVDT and rotation.	Reliant on sight-lines	Accuracy = ±0.1mm Resolution = ± 0.01mm Repeatability/stability = ±0.2mm/a Range = 200-500m (ability to measure a 0.4mm displacement on a 30m stretch of bridge from a 700m distance range)

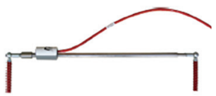
Appendix D. Geospatial/geodetic monitoring equipment cont.

Survey Equipment	Outline	Advantages	Disadvantages	Expected accuracy/range, resolution, repeatability
Terrestrial laser scanning 	Two types of scanner exist; time of flight suited to longer range data capture applications, or phased based which is more suited to medium and short range. Terrestrial laser scanning is suited to detection of plane movement and not vertical movement, such as deforming surfaces like walls.	Inaccessible objects or locations can be measured. Mitigates health and safety hazards. Shorter and faster project cycle times, less ambiguity, multiple data-sets. The technique can be automated and integrated in monitoring solutions with real time surface to surface comparison using total stations with laser scanning capabilities. High intensity point capture.	Processing and data interpolation time increased. Resolution (point spacing) varies on sight-line distance. Only gives a single plane (Z,Y or Z) displacement. Accuracy of distance measurement depends mainly on the intensity of the reflected laser light and therefore directly on the reflectivity of the object surface. The reflectivity depends on the angle of incidence, and surface properties. Can be expensive to hire.	Accuracy of a single point ±3mm at 50m ±6mm at 100m Angular accuracy = 8″ Distance accuracy (single) ±1.2mm+10ppm Range = 270m Accuracy band: C-D
Total station (theodolite with built-in EDM)  	Tripod mounted or bracket mounted digital theodolite with infrared distance unit, used in conjunction with precise glass prisms fixed to ground control survey stations. Measures angles and distances. Reflectorless infra-red distance measurement to remotely coordinate points of detail (reference points, structure). Some offer integration with laser scanning capabilities (1,000 points/sec) and imaging sensors to provide additional information for checking via picture capture of the site and of condition of prisms.	Provides relative 3D coordinates to a high accuracy. No access required. Multiple observations taken over time – provides redundancy. Flexible. Remote observational method. Surface to surface comparison and deformation analysis in real time where prisms are difficult or too expensive to be installed. Can be used in permanent location and/or on manual campaigns. Network of multiple sensors can be realised for improved accuracy. Imaging can save time on site allowing remote visual inspections of the instrument field of view. Autonomous solution allows movement within data to be aligned to temperature, pressure and humidity variations. A history record can be created to predict seasonal variations and trends in real time. Autonomous and manual method.	Only measures snapshot of points at moment of survey unless laser scanning technology is merged in the sensor. Data requires post-processing. Dependant on stable instrument setup. Vertical movements not as accurate as precise levelling. Equipment is more suited to plane movement than vertical movement.	System accuracy ±2-3mm Angular accuracy = 0.5″ Distance accuracy (single) ±0.6mm+1ppm Repeatability = ±1-2mm Range 1.5m to 3500m (prisms) 1.5m-1000m (non-prism) Accuracy band: A-D

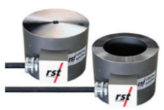
Table 6: Typical geospatial equipment monitoring solutions and options.

Note: RMSE refers to vector errors. RMSE is equivalent to 67% tolerance, and 90% tolerance is 1.65 times the RMSE when a representative sample of points is tested. Thus a RMSE of ±10mm indicates that in a representative sample of 100 points, it is expected that not less than 67 points will be correct to better than ±10mm, and not less than 90 points will be correct to better ±16.5mm.

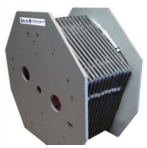
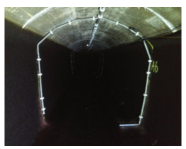
Appendix E. Geotechnical monitoring equipment

Survey equipment	Outline	Advantages	Disadvantages	Expected accuracy/range, resolution, repeatability
Crack measurements (displacement transducers) Crackmeters (automated or manual, wireless or wired), demec gauge, digital calipers, potentiometric/ vibrating wire, tell-tales 	Designed to measure movement across surface cracks and joints. They are installed via grouting, bolting or bonding and have varying levels of accuracy dependant of the user's requirements.	Can be manually read or automated. Can be compatible to wireless solution.		Accuracy = ±0.2% FS* Resolution = ±0.025% FS* Range = 30mm-100mm Dependant on model type Accuracy band: A-D
Distributed strain sensing (DSS) BOTDR, BOTDA, OBR 	Distributed fibre optic sensing allows for real-time measurements at thousands of points along an optical fibre cable, enabling imaging of continuous temperature and acoustic profiles, both in time and space. Distributed temperature sensing (DTS) is the most widely used form. It can precisely measure temperatures up to 300°C every metre along the fibre to an accuracy of ±1°C and a resolution to ±0.01°C. Distributed acoustic sensing (DAS) effectively turns the fibre cable into a series of geophones (or microphones). Distributed strain sensing (DSS) can help to determine deformation location and severity, or provide insight into stresses.	Single cable. Tolerant of harsh environments, immune to electromagnetic interference. Acoustic and thermal data can be acquired from both multimode and single mode optical fibre sensing cables. Long term stability. Soil moisture, waterflow, anchor strain, foundation strain, thermal, acoustic changes in dam tailings.	High cost of data logger in some applications. Data interpretation tools.	Accuracy ±1°C Resolution to ±0.01°C Strain ±1με Temp ±0.1°C Distance between data logger and sensors can be up to 20km
Digital tape extensometers 	Designed to measure small changes in distance between opposite walls or between the roof and floor for excavations, tunnels or mine openings. Can also be used to monitor deformation in structures.	Cheap methodology. Direct measurement.	Manual method. Access dependant. Requires skilled operative.	Accuracy = ±0.01mm Resolution = ±0.01mm Range = 1m-30m Repeatability = ±0.1mm Accuracy band: A-D

Appendix E. Geotechnical monitoring equipment cont.

Survey equipment	Outline	Advantages	Disadvantages	Expected accuracy/range, resolution, repeatability
Magnetic extensometers 	Designed to measure settlement or heave of soft ground under the influence of loading or unloading. Probe is lowered into a guide tube and measures the position of magnetic anchors located around the guide tube at various depths.	Suitable for large movement monitoring such as soft ground geotechnical applications.	Manual measurement.	Resolution = ±1mm Range = 30m-200m Repeatability = ±2mm Accuracy band: A-D
Rod extensometers (manual or automated, wireless or wired) 	Various in-ground types exist ranging from single, multiple and magnetic. The probes are installed within boreholes to varying depths and fixed/anchored at the top or bottom in the case of single or in multiple depth locations.	Easy to install and recessed within a borehole. High accuracy. Can be wirelessly read from a borehole.		Accuracy = ±0.02mm Resolution = 0.01mm Accuracy band: A-D
Fibre optic fibre bragg 	A fiber optic FBG monitoring system consists of a data logger (interrogator), sensors, cables and software for civil structures and geotechnical projects. Tuned for plug and play installation, quick set up and maintenance-free usage.	Electrical immunity (being zero power, they are 100% intrinsically safe and can be used in the most hazardous explosive environments). The flexible architecture of the system allows continuous increases in configuration for higher numbers of measuring locations. Remote sensing. Long-term stability.	Cost of data logger is higher compared to electrical sensors (can be mitigated by multiplexing of higher number of sensors).	Strain ±1 Temp ± 0.1°C Distance between data logger and sensors can be up to a few kilometres
Inclinometer (manual or automated, wireless or wired) 	Required before, during and after construction works. Used for the measurement of lateral or vertical displacement of soil and rock or deflection on manmade structures such as piles or retaining walls and inserted into vertical and horizontal boreholes with pre-determined intervals to create profile sections.	Applied to both natural and manmade structures. Combines an assessment of stability and composition. Can be converted to wireless system above assembly if required.	Data can be difficult to interpret. Requires vigorous calibration and checking.	System accuracy ±2mm over 25m Resolution = ±0.005mm/m Sensor accuracy ±0.01% FS* Accuracy band: A-D
Load cells (automated or manual, wireless or wired) 	Designed for measuring loads in rock bolts, cable anchors and tendons, for monitoring loads in crosslot struts and tunnel supports and load in pull-out tests on trial anchors. Used in conjunction with hydraulic jacks and bearing plates.	Can be manually read, automated and wirelessly read if required.	Installation can require significant preparation of reaction surface/plate. Any load cell and connectivity to gateway or logger potentially prone to damage due to location and site. Wireless system helps but wireless node must be resilient.	Accuracy = ±0.5% FS* Resolution = ±0.025% FS* Accuracy band: A-D

Appendix E. Geotechnical monitoring equipment cont.

Survey equipment	Outline	Advantages	Disadvantages	Expected accuracy/range, resolution, repeatability
Piezometers (wireless or wired) Inc vibrating wire 	Designed to measure fluid pressures such as ground water elevations and pore pressures when buried in embankments, fills etc. Can be used to convert manual standpipe piezometers to automated piezometers.	Read manually or automated, can be wirelessly automated from the top of the borehole.		Accuracy = ±0.1% FS* Resolution = ±0.025% FS* Range = 300-4000 (kPA) Accuracy band: A-D
Pressure cells (automated or manual, wireless or wired) 	Designed to measure earth pressure. Two steel plates are welded together and spaced apart by oil. A change in earth pressure will squeeze the plates together causing an increase in fluid pressure.	Can be either manually or automatically read. Can utilise wireless technology at ground level.	Any pressure cell and its connectivity to gateway or logger are potentially prone to damage due to inherent location and site conditions. Eliminating wires with wireless system helps but wireless node must be resilient.	Accuracy = ±0.1% FS* Resolution = ±0.025% FS* Range = 300-15000 kPa Accuracy band: A-D
Settlement sensors (automated or manual, wireless or wired) Inc vibrating wire 	Designed to monitor settlement or heave in soils and others structures such as embankments, earth and rockfill dams. Systems available range from a simple rod and sleeve, to vibrating wire liquid level settlement and profiler systems.	Automatically provides relative settlements between discrete locations.	Complex installation often requiring significant protection on earthworks.	Accuracy = ±0.1% FS* Resolution = ±0.025% FS* Range = 7-35m Accuracy band: A-D
Shape accel arrays (SAA)  	A sensor that can be placed in a borehole or embedded within a structure to monitor deformation. It consists of a continuum of segments containing tri-axial, micro electro mechanical system (MEMS) accelerometers. Each segment has a known length. By sensing the gravity field at each segment, the bend angles between each segment can be calculated. Using the calculated bend angles and known segment lengths, the shape of an SAA can be determined. SAA can be used to determine 3D shape when installed vertically and 2D shape when installed horizontally.	Can be used in utility tunnels and in explosive atmospheres such as sewers. It must be used with a form of ATEX protection; a flameproof enclosure in an explosive atmosphere. Can be used to monitor tunnel convergence at critical points/locations (i.e. when excavating below the asset), settlement/ heave along the crown or invert of a pipe, tunnel, aqueduct or sewer. Can be installed within concrete slabs in TBM launches or below embankments. Can be installed into inclinometer casings that can no longer be read with a manual probe.	System designed for particular application geometry – difficult to lengthen or shorten.	Accuracy ±1.5mm for 32m (long term >1.5 years) Accuracy ±0.5mm for 32m (short term <24 hours) Accuracy = ±0.0005 radians when within 20º of vertical Accuracy band: A-D

Appendix E. Geotechnical monitoring equipment cont.

Survey equipment	Outline	Advantages	Disadvantages	Expected accuracy/range, resolution, repeatability
Still imaging/camera 	Still image for measuring gross movement. Integrated wireless with tilt sensors on earthworks that trigger images at set levels of movement.	Solar powered; mains power free. Acts as secondary corroboration of potential movement on earthworks. Allows rapid response to stop trains when there is a possible earth slippage on track. Avoids site visits. Day and night viewing possible.	Range of image limited to 50m at night. Designed only for larger movements.	1600x1200 pixels Angle of view 35º wide/25º high with 6mm lens
Strain gauges (automated or manual, wireless or wired) Inc vibrating wire 	Designed for the measurement of strains in and on structural elements. Consists of an electromagnetic coil to provide a pulse and receive a resonant frequency of a wire tensioned between the end mountings of the gauge used for measuring static strains. A common dynamic strain gauge consists of a very fine metallic wire, foil or semiconductor material in a grid bonded to a surface. Variations in electrical resistance of the grid indicate strain.	Can be read manually or automatically. Wired or wireless.	Any strain gauge and its connectivity to the gateway or logger is potentially prone to damage due to inherent location and site conditions. Eliminating wires with a wireless system helps but wireless node must be resilient.	Accuracy = ±0.1%FS* Resolution = 1 Microstrain Range = 3000 Microstrain Accuracy band: A-D
Stressmeters (automated or manual, wireless or wired) 	Designed to measure stress changes in rock. Can be installed in boreholes up to 100ft deep. Consists of a vibrating wire tensioned inside the stressmeter. Changes in rock stress cause a related change in the resonant frequency of vibration of the tensioned wire.	Can be read manually or automatically. Can utilise wireless technology at ground level.		Accuracy = ±0.1%FS* Resolution = 14-17kPa Range = 70MPa Accuracy band: A-D

Appendix E. Geotechnical monitoring equipment cont.

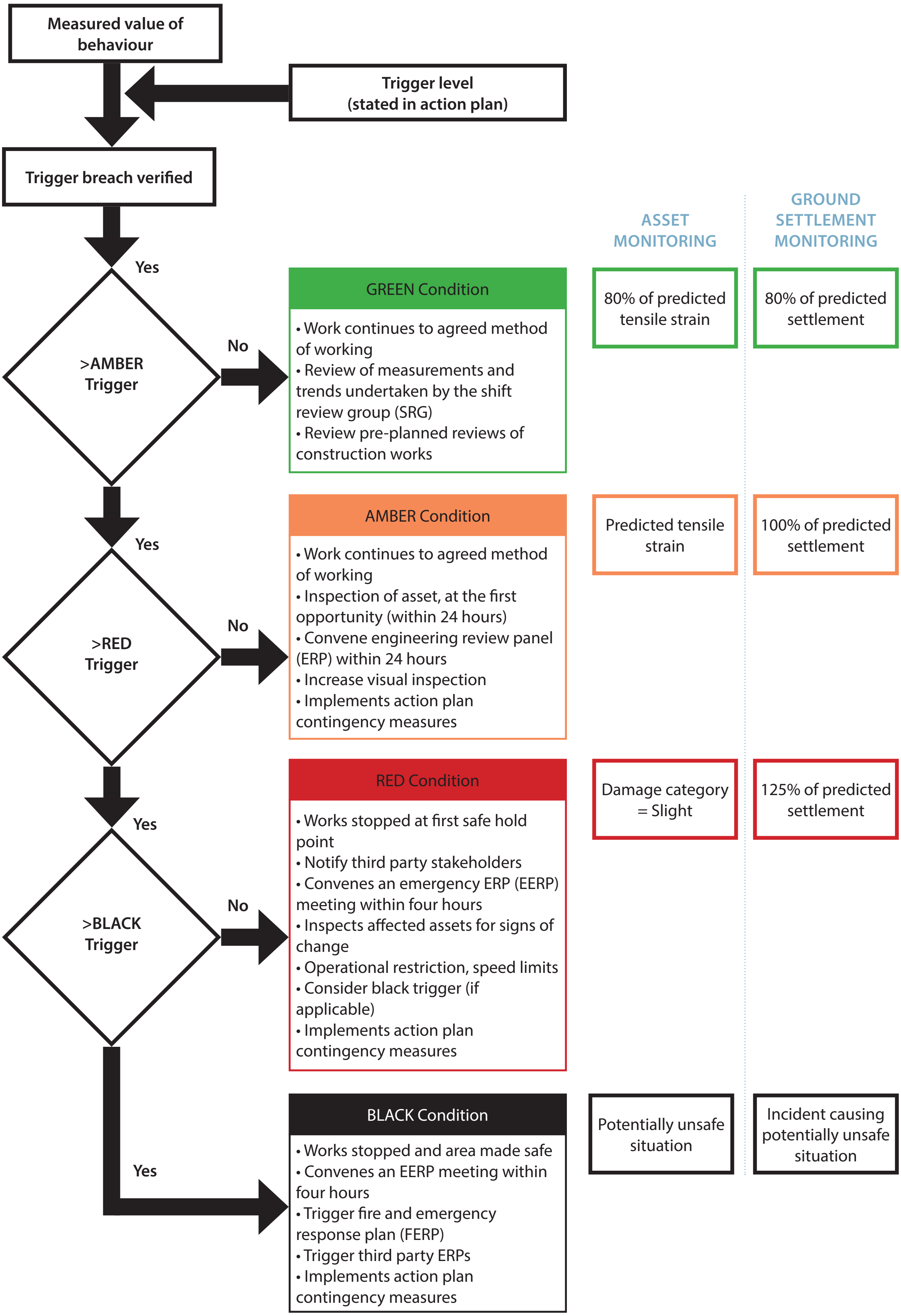
Survey equipment	Outline	Advantages	Disadvantages	Expected accuracy/range, resolution, repeatability
Wireless tiltmeters  	Wireless tilt sensors measure single, dual or tri axis movement. Built-in temperature sensors help understand local conditions. Can be installed in a mesh network and linked to a multi-year solar GSM gateway for data collection, storage and retrieval. Enclosures with IP 67/68 ratings. Fitted with low profile aerials, also options for additional protective caps and aerial free for challenging environments (notably track bed building sites). When combined with real or 'virtual' beams they can provide low millimetre accuracy for longitudinal measurement (settlement and heave) on track and tunnels.	No cabling. Ready commissioned. Long battery life (10-15 years/15-20 minute reporting rates). Remotely adjustable reporting down to 1 second with battery life reduced to circa nine months. Unlimited life solar power systems, plus battery or mains options within same compact unit. Auto fail-safe gateway back-up for connectivity resilience. Wireless connectivity, up to 110 sensors per network, range up to 300m. Adjustable reporting rates. Ease and speed of install for wide range of applications. Any orientation. Not line of sight dependant. Can be attached to interlocking beams and magnetic brackets. No cleaning/calibration/maintenance required after installation.	Range dependant on terrain. Can be liable to drift or exhibit data spikes from temperature, movement or humidity and may need data to be filtered or compensated. Potential aerial damage with longer aerials unless protected or no external aerial.	Bi-axial accuracy resolution ±0.0018mm/m Repeatability ±0.009mm/m Range = 360° Tri-axial accuracy resolution 0.0018mm/m Repeatability ±0.009mm/m Range = 360° Accuracy band: A-D

Table 7: Typical geotechnical equipment monitoring solutions and options.

*FS refers to the full scale of the measurement range capacity of the device that is in use. For instance, a voltmeter has a quoted accuracy of ±2.0%FS and a measurement range of between 0–100 volts. If a readout is 50 volts this means the accuracy of the device is between 48 and 52 volts (±2.0%).

Note. Although specific manufacturers' equipment has been illustrated to give examples, it does not imply a recommendation. Other suppliers may also produce similar kit.

Appendix F. Trigger level and actions



This edition: November 2017

The Survey Liaison Group comprises the Chartered Institution of Civil Engineering Surveyors, Institution of Civil Engineers, Royal Institution of Chartered Surveyors and The Survey Association

Produced and designed by the Chartered Institution of Civil Engineering Surveyors for the Survey Liaison Group