Citation for published item:

Smethurst, J. A. and Smith, A. and Uhlemann, S. and Wooff, C. and Chambers, J. and Hughes, P. N. and Lenart, S. and Saroglou, H. and Springman, S. M. and Löfroth, H. and Hughes, D. (2017) 'Current and future role of instrumentation and monitoring in the performance of transport infrastructure slopes.', Quarterly journal of engineering geology and hydrogeology., 50 (3). pp. 271-286.

Further information on publisher's website:

https://doi.org/10.1144/qjegh2016-080

Thematic set:
COST Action TU1202 – Impact of climate change
on engineered slopes for infrastructure

QJEGH

Quarterly Journal of Engineering Geology and Hydrogeology

https://doi.org/10.1144/qjegh2016-080 | Vol. 50 | 2017 | pp. 271–286

Current and future role of instrumentation and monitoring in the performance of transport infrastructure slopes

J. A. Smethurst[1]*, A. Smith[2], S. Uhlemann[3], C. Wooff[4], J. Chambers[3], P. Hughes[5], S. Lenart[6], H. Saroglou[7], S. M. Springman[8], H. Löfroth[9] & D. Hughes[10]

[1] Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, UK
[2] School of Civil and Building Engineering, Loughborough University, Loughborough LE11 3TU, UK
[3] British Geological Survey, Environmental Science Centre, Keyworth, Nottingham NG12 5GG, UK
[4] London North Eastern (LNE), Network Rail, Floor 3, George Stephenson House, Toft Green, York YO1 6HP, UK
[5] School of Engineering and Computer Sciences, Durham University, Durham, UK
[6] Slovenian National Building and Civil Engineering Institute (ZAG), Dimičeva ulica 12, Si-1000 Ljubljana, Slovenia
[7] School of Civil Engineering, National Technical University of Athens, 9, Iroon Polytechniou Street, 157 80 Zografou, Athens, Greece
[8] Institute for Geotechnical Engineering, ETH Zurich, Rämistrasse 101, 8092 Zurich, Switzerland
[9] Swedish Geotechnical Institute, SE-581 93 Linköping, Sweden
[10] School of Planning, Architecture and Civil Engineering, Queens University Belfast, David Keir Building, 39 Stranmillis Road, Belfast BT9 5AG, UK
S.U., 0000-0002-7673-7346; H.S., 0000-0002-5253-7972
* Correspondence: jas@soton.ac.uk

Abstract: Instrumentation is often used to monitor the performance of engineered infrastructure slopes. This paper looks at the current role of instrumentation and monitoring, including the reasons for monitoring infrastructure slopes, the instrumentation typically installed and parameters measured. The paper then investigates recent developments in technology and considers how these may change the way that monitoring is used in the future, and tries to summarize the barriers and challenges to greater use of instrumentation in slope engineering. The challenges relate to economics of instrumentation within a wider risk management system, a better understanding of the way in which slopes perform and/or lose performance, and the complexities of managing and making decisions from greater quantities of data.

Received 23 August 2016; **accepted** 4 May 2017

Linear earthwork assets in the form of cuttings and embankments are a major component of modern transport systems, and their performance is critical to ensuring transport operations are safe and reliable. Earthwork slope failures pose significant hazard: failures in embankments may undermine roads and railways, slips in cuttings may cause material to obstruct transport routes, posing risks to drivers and causing derailment of trains (e.g. Table 1), and there are numerous locations where road and rail routes span large, and often slow-moving, landslides. Across Europe, field monitoring is widely used to help understand mechanisms of movement and deterioration, assess condition and risk, and provide design parameters for repair of slopes.

Geotechnical monitoring is usually applied only to earthworks or natural slopes that are causing or showing specific problems, often in the form of excessive displacements. A common approach is to drill boreholes and install instrumentation to measure soil displacement and groundwater levels; these may be used in assessment of potential risk or early warning (if movements accelerate), or in analysis of stability or design of remedial measures. Accessing steeply sloping ground to drill boreholes for instrumentation can be costly, and monitoring of this type can be applied only to slopes causing significant hazard.

Regular assessment can identify slopes that may be at risk of failure: this is often carried out by visual inspection (looking for signs of movement), combined with information on the slope angle, and the nature of ground and potential groundwater conditions. There are limitations to such assessments: vegetation can often obscure signs of ground movement; slopes may not always show signs of distress and instead fail in a brittle and rapid manner; the exact nature of ground and groundwater conditions is often estimated. Visual inspections may have limited usefulness in predicting the onset of instability, as they provide little or no information on subsurface processes that are a precursor to slope failure. Slopes that are not necessarily known to be a hazard can fail unexpectedly, presenting problems for the safe operation of transport systems. As a result, there is growing interest from asset owners in more pervasive approaches that would allow more widespread condition monitoring of geotechnical assets. Such approaches rarely involve drilling boreholes as this would be too costly to apply to long lengths of asset; instead, many apply monitoring of surface displacements or strain, soil water content or climate. A network of sensors can also be linked by wireless connections, with data uploaded to the internet. Geophysical monitoring (e.g. by means of electrical resistivity tomography (ERT) and seismic methods), remote sensing using satellites, or ground-based radar or light distance and ranging (LiDAR) all provide alternative pervasive approaches. However, many such systems are relatively untried for monitoring of engineered slopes, and it is not completely clear how monitored parameters such as surface displacements or soil moisture content should be used in indication of increased risk or incipient failure; there is often insufficient knowledge about slope processes to link physical parameters with risk of failure.

Where problem slopes are large, or are in very challenging terrain, continual monitoring and assessment may be applied instead of remedial measures, which may simply be impractical owing to excessive size or cost. Monitoring can be used to gauge the

Table 1 *Recorded earthwork failures in the UK Network Rail system 2003–2014 (from Abbott et al. 2014)*

	Embankments	Soil cuttings	Rock cuttings
Number of formally recorded failures	307	485	488
Number of derailments caused by earthworks failure	2	11	4
Average probability of derailment given failure (%)	0.7	2.3	2.1

likelihood of incipient failure and provide early warning. In such circumstances, monitoring needs to be continuous, reliable and reported in near 'real time', with clear criteria to suit the level of expertise needed to make a judgement (Stähli *et al.* 2014). Asset owners commonly differentiate their monitoring systems depending on function, so that a safety critical system would be defined as an 'alarm' system and would have additional stipulations on its set-up and use compared with a conventional 'monitoring' system. For large time-series datasets, for which manual interrogation is impractical, automated systems may process and analyse data to determine when critical predefined thresholds have been exceeded (e.g. Smith *et al.* 2014*b*). The reliability of an instrumentation system is dependent on continued operation of instruments often placed in challenging environmental conditions, and the setting of suitable thresholds. False alarms can be costly in terms of money, confidence and reputation if they unnecessarily halt rail and road traffic.

Instrumentation may also be used for research or to provide long records of how slopes may progressively deteriorate with time, or how long periods of climate may influence pore pressures and movements (e.g. Smethurst *et al.* 2012; Springman *et al.* 2012). This information obtained from instrumentation may be vital in understanding deterioration and modes of failure (of which there may be many); this information can feed back into improved conceptual and numerical models that seek to identify assets that may be at risk. In some geologies and environments, deterioration mechanisms are complex, and there is considerable progress still to be made in working out how to monitor these and incorporate them in models (Dijkstra & Dixon 2010; Springman *et al.* 2012; Briggs *et al.* 2017).

Climate change presents an increased risk to slopes. Research starting to investigate the impact that climate change may have on transport slopes indicates that more extreme periods of climate, coupled with ageing assets, may cause a higher rate of failures. Climate changes that pose a threat to engineered slopes include more extreme rainfall events (both heavy showers and long periods of rain), drought and increased freeze–thaw cycles (Springman *et al.* 2009; Clarke & Smethurst 2010; Bles *et al.* 2015). A greater use of instrumentation may help to manage the risk that climate change poses to transport systems.

There is evidence that proactive management of slopes can be much more cost effective than reactive repairs following failure (Glendinning *et al.* 2009). Instrumentation and monitoring can form an important component of a long-term earthworks asset management strategy. Asset owners are often required by regulatory bodies to show continual improvement in asset management and safety; this has included investing in greater use of monitoring to control and manage risk. Thus the opportunities to use and develop techniques for condition monitoring are now very favourable.

In summary, there are several uses for instrumentation and monitoring in geotechnical asset management; and a plethora of challenges. This state-of-the-art review seeks to consider existing conventional approaches to instrumentation for slopes (what to monitor for a range of applications), to look at new instrumentation and technology that may seek to change monitoring approaches for slopes (with examples of several systems under development or trial), and to seek to 'futuregaze' at the next set of challenges that new technology will pose, and suggest how instrumentation should be developed in the future.

Applications for monitoring

A number of applications for instrumentation and monitoring of infrastructure slopes have been considered in the introduction, and these will be described in further detail here. These may be summarized as: (1) monitoring the condition of slopes (which may include earthworks that are subject to significant changes in loading or profile, and verifying the performance of remedial measures); (2) obtaining parameters for use in design of remedial schemes (in combination with a model); (3) early warning systems to provide alarm or indication of incipient failure; (4) monitoring slopes to manage risk at the infrastructure corridor scale; (5) monitoring slopes to understand mechanisms of degradation and response to trigger events, to provide better conceptual models of slope performance; (6) development and testing of new instrumentation. This list may not be exhaustive, but many monitoring needs should fall within one of these categories.

All applications for monitoring should have an overarching aim of assisting asset management, which may be defined as 'co-ordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditure over their life cycles for the purpose of achieving its organisational strategic plan' (Hooper *et al.* 2009). However, each of the applications listed above may address different parts of an asset management strategy, and thus have a differing specific aim for which the type of instrumentation, reading intervals and duration, volume and processing of data, and analysis and decision-making process may all be very different (Dunnicliff 1993). Table 2 provides further consideration of these common applications. It should be noted that Table 2 may not cover all applications, and there are also other ways of categorizing monitoring approaches and systems (e.g. see Hooper *et al.* 2009).

Members of the COST Action have provided details for a number of key example case histories, for which extensive monitoring datasets are available, covering a range of the applications above. Some are referenced in the 'example case histories' column of Table 2, and full details of the sites, including owners of the datasets, are given on the Action website www.bgs.ac.uk/cost1202/ (where they are labelled 'WG2 completed proformas').

What to monitor

An instrumentation and monitoring scheme should be designed and set up to achieve specific aims (Dunnicliff 1993; Chapman *et al.* 2012); six applications with different aims have been considered in the previous section. The intended aims of the scheme should dictate the monitoring objectives, which lead to detailed design of instrumentation type, number of instruments, method of installation, data collection approach and reading interval, and how the data are stored, analysed and interpreted. The design of a monitoring scheme should be guided by previous site investigation information, and in some cases a detailed ground model (Fookes 1997) and the predicted hazard.

This paper does not intend to be an exhaustive guide to all available types of instrumentation; however, suggestions for the parameters that could be monitored for each of the applications of monitoring are given in Table 2. These are only indicative, and may vary considerably for the wide range of possible sites and geology that could fall into each category.

Table 2 *Applications for instrumentation and monitoring of infrastructure slopes*

Application	Objectives of monitoring scheme	What to monitor? And number of instruments	Frequency of readings, and duration of monitoring	Analysis and interpretation of data	Example case histories
(1) Monitoring the condition of problem slopes (including earthworks that are subject to significant changes in loading or profile, and ensuring function of remedial measures)	To understand the depth and extent of an existing failure, and the conditions (such as porewater pressure) that may have caused it. To ensure that any continuing displacements of materials that have already slipped remain small. To demonstrate if remedial works are (or are not) required. To check the performance of remedial measures	Displacements with depth using inclinometers; porewater pressure using piezometers; weather/climate. For large areas of instability, ground surface displacements may be monitored using large-area approaches such as satellite-based LiDAR	If the hazard posed by the slope is low, and initial displacements are small, readings could be relatively infrequent, and data may not need to be logged continuously. Duration may depend on hazard posed; may be months or years if monitoring is needed to limit risk to infrastructure	Readings may be plotted and analysed on a periodic basis (e.g. once a week or month)	Monitoring of earthwork porewater pressures and displacements (Smethurst *et al.* 2015; Hughes *et al.* 2016)
(2) Obtaining parameters for use in design of remedial schemes	To understand the depth and extent of an existing failure, and groundwater conditions	Displacements with depth using inclinometers; porewater pressure using piezometers; weather/climate parameters (precipitation, temperature)	If the hazard posed by the slope is low, readings could be relatively infrequent (e.g. monthly). Duration needs to be sufficient to make a reasonable assessment of extent of failure and likely worst porewater pressure conditions	Readings can be plotted and analysed on a periodic basis (e.g. once a week or month)	For example, in stabilization of earthworks using piles; see Smethurst & Powrie (2007) and O'Kelly *et al.* (2008)
(3) Early warning systems to provide alarm of actual failure, or indication of incipient failure	To warn of actual or incipient failure that may pose a direct risk to safety of transport systems	Displacement is the obvious indicator of incipient failure in many non-brittle materials; commonly assessed using inclinometers or tilt meters. Climate, porewater pressures/ suctions and soil moisture content may be secondary indicators	Frequency of readings may be high, to attempt to assess risk in 'real time' if failure may occur rapidly. This would lean towards in-ground instrumentation, or tilt meters fixed to points on the slope surface, that are continuously datalogged	Data may need to be interpreted rapidly, and in part by machine (computer or datalogger), assessing monitoring data against pre-determined thresholds	A review of early warning systems has been given by Stähli *et al.* (2014). Details of a system using acoustic emission monitoring in a cutting slope have been given by Dixon *et al.* (2015)
(4) Monitoring slopes to manage risk at the infrastructure corridor scale	To investigate changes in key parameters along significant lengths of asset. To warn of incipient failure that may pose a direct risk to safety	Large numbers of instruments may be used along significant lengths of transport corridor. The need to contain cost leads to measurements of ground surface displacement, or near-surface changes in porewater pressure/ suction, or parameters such as soil moisture content. Ground surface displacements may be monitored using large-area approaches such as satellite-based LiDAR	Frequency of readings may be high (every few minutes), if there is a need to assess risk in real time because failure may occur rapidly. Condition monitoring may take place over many years	Large volumes of data may need to be interpreted rapidly, and thus probably in part by machine (computer or datalogger), assessing monitoring data against pre-determined thresholds	Utili *et al.* (2015) described the use of monitoring information to consider the stability of longer lengths of asset. An overview for consideration of slopes at the corridor scale has been given by Dijkstra *et al.* (2014)

(continued)

Table 2 (Continued)

Application	Objectives of monitoring scheme	What to monitor? And number of instruments	Frequency of readings, and duration of monitoring	Analysis and interpretation of data	Example case histories
(5) Research: monitoring slopes to understand mechanisms of degradation and failure	To investigate particular modes of deterioration or failure. To investigate processes (such as changes in porewater pressure) that lead to failure	A wide range of instrumentation may be used, including more unusual types to determine less commonly measured parameters (e.g. permeability). Instrumentation may be extensive to obtain a detailed profile of variation with, for example, depth	Frequency of readings from instruments is likely to be high (hourly or sub-hourly), to obtain high-quality temporal datasets. Duration of monitoring may be long, to assess, for example, long-term changes in porewater pressures over several years of climate	Readings may be collected and analysed infrequently, depending on the needs of the research programme	Examples include: Long-term variations of porewater pressure (Smethurst *et al.* 2012; Glendinning *et al.* 2014) Investigations of extreme wet winter porewater pressures (Briggs *et al.* 2013) Investigation of suctions supporting silt/silty sandy slopes (Casini *et al.* 2013; Westerberg *et al.* 2014, 2017) Controlled failure of a full-scale test embankment (Lehtonen *et al.* 2015) Understanding rainfall infiltration driven failure (Akca *et al.* 2011; Askarinejad *et al.* 2012)
(6) Development and testing of new types of instrumentation	To understand the performance of new instrumentation systems. Calibration and validation of instruments	A mix of conventional and new instruments	Frequency of readings is likely to be high (hourly or sub-hourly), to obtain high-quality temporal datasets. Duration of monitoring may be longer, if new instrumentation needs to be proved in full range of conditions	Readings may be collected and analysed infrequently, depending on the needs of the research programme	Research sites such as Hollin Hill, North Yorkshire, UK (Chambers *et al.* 2011) and Nafferton embankment, Northumberland, UK (Glendinning *et al.* 2014) are being used to assess the performance of new monitoring instruments and techniques. Examples of new instrumentation include moisture and displacement monitoring using ERT (Wilkinson *et al.* 2010; Lehmann *et al.* 2013; Chambers *et al.* 2014; Gunn *et al.* 2015), and movement monitoring using AE (Smith *et al.* 2014*b*)

The commonly measured parameters are as follows.

1. *Ground displacements.* These are commonly measured using inclinometers, extensometers, tilt meters and crack meters (measuring lateral, vertical, rotational and extensional movements respectively). There are also many approaches to measurement of surface displacement, such as using photogrammetry, radar interferometry and LiDAR. Displacement or strain tends to be fairly easy to measure, and in-ground instruments in particular can do so with considerable precision, if installed and read carefully. Measurements can show if ground displacements are taking place, to what depth movements occur, and the magnitude of displacements. It is notable that slope stability is controlled by stress (the strength of soil and rock materials, as input into a stability analysis), but stresses in the ground are difficult to measure and may be dependent on the stress history of the soil, which is often unknown. Strains (or displacements) are measured instead. However, to gain understanding of the failure mechanism from these measurements there is generally a need to understand the stiffness and deformation behaviour of the soils concerned. Trying to judge incipient failure using displacements in very stiff (or very soft, in the case of some glaciomarine clays) brittle materials, may be difficult.
2. *Ground water pressures*. Increased strain or complete failure in many slopes is caused by changes in effective stress, in turn caused by increases in porewater pressure. Thus porewater pressures are commonly monitored, using a range of differing types of piezometer. In partially saturated slopes, stability may be aided by porewater suctions, and instruments that can measure suction or loss of suctions may be important (see Ridley *et al.* 2003; Springman *et al.* 2012).
3. *Climate or weather*. Rainfall is commonly monitored, as this has a direct influence on saturation of the ground and soil porewater pressures. Depending on the nature of the ground, periods of prolonged heavy rainfall, over hours, days or months, will cause porewater pressures to rise, possibly triggering failure. Longer term records of rainfall, often combined with evaporation or evapotranspiration to give effective rainfall, can be used as an indication of increased periods of risk of slope instability (Clarke & Smethurst 2010). Very short high-intensity rainfall events can trigger slope failure, and are also often of interest. Temperature, and in colder climates ground temperature, is also important; for example, thawing of frozen ground can lead to increased water pressures, which may destabilize slopes.

There are a wide selection of monitoring approaches available for slopes, including different modes of sensor deployment (explored further in the next section), the measurement of parameters not listed above, and use of techniques that are less well established and/or are still in development. The selection of instrumentation to meet the specific objectives of a monitoring scheme usually considers the accuracy, precision, sensitivity, reliability and spatial and temporal resolution of different techniques (Dixon *et al.* 2015). Detailed descriptions of well-established geotechnical instrumentation approaches have been given by Dunnicliff (1993), and are also categorized in the recent European geotechnical monitoring standard (BS EN ISO 18674-1:2015, BSI 2015). Novel monitoring approaches will be considered later in this review.

Comments on the frequency of readings, and interpretation of resulting data, for the six categories of monitoring application are given in Table 2. Some of the applications that require large quantities of data to be analysed rapidly remain challenging, and some of the issues surrounding these will also be discussed below.

How to monitor

Monitoring can be carried out using a wide range of modes of sensor deployment; for example, from repeated manual measurements within a borehole for determining changes at a site scale, to satellite-based sensors for monitoring ground surface displacements at a regional scale. Key distinctions include the following: (1) ground-based v. remotely located sensors (airborne or satellite); (2) static v. dynamic (moving) sensors; (3) surface v. subsurface information; (4) point sensors v. spatial or volumetric monitoring technologies; (5) permanently deployed sensors v. manually repeated measurements with temporary sensors; (6) telemetric v. manual data retrieval. The mode of deployment has major implications for coverage, spatial and temporal resolution, and the cost of monitoring.

Remote sensing techniques using airborne and satellite-based sensors can provide a very cost-effective means of acquiring high-resolution information for the ground surface over very large areas (Hardy *et al.* 2012; Miller *et al.* 2012; Castagnetti *et al.* 2013; Cigna *et al.* 2015; Wasowski *et al.* 2014; Hugenholtz *et al.* 2015), but are generally limited in terms of temporal resolution (which is based on satellite orbits or flight schedules) and provide only surface or very near-surface information. For smaller infrastructure slopes (v. large landslides) spatial resolution may also be insufficient, and remote sensing techniques can also be impeded by the dense vegetation cover present on some infrastructure slopes (e.g. Miller *et al.* 2008).

Dynamic ground-based sensing systems, such as terrestrial LiDAR (Lato *et al.* 2009, 2012; Marjanovic *et al.* 2013; Fan *et al.* 2014), radar inferferometry (Springman *et al.* 2012; Caduff *et al.* 2014), ground penetrating radar (GPR; Donohue *et al.* 2011, 2013; Silvast *et al.* 2013) and capacitive resistivity imaging (CRI; Kuras *et al.* 2007) can obtain greater spatial and subsurface information, but are limited in terms of temporal resolution by the need for manual data collection, and therefore can be expensive when frequent (i.e. high temporal resolution) monitoring is required.

Point sensors can give very good resolution and accuracy, but are inherently limited in coverage (i.e. they measure only within the immediate vicinity of the sensor), but spatial imaging techniques, such as electrical resistivity, seismic methods and ground penetrating radar (Donohue *et al.* 2011; Loke *et al.* 2013) can complement point information and help with interpretation in ground or groundwater conditions that are heterogeneous. Wireless sensor networks (Gong *et al.* 2013) and fibre-optic approaches (Zhu *et al.* 2015) have been developed that can also provide information at increasing spatial scale. Permanently deployed point sensors coupled with low-power electronics and data telemetry can achieve very high temporal resolution and near-real-time information delivery (Smethurst *et al.* 2006; Chambers *et al.* 2014). Systems that operate remotely and automatically and interface with a wide range of permanently deployed sensor types are becoming increasingly well developed (Intrieri *et al.* 2012).

New instruments and innovation

New forms of instrumentation and the increasing ability of computing and the internet to distribute, manage and process large amounts of data provide exciting opportunities, as well as challenges, for slope monitoring. This section looks at a number of developing monitoring technologies, their maturity (whether they are at early phases of development, or becoming increasingly established; e.g. with numerous field trials) and the changes that they will or may provide in monitoring of infrastructure slopes for a wide range of purposes. It also considers potential effects that more sophisticated monitoring systems may have on management of data, decision making and communication.

New measurement technologies

A range of new monitoring technologies are being used or developed for monitoring of slope stability, and a number of these, with their abilities, limitations and maturity, are described in Table 3. It should be noted that Table 3 is not exhaustive, as turning to landslide monitoring gives other novel approaches, such as using extensometers running parallel to the slope surface (Wang *et al.* 2008). The constraints on space also mean that it is not possible to include all advantages or limitations, particularly those relating to very specific applications.

The novel forms of instrumentation in Table 3 seek to provide a range of improvements over conventional techniques, including the following.

(1) Higher resolution data, both in time and space.
(2) Lower costs, including the cost of both the instrumentation and installation, particularly the need to drill fewer or smaller boreholes, or, in the case of some remote sensing approaches, drill no holes at all. Cost can be a major driver in instrument and technique selection.
(3) Automated monitoring: systems that collect and transmit data, and in some cases automatically process and compare it with thresholds to provide an alarm (e.g. of increasing displacements). Automated systems also reduce the need for manual measurements and the need to put personnel in potentially hazardous environments.
(4) Greater lifespan for instrumentation. For example, localized shear surface displacements of about 50 – 100 mm can render inclinometer casings unusable; in contrast, shear surface displacements in excess of hundreds of millimetres have been recorded using shape acceleration array (SAA) systems (Buchli *et al.* 2013; Dasenbrock 2014) and active waveguide acoustic emission (AE) monitoring systems (Smith *et al.* 2014*a*).

Several of the techniques in Table 3 are reaching maturity, and are starting to be commonly adopted for geotechnical and structural monitoring (e.g. the shape array), whereas others are still in the earlier stages of development. Some are well-established monitoring techniques, but their use for infrastructure slopes has been limited (e.g. optical fibres), and they still require application-specific development, with careful trials before wider application to the transport network.

Several of the relatively new techniques are being actively developed by members of COST TU1202: the British Geological Survey has been developing ERT for earthworks moisture monitoring (e.g. Chambers *et al.* 2014; Gunn *et al.* 2015), and Loughborough University, UK, has been developing and is now starting to commercialize an acoustic system for monitoring slope displacement rates (called ALARMS; Dixon *et al.* 2014; Smith *et al.* 2014*a*, 2017). Both of these systems show considerable promise: ERT as a means of imaging moisture changes in earthworks, and ALARMS as a low-cost warning system for slope movement. Both have been installed in an embankment research facility at Nafferton, Northumberland, UK, to test their abilities against conventional instrumentation (Fig. 1; for further details, see Hughes *et al.* 2009; Glendinning *et al.* 2014); such facilities are valuable for testing new approaches in a controlled environment.

Table 3 identifies three techniques that have been little used so far for monitoring infrastructure slopes and that all show some promise, particularly as more pervasive approaches for condition monitoring of long lengths of asset at relatively low cost. These are the following.

(1) Optical fibres used to measure surface strain in slopes (rather than in a borehole). As the monitored fibre can be long, the technique is potentially suited to monitoring significant lengths of asset. Fibres could be buried longitudinally, e.g. a short distance below the crest of a slope. The limitations and challenges are the relatively high cost of the equipment needed to read the strain in the fibre (although this is reducing in price), the need to correct for temperature effects, and the uncertainty as to how the fibre will deform in response to slope movements. Time domain reflectometery (TDR) does not measure strain, but can identify the location where distortion takes place within a coaxial cable, and thus may be able to perform a similar role, potentially at lower cost.
(2) Remote sensing technologies such as LiDAR, and photogrammetry, using data from satellites, aerial vehicles or terrestrial systems. Both techniques are becoming common for terrain mapping and monitoring surface change for large landslides and rock slopes. The methods could be used to measure surface deformation of infrastructure slopes, but challenges include developing a suitable monitoring platform (rail or road vehicles, or an aerial approach), a system for handing large quantities of data (point cloud data from LiDAR; images for photogrammetry), and the resolution and accuracy of surface change detection including in the presence of vegetation.
(3) Wireless sensor systems, with wirelessly networked probes such as tiltmeters and moisture content probes used across or along an asset. These are already being developed for slope monitoring applications, particularly to provide alarm of slope movements (Network Rail 2015). If a record of measurements is required for condition monitoring, transmission of large quantities of data has significant power demands, and there is still some uncertainty as to how surface or near-surface point measurements can be used to indicate deterioration or incipient failure of a slope.

All of the above require further investigation and then potentially development and testing for use with infrastructure slopes. In development of new approaches, collaboration between asset owners, instrumentation contractors and research institutions is important to ensure any new methods align to practical monitoring and asset management needs.

Datalogging and transmission

Not included explicitly in Table 3 are recent advances in datalogging and transmitting technologies, which may be summarized as follows.

(1) Use of less power: commercial datalogging systems can operate with low power consumption, particularly to monitor instruments and store data, such that it is possible to run small dataloggers for many months or even years from a single small battery cell. Transmission of data wirelessly has a greater power need, and batteries then need charging systems such as fuel cells or photovoltaic panels, although approaches to careful use of power, such as turning on only once every hour to transmit data, can be adopted. Energy harvesting from vibration is also used, for which a number of commercial systems are available (e.g. Perpetuum 2016).
(2) Ability to transmit greater quantities of data at speed: new third and fourth generations of mobile data technology

Table 3 *New monitoring technologies*

Instrument/technique	Description	Accuracy	Resolution		Other notes
			Temporal	Spatial	
Surface deformation monitoring					
Global positioning system (GPS)	GPS system receives time signals from orbiting satellites and positioning is based on signal travel times. Minimum of 4 satellites required for position calculation (i.e. x, y and z) accurate to *c.* 15 m. Accuracy improvements can be achieved by using: (1) differential GPS: correction of atmospheric disturbances from comparison of GPS position with known fixed position of a base station; accuracy *c.* 0.1 m; (2) real time kinematic (RTK) GPS: for positioning the carrier phase of the signal is used rather than the actual time signal; accuracy <0.01 m. Accuracy of RTK-GPS is required for monitoring of mass movements (Millis *et al.* 2008).	m to mm	Low: manual repeated surveys High: continuous monitoring on spatially fixed receivers	High: depending on number of monitoring locations	Dependent on satellite coverage; reception limited in strong topographic depressions (e.g. alpine valleys). Affected by signal scattering: limited accuracy in forested areas. Considerable time requirement for full site surveys. Instrumentation and processing software are of high cost. Permanent installations have been used to monitor movements of large natural landslides causing damage to transport infrastructure (e.g. Massey *et al.* 2013). Most likely to be used for applications (1), (3), (4) and (5) in Table 2
Photogrammetry	3D reconstruction of surface topography from overlapping photographs taken from different positions (at least 2). Accuracy mainly dependent on photograph resolution and number of overlapping photographs (i.e. number of shot positions per covered area, Bemis *et al.* 2014). Both aerial (e.g. using manned or unmanned aircraft/aerial vehicles) and terrestrial photogrammetry can be used	m to mm	Low: restricted by time requirements for photograph acquisition and data processing High: continuous monitoring on permanently installed cameras	High: high accuracy point cloud/DEM, deformation monitoring for entire study site	Application limited by high cost and time requirements. Post-processing of data relatively complex (e.g. see Akca *et al.* 2011). Widely used for digital terrain mapping and monitoring surface change for natural rock slopes and landslides; a small number of examples of application to infrastructure slopes (e.g. Jang *et al.* 2008). Most likely to be used for applications (1), (4) and (5) in Table 2
Remote sensing	Terrestrial-, aerial-, or satellite-based recording of reflected electromagnetic energy from the Earth's surface. Typical examples used in investigations of surface deformation (Scaioni *et al.* 2014; Petley *et al.* 2005): (1) LiDAR (light detection and ranging): distance measurement employing backscattered energy of laser beam, used to create digital elevation models (DEMs); (2) InSAR (interferometric synthetic aperture radar): mapping of phase differences between reflected radar waves of different acquisition times, representative of surface deformation	m to mm	Medium to low: restricted by time required for survey (i.e. in case of terrestrial and aerial surveys) and processing	High: high accuracy point cloud/DEM, deformation monitoring for entire study site	Application limited by high cost and time requirements (i.e. terrestrial and aerial surveys). Post-processing of data relatively complex. Temporal resolution dependent on satellite orbit (i.e. time between repeated data acquisition over same location). Accuracy dependent on signal wavelength and atmospheric condition. Positioned reflectors may be required to overcome seasonal changes in vegetation. Aerial surveys (e.g. Miller *et al.* 2012) have been used to characterize and look at longer duration changes within infrastructure earthworks. Most likely to be used for applications (1), (4) and (5) in Table 2

(continued)

Table 3 (Continued)

Instrument/technique	Description	Accuracy	Resolution		Other notes
			Temporal	Spatial	
Fibre optics (e.g. Brillouin optical time domain reflectometry; BOTDR)	Determination of locally applied strain to a single optical fibre cable by time-domain analysis of frequency spectra of backscattered light pulses (Thévenaz 2010). Frequency shifts caused by changes in fibre density. Time-domain analysis allows for determination of strain/deformation location. Other optical fibre strain measurement approaches can be used, e.g. Bragg gratings (Glisic & Inaudi 2007)	Strain measurement: 0.2% (e.g. 2 mm for 1 m spatial resolution)	High: continuous monitoring of permanent installations	High: cable layout can be adapted to site conditions to optimize coverage and resolution	No absolute measure for displacements. Relatively high cost. Need for correction of temperature effects. Complex processing required. Can also be used subsurface, such as in a borehole. Widely used to measure strain in structural elements, but no known applications to unreinforced transport infrastructure slopes. Most likely to be used for applications (1), (3) and (4) in Table 2
Accelerometer, geophone	Recording of ground surface velocity or acceleration in response to: (1) earthquakes (i.e. as trigger for slope destabilization); (2) rapid (i.e. brittle) landslide movements. Usually measured employing spring-mounted magnetic masses moving within wire coils generating electric signals. Microchip micro-electrical mechanical system (MEMS) accelerometers are widely used	Acceleration: 0.1 m s^{-2}	High: continuous monitoring of permanently installed sensors	Low to high: dependent on number and distribution of accelerometers or geophones	Recording of movement changes only; limited detection capability of low-velocity ductile movements (e.g. creep). Extraction of movement periods from background noise may be difficult. Requires complex post-processing. No known applications for transport infrastructure slopes. Most likely to be used for applications (1) and (3) in Table 2
Electrode tracking using electrical resistivity monitoring	Resistivity measurements are sensitive to the subsurface resistivity distribution and electrode separations. Monitoring installations usually consist of either a line or grid of electrodes, with electrode spacing ranging from 0.5 to 5.0 m. Measured resistivities can be inverted to track electrode, and thus landslide movement (Wilkinson *et al.* 2010, 2015), along a line or surface grid	5–10% of electrode spacing (e.g. 0.025–0.5 m, dependent on electrode layout)	Medium to high: dependent on measurement layout; 2D lines can be measured hourly, 3D grids usually daily	Medium to high: dependent on measurement layout	Accuracy dependent on resistivity data quality. Other data streams required to calibrate/confirm measurements. Requires complex installation and post-processing. High-cost measurement system. The approach has been demonstrated using an installation installed within a natural landslide (Wilkinson *et al.* 2010). Most likely to be used for applications (1) and (5) in Table 2
Subsurface deformation monitoring					
Time domain reflectometry (TDR)	Deployment of coaxial cables (or optical; see BOTDR) in vertical boreholes. Measurement of reflections along a conductor. Localized deformation of coaxial cable leads to local impedance contrast at which a pulse is reflected. Time-domain analysis allows for determination of deformation location. Rate of impedance change is indirectly proportional to ground movement rate (Kane *et al.* 2001; Millis *et al.* 2008)	cm to mm (dependent on cable length)	Low: manual surveys using portable pulse generators. High: continuous monitoring of permanently installed systems	Low to medium: depending on whether used in single borehole or borehole network	No direct measurements of deformation or deformation rate. Costs range from low (infrequent, manual surveys) to high (continuous, permanent monitoring or borehole network). Sold as a commercial system, and has been installed into numerous natural and engineered slopes (Kane *et al.* 2001). Most likely to be used for applications (1), (2), (3) and (5) in Table 2

Shape acceleration array (SAA)	Comprises a string of MEMS sensors, installed inside boreholes. Sensors are placed at regular intervals. Each section of the array measures 3D displacements (Abdoun *et al.* 2013)	±1.5 mm per 30 m array length	High: continuous monitoring	Low to medium: depending on whether used in single borehole or borehole network	Instrumentation and processing software are of high cost. SAA string can be retrieved from the borehole. Can provide early warning of slope instability. Care should be taken with processing software (Buchli *et al.* 2016). Sold as a commercial system and has been used fairly widely in stable and unstable infrastructure slopes (e.g. Dixon *et al.* 2015). Most likely to be used for applications (1), (2), (3) and (5) in Table 2
Active waveguide and slope ALARMS sensor (i.e. acoustic emission monitoring)	Comprises a steel waveguide (i.e. as conductor for acoustic emission signals) and angular granular backfill. Host slope deformation causes deformation of granular backfill, creating high-energy acoustic emission (AE) signals travelling along the waveguide (Dixon *et al.* 2003). AE rates are proportional to slope movement rates, highlighting accelerations and decelerations of movements (Smith *et al.* 2014*b*; Dixon *et al.* 2015; Smith & Dixon 2015)	Differentiation of movement rates that differ by an order of magnitude (e.g. 0.01 and 0.1 mm h^{-1})	High: continuous monitoring	Low to medium: depending on whether used in single borehole or borehole network	Sensitive to slow rates and small displacements. Most applicable to slopes failing along a defined shear surface. Relatively low-cost instrumentation. Can provide early warning of slope instability. Emerging technology; has been trialled in a clay cutting slope (Dixon *et al.* 2015) and at the BIONICS facility (Glendinning *et al.* 2014), with a number of other installations in natural landslides. Most likely to be used for applications (1) and (3) in Table 2
Electrical resistivity tomography (ERT)	ERT measurements consist of electrodes placed at the surface and/or in boreholes. Resistivity is sensitive to the subsurface lithology, e.g. clay content; inverted resistivity models represent a volumetric image of the local lithology. Temporal changes in the resistivity distribution can inform about mass movements. Changes can be quantified using emerging boundary extraction algorithms (e.g. Chambers *et al.* 2015; Uhlemann *et al.* 2016)	m to cm, dependent on data quality and depth of changes	Medium to high: varies between daily and hourly, depending on measurement layout	Medium to high: depending on measurement layout (i.e. 2D or 3D acquisition)	Measurement sensitivity reduced with increasing distance to electrodes. Complex installation and processing required. Used to measure ground movements for a range of applications, including natural landslides; no known applications to transport infrastructure slopes. Most likely to be used for applications (1), (2) and (5) in Table 2
Subsurface condition monitoring					
Conventional soil moisture probes	Based on relative permittivity measurements, which are related to moisture content using Topp's equation (Topp *et al.* 1980). Main techniques: (1) time-domain reflectometry (TDR): relative permittivity derived from the travel time of an electromagnetic pulse through a waveguide; (2) capacitance sensors: relative permittivity determined based on the charging time of a capacitor, employing the soil as dielectric	Relative permittivity: ±1; moisture content: ±3% of measurement	High: continuous monitoring on permanently deployed sensors	Low to medium: sensor samples only surrounding medium, can be increased if used in sensor networks	Moisture content derived through empirical relationships. Usually requires calibration. Robust and reliable sensor technology. Latest developments include web-based real-time delivery of multi-location moisture data from sensor networks at field sites. Several commercially available devices; fairly widely used to measure soil moisture content in the near-surface zone of infrastructure slopes (e.g. Smethurst *et al.* 2012; Glendinning *et al.* 2014). Most likely to be used for applications (1), (3), (4) and (5) in Table 2

(continued)

Table 3 (Continued)

Instrument/technique	Description	Accuracy	Resolution		Other notes
			Temporal	Spatial	
Electrical resistivity tomography (ERT) monitoring of soil moisture	The resistivity of a soil depends mainly on its mineralogy and degree of saturation. Laboratory-derived relationships can be used to translate resistivity into moisture content. Repeated ERT surveys on permanently installed electrodes can be used to image volumetric moisture movements (e.g. Chambers *et al.* 2014; Gunn *et al.* 2015). ERT could also be used to monitor cavity development	Moisture content: < ±5%	Medium to high: varies between daily and hourly, depending on measurement layout	Medium to high: depending on measurement layout (i.e. 2D or 3D acquisition)	Measurement sensitivity reduced with increasing distance between electrodes. Complex installation and processing required. Measurement accuracy dependent on resistivity data quality. Several installations have been used to image moisture changes in clay infrastructure slopes (Glendinning *et al.* 2014; Gunn *et al.* 2015). Many other examples of use in natural slopes. Most likely to be used for applications (1), (4) and (5) in Table 2
High-capacity porewater suction probes	Probes consist of (1) filter, acting as interface between soil and measurement device, (2) water reservoir and (3) pressure measuring device. Recent improvements of measurement range and accuracy through reduction of water reservoir and higher air entry pressures of the ceramic filter (Toll *et al.* 2011, 2013). Allows suction measurements in the range of 0 – 2000 kPa	Porewater pressure/suction: > ±5 kPa	High: continuous monitoring of permanently installed sensors	Low to high: dependent on number and distribution of probes	Limited accuracy if applied at low suctions. Long-term measurement drift may occur. Laboratory re-saturation necessary if water reservoir dries out. Probes have been trialled in a clay embankment in the UK (Toll *et al.* 2011, 2013). Most likely to be used for applications (1), (3), (4) and (5) in Table 2
Probes for indirect measurements of porewater suction	Probes consist of a soil moisture device encapsulated within a porous ceramic of known water retention properties. Soil moisture in ceramic measured, and related to suction in the soil. Accuracy is dependent on correct calibration between suction and moisture content of ceramic (Smethurst *et al.* 2012)	Porewater suction: high readings ± 10%	High: continuous monitoring on permanently deployed sensors	Low to medium: sensor samples only surrounding medium, can be increased if used in sensor networks	Requires careful calibration. Generally robust sensor technology. Latest developments include web-based real-time delivery of multi-location suction data from sensor networks at field sites. Several commercially available devices; fairly widely used to measure porewater suction in the near-surface zone of infrastructure slopes (e.g. Smethurst *et al.* 2012; Glendinning *et al.* 2014). Most likely to be used for applications (1), (3), (4) and (5) in Table 2
Ground penetrating radar (GPR)	Measurement based on the propagation of electromagnetic waves in the subsurface, i.e. wave speed dependent on dielectric properties. Use of non-guided waves (in contrast to TDR where guided waves are used). Properties of reflected, ground, and cross-borehole waves can be used (Huisman *et al.* 2003; Steelman *et al.* 2012). GPR could also be used to characterize (Di Prinzio *et al.* 2010) and monitor cavity development	Moisture content: > ±0.02 $m^3 m^{-3}$	Low to medium: manual surface or borehole surveys	Medium to high: depending on measurement layout and employed frequency	High-cost measurement system. Requires complex post-processing. Limited applicability in highly conductive soils (i.e. clay) owing to attenuation of the GPR signal. Commonly used to establish ballast depth in railway formations. Used by Donohue *et al.* (2011, 2013) to investigate an old clay railway embankment. Most likely to be used for applications (1), (4) and (5) in Table 2

Fig. 1. BIONICS research embankment, Northumberland, UK. The facility has been used to understand earthworks behaviour in relation to climate and test new instrumentation approaches (photograph courtesy of R. Stirling, Newcastle University, UK).

mean it is now possible to send significant quantities of data via mobile phone networks. Local wireless data networks that transmit between adjacent monitoring nodes are also becoming commonplace, and are particularly helpful in geographically diverse systems.

(3) On-site data processing: the reducing cost of computing power and bespoke circuitry mean that it is now possible to have systems that monitor and process data continuously. This has been critical for the development of some novel systems; for example, acoustic emission monitoring (Dixon *et al.* 2015) and monitoring by geophones and accelerometers.

All of the above allow systems that require less human intervention, in readings, downloading data and in maintenance (e.g. changing batteries). This is likely to reduce costs, and avoid the need to put people into remote and potentially hazardous environments.

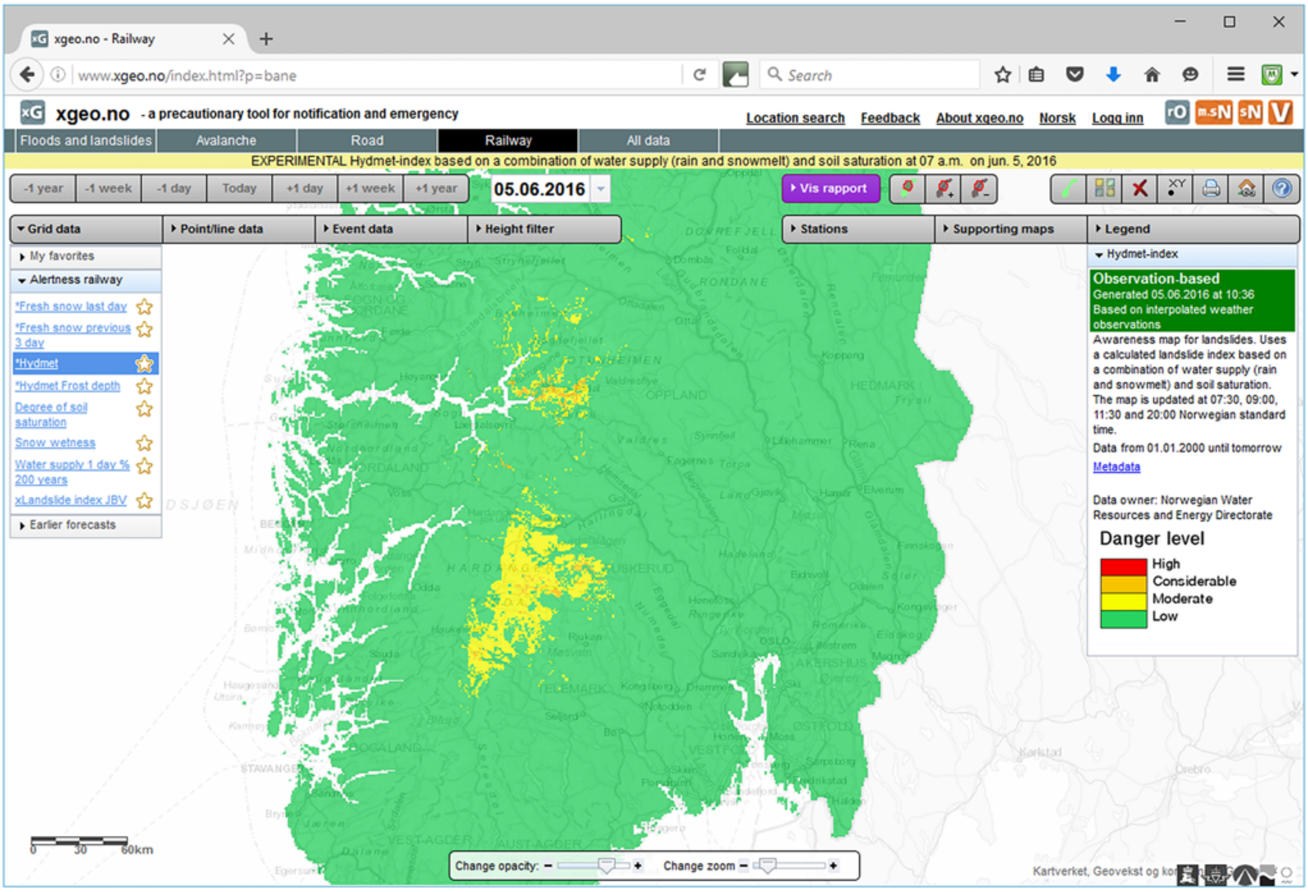
Data management

The reducing cost of electronic in-place sensors and improved datalogging systems mean that it is now possible to both install more sensors and take and store many more readings from instruments than was possible in the past. This allows a much better granularity of spatial and time-based information; for example, readings every few minutes rather than days or even weeks apart can provide truer representations of physical processes, such as how water pressures may react to extreme short-duration rainfall events. This level of detail can be helpful in assessing risk, as well as in understanding the physical processes that take place. Such short-interval readings are essential to real-time alarm systems.

The disadvantage is more data to transmit, store and process. However, there are increasingly sophisticated commercial systems that collect and store data, process it into engineering units, and post it onto secure web portals where it can be viewed. Alarms can be set to alert key decision makers if certain pre-set trigger levels are exceeded. Standardized data formats such as the Association of Geotechnical and Geoenvironmental Specialists Monitoring Standard (AGS-M), which allow easier sharing of information, are becoming common (Richards *et al.* 2003). These are likely to become more important as assets are monitored over longer periods, giving flexibility in updating hardware and software and interoperability between proprietary systems. There have also been advances in commercialization of techniques for processing data, such as in software for photogrammetry applications.

Collection and monitoring of more information is part of a technological trend towards ‘big data’, which is becoming increasingly important across wide areas of the European economy. Data on engineered slopes may be generated during design, construction and operational phases (i.e. the whole life cycle of the asset); geotechnical monitoring information may be a part of this dataset. Many large highway and railway infrastructure owners increasingly store information on their assets within large databases, many of which are linked to geographical information systems (GIS). These are a digital representation of the physical and functional characteristics of assets, and act as a resource for sharing and visualizing information and knowledge. For example, the UK highway agencies have a system known as HAGDMS (Highways Agency Geotechnical Data Management System; Morin *et al.* 2014), in which information is associated with relevant assets in geographical space. These systems share many similarities with building information modelling (Eastman *et al.* 1974), although there are differences; for example, the linear nature of the infrastructure makes 2D rather than 3D representation of an asset more appealing.

Traditional monitoring approaches produce periodic reports, which might be attached to an asset within the GIS. The capability of current systems to hold large datasets is less certain, and may become challenging as the number of sensors and frequency of readings increase. However, GIS that distribute risk information on a fine spatial scale, often in real time (for example, linked to antecedent and forecast rainfall), are becoming more commonplace, and it is plausible that in the future this could include near real-time



EXPERIMENTAL Hydmet-index based on a combination of water supply (rain and snowmelt) and soil saturation at 07 a.m. on jun. 5, 2016

Observation-based
Generated 05.06.2016 at 10:36
Based on interpolated weather observations

Awareness map for landslides. Uses a calculated landslide index based on a combination of water supply (rain and snowmelt) and soil saturation. The map is updated at 07:30, 09:00, 11:30 and 20:00 Norwegian standard time.

Data from 01.01.2000 until tomorrow

Data owner: Norwegian Water Resources and Energy Directorate

Fig. 2. Norwegian XGEO system, showing colour coded landslide hazard determined from rain and snowmelt, and soil saturation data. The hazard map is updated four times a day.

weather or asset monitoring data (e.g. local rainfall, or soil water content). A good example of this is the Norwegian national system XGEO (Fig. 2; www.xgeo.no).

Decision making and communication

Monitoring of data is commonly used to make a range of decisions about infrastructure slopes, including assessing risk of failure, and the need for interventions such as stabilization works. Where monitoring is already in place the asset will usually have already been identified as being at risk and there may be a requirement to make decisions (such as to reduce traffic speed or completely close a route) rapidly to maintain safe operations. Formal frameworks for these decisions vary according to operator (IPWEA 2006; Highways Agency 2010; CEDR 2011) and are usually linked directly to risk assessment frameworks (either generic or site specific; ERA-NET 2010). In some instances, exceedance of a particular threshold value(s) will result in automatic responses, which will then be validated by a responsible engineer. It is important that a control and decision-making framework carefully sets out the responsibilities of personnel that will be involved, and that decision makers have appropriate experience and confidence to ensure good judgements.

Setting or choosing appropriate thresholds against which to assess monitoring data can be difficult, as many infrastructure slopes are unique in construction history, geometry and geological conditions. Where the ground is actively moving, rates of displacement can be monitored, but it can nonetheless be difficult to decide the risk posed by an increased rate of movement. Predicting the transition from slow acceptable movement to rapid catastrophic movement is difficult. Sometimes it is necessary to monitor slopes over a period of time to assess movements in response to hydrological changes to understand how local thresholds may be set (e.g. Eberhardt *et al.* 2008; Reid *et al.* 2008); this observational approach is common in managing uncertainty in geotechnical engineering (Chapman *et al.* 2012). Thresholds levels can be set using a green–amber–red system of increasing risk with colour (e.g. the XGEO system in Fig. 2 uses this in context of national hazard mapping). Thresholds are often based on safety or performance criteria, such as the need to maintain railway track line and level.

Where monitoring systems play a critical safety role, reliability of the instrumentation and monitoring system is particularly important. False alarms can be a major issue, particularly if these result in rail and road traffic being halted unnecessarily, or are in remote sites that take an engineer a long time to reach. It is important that instrumentation systems are designed to be robust, and that may include incorporating redundancy, or providing other means by which alarms can be rapidly checked by experienced personnel such as providing video or images of the site accessed via the internet (e.g. Network Rail 2015).

In the context of engineered slopes, important decision makers will include the earthworks engineering or asset management team, who are typically responsible for the performance and safety of assets in a particular region of the transport network, and operations personnel involved with ensuring the smooth running of transport systems. Others potentially using monitoring information to make decisions include strategic transport planners within government who will make investment decisions for major upgrade programmes or for new routes, and the general public who will make decisions on journey planning when provided with appropriate information (e.g. enhanced risk of disruption owing to extreme weather).

Forecasting and communicating periods of enhanced risk

Risk is often assessed at the corridor or network scale, where there may be an increased risk of failure and thus disruption to operations during and after long periods of heavy rainfall, or prolonged very dry periods (which may cause shrinkage of clay earthworks). There are established methods for assessing geotechnical risk over lengths of corridor (Gavin *et al.* in review) and these can incorporate antecedent conditions and/or forecast weather, combined with geological and topographical information. The Norwegian XGEO system uses hydrological (soil water content) information to assess potential risk of landslips on 1 km grid squares at a national scale (Fig. 2; Devoli *et al.* 2015; Boje *et al.* 2014), and a demonstrator system is being developed for the UK London to South West rail routes called GeoSRM (Sadler *et al.* 2016) that determines earthworks risk based on geology, soil moisture conditions and forecast rainfall. More sophisticated systems could incorporate underlying slope failure models based on approximate soil properties and the geometry of the earthworks, although it could be challenging to predict failure within particular slopes as key data (geometry, geology, condition) and models of failure are often insufficient or too simplified (Glendinning *et al.* 2015; Elia *et al.* 2017). Nonetheless, such a system could be valuable if coupled with near-future weather data (e.g. impending storms) to assess the broader probability of slope failure causing disruption to transport operations. Local monitoring data could also be incorporated within a system to improve estimates of risk, although this may require processing of large amounts of data through multiple iterations of models, requiring significant computational resources.

XGEO is publically available in Norway, and is used to help communicate risk and thus the potential for travel disruption (from a range of hazards including geotechnical failure) to the general public. This information provision can be critical in helping the public to make informed decisions about how and when to travel.

The future; where do we go next?

Many European countries have mature road and rail systems, some of which are now old; for example, many rail earthworks have been used for 100 years or more. Despite their age, the demand for travel is growing in many European countries; for example, rail use in the UK has grown by more than 50% since 2000 (Powrie 2014) and is expected to double in the next 25 years. The public expectation for performance and reliability is also greater, and this poses challenges for linear infrastructure systems in which elemental failure can cause disruption to large lengths of route. Increasing safety is also expected of public infrastructure systems; in the UK during periods of adverse wet weather railway earthworks pose a greater safety risk to the travelling public and railway staff than the other infrastructure types (such as track, signalling and bridges) combined (Hutchinson 2015). Climate change may also affect asset performance. The main driver for slope failure is rainfall, and it is possible that a hotter future European climate will see rainfall arrive in more intense storm events. Drier summers may also pose difficulties for earthworks, causing cracking and shrinkage problems in clay soils (Clarke & Smethurst 2010). Both the public and transport operators want safe and disruption-free systems, and this is likely to be a driver for change to the way that assessment and monitoring of geotechnical assets is approached.

Monitoring of data is also needed to help understand and reduce failure in newly built infrastructure. New road and rail systems often operate at higher speed, and the hazard posed by running into slipped debris (causing derailment or crash) is greater. The lessons from understanding deterioration and failure in older systems is needed to help design, monitor and maintain new geotechnical assets.

This is also an exciting time for monitoring technologies. The emergence of the internet, increasingly powerful wireless transmission and data recording technologies, cheaper sensors, enhanced remote sensing technologies, the ability to process large amounts of data in real time, and greater commercialization of monitoring technology across domains are all making possible things not available to us even a few years ago. All of the above are feeding into new technology development in geotechnical monitoring; the above sections in this paper detail some novel approaches being developed by COST Action members, although there are also many others.

Specific slopes with known stability problems require careful monitoring using more conventional instrumentation (inclinometers, piezometers) to manage the risk that they present. However, generally the majority of earthworks will not be monitored, subject at best only to visual inspection by experienced personnel at frequencies between annual and 10 yearly. Some of these slopes do and will fail unexpectedly, causing disruption, at considerable cost to the economy. To try and monitor longer lengths of earthwork, operators are increasingly keen on more pervasive condition monitoring approaches (i.e. those that monitor surface displacement and soil water content, etc. over long lengths of asset at low cost), that may be able to highlight earthworks that are showing initial distress. Such systems could require little human intervention; remote sensing, wireless and internet technologies may all allow systems that are significantly automated.

There is also considerable potential to enhance the way that we view, manage and disseminate monitoring data using the internet; this paper has looked at two examples in the Norwegian XGEO and UK GeoSRM systems. Condition monitoring data could be used in the future to determine earthwork risk along significant lengths of route using physically based models; this has the potential to be updated in near-real time with, for example, forecast weather to show future probabilities for earthwork failure and thus disruption to transport operations.

Although such systems are very desirable, there are of course significant challenges to achieving these types of monitoring systems. These can be summarized in three points.

The assets: earthworks are difficult. They can be very variable in terms of geometry and material properties, there can be local ‘defects’, they are often covered with vegetation that can make assessment and condition monitoring difficult, and there are multiple modes of failure, some of which are complex and not well understood. Generally we need a much better understanding of the condition of these assets and the way in which they perform (or fail). This is also needed for the development of more pervasive monitoring approaches; for long lengths of asset what are the indicators of loss of performance? Instrumentation and monitoring data fundamentally underpin the models of physical asset behaviour, and risk, that are being explored further in other parts of the COST Action. The collection, storage, analysis and dissemination and sharing of more and better quality monitoring data can provide the information and models to properly understand modes of failure and deterioration, and the level at which to set thresholds for intervention. Any future automated system relying less on human input will be dependent on better models. The COST Action provides opportunities for closer collaboration and sharing of data between, for example, asset owners and research bodies.

The economics: new monitoring technologies and pervasive condition monitoring approaches offer promise, but there must be a good economic case for their use. Investment in more widespread use of monitoring needs to be based on savings to the economy from fewer failed earthworks and less disruption. It is doubtful that thus far the case is made in its entirety; the technologies and understanding of earthworks required to make these monitoring approaches work are incomplete, and asset owners often do not have the needed data on delay costs. This will change, as the technology and our expectations of ageing infrastructure systems also change. Regulatory bodies, government and public expectation will play a role in challenging operators to show continual improvement in safety and management systems. Many of the new instrumentation approaches described above have also been developed using national government and European Union grants, with financial and other support from road and rail asset owners. Continued strong investment in the development of technology for monitoring of earthworks, and a pro-active approach to seeking to prevent failure, will be critical.

Technological and human systems: the paper has described the developments in instrumentation for monitoring earthworks, with many systems providing enhancements in monitoring ability, reliability, longevity, cost, and the quality and quantity of data obtained. Several new techniques are very promising, but need further development for use in infrastructure slope monitoring. The ability to monitor more slopes at greater spatial and temporal resolution also requires handling, processing and analysis of significantly more data. This follows the economic trend for understanding systems using 'big data'. Automated systems that analyse large quantities of data are desirable, although their application may have limits; it could still be best to have human judgement of the data in major decision-making processes (e.g. before stopping traffic). This introduces the need to have enough suitably trained people to understand and review situations and make good and consistent decisions, and, where appropriate, the use of standardized monitoring (avoiding having large numbers of highly bespoke systems) and centralized control. The human influence in decision making requires careful processes and clear risk, decision and response plans are an essential part of major monitored systems.

These are all significant challenges, and it will require time and investment to achieve enhanced monitoring of European transport systems. These challenges can be overcome more easily if we collaborate, and share ideas and data as European partners, something the COST Action has been trying to achieve.

Conclusions

(1) This paper has explored the context and background to instrumentation and monitoring of infrastructure slopes in Europe. It has considered typical applications for monitoring, ranging from systems to warn of imminent failure, to monitoring for research to better understand the physical processes that take place in slopes.

(2) A number of novel instrumentation approaches have been described; some of these are gaining widespread use, and others are at the research and development stage. New technologies and systems are providing enhancements in monitoring ability, reliability, longevity, cost, and the quality and quantity of data obtained.

(3) There is considerable potential for the changing demands and expectations of infrastructure systems and new monitoring technologies to completely change the way that slopes are monitored in the future. It will probably be possible to monitor greater lengths of earthwork, with the intention of providing warning of and reducing incidences of unexpected failure (i.e. condition monitoring), rather than the fairly reactive monitoring approaches commonly seen today.

(4) Several new techniques for monitoring longer lengths of slope are promising, but need application-specific development before use for infrastructure slope monitoring. These techniques include optical fibres, LiDAR and photogrammetry, and wireless sensor networks.

(5) The ability to monitor more slopes at greater spatial and temporal resolution requires handling, processing and analysis of significantly more data. Automated systems that analyse large quantities of data are desirable, although human judgements in conjunction with careful decision-making frameworks will still be required.

(6) Improved modelling of risk at the route scale, and improving database and internet systems may allow the possibility of hazard or risk maps that update continually with asset condition-monitoring data and current or forecast climate. Such systems could prove invaluable to transport operators, as well as in communicating risk to the travelling public. This paper has looked at examples of such systems in use and in development.

(7) To allow more widespread monitoring and better communication of risk, improved models of slope performance and failure are required, as well as a better financial case. Parts of this are discussed in more detail in other papers from COST Action TU1202. Both will be underpinned by improved quality, collection, analysis and communication of monitoring data from infrastructure slopes.

(8) Greater communication and sharing of data and ideas between European nations and continued investment in monitoring technologies by European transport operators and governments is required to aid the monitoring challenges elucidated above.

Acknowledgements This paper is an output of Working Group 2 of EU COST Action TU1202 – Impacts of climate change on engineered slopes for infrastructure. TU1202 comprises four working groups: WG1 – Slope numerical modelling; WG2 – Field experimentation and monitoring; WG3 – Soil/vegetation/climate interactions; WG4 – Slope risk assessment. Outputs from each working group have been submitted to QJEGH and are intended to be read as a thematic set. The contributions of S. Uhlemann and J.E. Chambers are published with the permission of the Executive Director of the British Geological Survey, NERC.

Funding The authors gratefully acknowledge the funding for COST Action TU1202 through the EU Horizon 2020 programme, without which this Working Group output would not have been possible. J. Smethurst was also supported by the UK Engineering and Physical Sciences Research Council grant number EP/K027050/1. A. Smith was supported by the UK Engineering and Physical Sciences Research Council via a PhD studentship, a Doctoral Prize Fellowship, and two grants, numbers EP/H007261/1 and EP/D035325.

Scientific editing by Nick Koor; Sophie Messerklinger

References

Abbott, S., Power, C. & Mian, J. 2014. Presentation to the Slope Engineering & Geotechnical Asset Management Conference, London, held on 19 November 2014.

Abdoun, T., Bennett, V., Desrosiers, T., Simm, J. & Barendse, M. 2013. Asset management and safety assessment of levees and earthen dams through comprehensive real-time field monitoring. *Geotechnical and Geological Engineering*, **31**, 833–843.

Akca, D., Gruen, A., Askarinejad, A. & Springman, S. M. 2011. Photogrammetric monitoring of an artificially generated land slide. International Conference on Geo-information for Disaster Management (Gi4DM), Antalya, Turkey, 3–8 May 2011 [CD-ROM only].

Askarinejad, A., Casini, F., Bischof, P., Beck, A. & Springman, S.M. 2012. Rainfall induced instabilities: a field experiment on a silty sand slope in northern Switzerland. *Rivista Italiana di Geotecnica*, 3/2012 (Iuglio–Settembre 2012), 9–30.

Bemis, S.P., Micklethwaite, S., Turner, D., James, M.R., Akciz, S., Thiele, S.T. & Bangash, H.I. 2014. Ground-based and UAV-based photogrammetry: a multi-scale, high-resolution mapping tool for structural geology and paleoseismology. *Journal of Structural Geology*, **69**, 163–178, https://doi.org/10.1016/j.jsg.2014.10.007

Bles, T., Bassembinder, J., Chevreuil, M., Danielsson, P., Falemo, S. & Venmans, A. 2015. *Roadapt. Roads for today, adapted for tomorrow. Guidelines*. CEDR Transnational Road Research Programme, May 2015.

Boje, S., Devoli, G., Cepeda, J. & Colleuille H. 2014. Landslide thresholds at regional scale for an early warning system in Norway. Proceedings of the World Landslide Forum 3, 2–6 June 2014, Beijing.

Briggs, K.M., Smethurst, J.A., Powrie, W. & O'Brien, A.S. 2013. Wet winter pore pressures in railway embankments. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, **166**, 451–465, https://doi.org/10.1680/geng.11.00106

Briggs, K.M., Loveridge, F.A. & Glendinning, S. 2017. Failures in transport infrastructure embankments. *Engineering Geology*, **219**, 107–117.

BSI 2015. *BS EN ISO 18674-1:2015. Geotechnical investigation and testing. Geotechnical monitoring by field instrumentation. General rules*. British Standards Institution, London.

Buchli, T., Merz, K., Zhou, X., Kinzelbach, W. & Springman, S.M. 2013. Characterization and monitoring of the Furggwanghorn Rock Glacier, Turtmann Valley, Switzerland: results from 2010 to 2012. *Vadose Zone Journal*, **12**, 1–15.

Buchli, T., Laue, J. & Springman, S.M. 2016. Amendments to interpretations of SAAF inclinometer data from the Furggwanghorn Rock Glacier, Turtmann Valley, Switzerland: results from 2010 to 2012. *Vadose Zone Journal*, **15**, 1–3.

Caduff, R., Schlunegger, F., Kos, A. & Wiesmann, A. 2014. A review of terrestrial radar interferometry for measuring surface change in the geosciences. *Earth Surface Processes and Landforms*, **40**, 208–228.

Casini, F., Serri, V. & Springman, S.M. 2013. Hydromechanical behaviour of a silty sand from a steep slope triggered by artificial rainfall: from unsaturated to saturated conditions. *Canadian Geotechnical Journal*, **50**, 28–40, https://doi.org/10.1139/cgj-2012-0095

Castagnetti, C., Bertacchini, E., Corsini, A. & Capra, A. 2013. Multi-sensors integrated system for landslide monitoring: critical issues in system setup and data management. *European Journal of Remote Sensing*, **46**, 104–124.

CEDR 2011. Adaptation to climate change – Task 16 Report 2011. Conference of European Directors of Roads. www.cedr.fr/home/fileadmin/user_upload/Publications/2013/T16_Climate_change.pdf [last accessed 21 April 2016].

Chambers, J.E., Wilkinson, P.B. *et al*. 2011. Three-dimensional geophysical anatomy of an active landslide in Lias Group mudrocks, Cleveland Basin, UK. *Geomorphology*, **125**, 472–484.

Chambers, J.E., Gunn, D. *et al*. 2014. 4D electrical resistivity tomography monitoring of soil moisture dynamics in an operational railway embankment. *Near Surface Geophysics*, **12**, 61–72.

Chambers, J.E., Meldrum, P.I. *et al*. 2015. Spatial monitoring of groundwater drawdown and rebound associated with quarry dewatering using automated time-lapse electrical resistivity tomography and distribution guided clustering. *Engineering Geology*, **193**, 412–420, https://doi.org/10.1016/j.enggeo.2015.05.015

Chapman, T., Skinner, H., Brown, M. & Burland, J. 2012. *Institution of Civil Engineers Manual of Geotechnical Engineering*. Institution of Civil Engineers, London.

Cigna, F., Jordan, H., Bateson, L., McCormack, H. & Roberts, C. 2015. Natural and anthropogenic geohazards in greater London observed from geological and ERS-1/2 and ENVISAT persistent scatterers ground motion data: Results from the EC FP7-SPACE PanGeo project. *Pure and Applied Geophysics*, **172**, 2965–2995.

Clarke, D. & Smethurst, J.A. 2010. Effects of climate change on cycles of wetting and drying in engineered clay slopes in England. *Quarterly Journal of Engineering Geology and Hydrogeology*, **43**, 473–486, https://doi.org/10.1144/1470-9236/08-106

Dasenbrock, D. 2014. Performance observations of MEMS ShapeAccelArray (SAA) deformation sensors. *Geotechnical Instrumentation News*, June, 23–26. www.bitech.ca/pdf/GeoTechNews/2014/GIN%203202.pdf [last accessed 23 April 2016].

Devoli, G., Kleivane, I. *et al*. 2015. Landslide early warning system and web tools for real-time scenarios and for distribution of warning messages in Norway. *In*: Lollino, G., Giordan, D. *et al*. (eds) *Engineering Geology for Society and Territory*, **2**. Springer, Cham, 625–629.

Dijkstra, T. & Dixon, N. 2010. Climate change and slope stability in the UK: challenges and approaches. *Quarterly Journal of Engineering Geology and Hydrogeology*, **43**, 371–385, https://doi.org/10.1144/10.1144/1470-9236/09-036

Dijkstra, T., Dixon, N., Crosby, C., Frost, M., Gunn, D., Fleming, P. & Wilks, J. 2014. Forecasting infrastructure resilience to climate change. *Proceedings of the Institution of Civil Engineers: Transport.*, **167**, 269–280.

Di Prinzio, M., Bittelli, M., Castellarin, A. & Pisa, P.R. 2010. Application of GPR to the monitoring of river embankments. *Journal of Applied Geophysics*, **71**, 53–61, https://doi.org/10.1016/j.jappgeo.2010.04.002

Dixon, N., Hill, R. & Kavanagh, J. 2003. Acoustic emission monitoring of slope instability: development of an active wave guide system. *Proceeding of the Institution of Civil Engineers: Geotechnical Engineering*, **156**, 83–95.

Dixon, N., Spriggs, M.P., Smith, A., Meldrum, P. & Haslam, E. 2014. Quantification of reactivated landslide behaviour using acoustic emission monitoring. *Landslides*, 1–12, https://doi.org/10.1007/s10346-014-0491-z

Dixon, N., Smith, A., Spriggs, M.P., Ridley, A., Meldrum, P. & Haslam, E. 2015. Stability monitoring of a rail slope using acoustic emission. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, **168**, 373–384.

Donohue, S., Gavin, K. & Tolooiyan, A. 2011. Geophysical and geotechnical assessment of a railway embankment failure. *Near Surface Geophysics*, **9**, 33–44.

Donohue, S., Gavin, K. & Tolooiyan, A. 2013. Railway earthwork stability assessment using geophysics. *In*: Coutinho, R.Q. & Mayne, P.W. (eds) *Geotechnical and Geophysical Site Characterization 4*, **2**, Taylor & Francis, London, 1519–1525.

Dunnicliff, J. 1993. *Geotechnical Instrumentation for Monitoring Field Performance*. Wiley, New York.

Eastman, C., Fisher, D., Lafue, G., Lividini, J., Stoker, D. & Yessios, C. 1974. *An Outline of the Building Description System*. *Research Report No. 50*. Institute of Physical Planning, Carnegie–Mellon University, Pittsburgh, PA.

Eberhardt, E., Watson, A.D. & Leow, S. 2008. Improving the interpretation of slope monitoring and early warning data through better understanding of complex deep-seated landslide failure mechanisms. *In*: Chen, Z., Zhang, J. *et al*. (eds) *Landslides and Engineered Slopes*, Vol. 1. Taylor & Francis, London, 39–51.

Elia, G., Cotecchia, F. *et al*. 2017. Numerical modelling of slope–vegetation–atmosphere interaction: an overview. *Quarterly Journal of Engineering Geology and Hydrogeology*, **50**, First published online 29 June 2017, https://doi.org/10.1144/qjegh2016-079

ERA-NET 2010. *Risk Management for Roads in a changing climate – a guide to the RIMAROCC method*. Road ERA-NET, Linköping, Sweden.

Fan, L., Powrie, W., Smethurst, J.A., Atkinson, P.M. & Einstein, H. 2014. The effect of short ground vegetation on terrestrial laser scans at a local scale. *ISPRS Journal of Photogrammetry and Remote Sensing*, **95**, 42–52, https://doi.org/10.1016/j.isprsjprs.2014.06.003

Fookes, P.G. 1997. Geology for engineers: the geological model, prediction and performance. *Quarterly Journal of Engineering Geology*, **30**, 293–424, https://doi.org/10.1144/GSL.QJEG.1997.030.P4.02

Gavin, K., Martinović, K. *et al*. in review. Use of risk assessment frameworks for the management of European transport infrastructure networks. *Quarterly Journal of Engineering Geology and Hydrogeology*.

Glendinning, S., Hall, J.W. & Manning, L.J. 2009. Asset-management strategies for infrastructure embankments. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, **162**, 111–120.

Glendinning, S., Hughes, P. *et al*. 2014. Construction, management and maintenance of embankments used for road and rail infrastructure: implications of weather induced pore water pressures. *Acta Geotechnica*, **9**, 799–816.

Glendinning, S., Helm, P.R. *et al*. 2015. Research-informed design, management and maintenance of infrastructure slopes: development of a multi-scalar approach. *IOP Conference Series: Earth and Environmental Science*, **26**, 012005.

Glisic, B. & Inaudi, D. 2007. *Fibre Optic Methods for Structural Health Monitoring*. Wiley, Chichester.

Gong, C., Zeng, G., Ge, L., Tan, C., Luo, Q., Liu, X. & Chen, M. 2013. Design of long-distance and high-accuracy rail subgrade deformation monitoring system based on Zigbee wireless network. *Applied Mechanics and Materials*, **303–306**, 676–684.

Gunn, D.A., Chambers, J.E. *et al*. 2015. Moisture monitoring in clay embankments using electrical resistivity tomography. *Construction and Building Materials*, **92**, 82–94, https://doi.org/10.1016/j.conbuildmat.2014.06.007

Hardy, A.J., Barr, S.L., Mills, J.P. & Miller, P.E. 2012. Characterising soil moisture in transport corridor environments using airborne LIDAR and CASI data. *Hydrological Processes*, **26**, 1925–1936.

Highways Agency 2010. *A risk based framework for geotechnical asset management – Phase 2 Report*. Issue 1, November 2010.

Hooper, R., Armitage, R., Gallagher, A. & Osorio, T. 2009. *Whole-life infrastructure asset management: good practice guide for civil infrastructure. CIRIA Report C677*. Construction Industry Research and Information Association (CIRIA), London.

Hugenholtz, C., Walker, J., Brown, O. & Myshak, S. 2015. Earthwork volumetrics with an unmanned aerial vehicle and softcopy photogrammetry. *Journal of Surveying Engineering*, **141**, 06014003.

Hughes, D.A.B., Clarke, G.R.T., Harley, R.M.G. & Barbour, S.L. 2016. The impact of hydrogeology on the instability of a road cutting through a drumlin in Northern Ireland. *Quarterly Journal of Engineering Geology and Hydrogeology*, **49**, 92–104, https://doi.org/10.1144/qjegh2014-101

Hughes, P.N., Glendinning, S., Mendes, J., Parkin, G., Toll, D.G., Gallipoli, D. & Miller, P. 2009. Full-scale testing to assess climate effects on embankments. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, **162**, 67–79.

Huisman, J.A., Hubbard, S.S., Redman, J.D. & Annan, A.P. 2003. Measuring soil water content with ground penetrating radar, a review. *Vadose Zone Journal*, **2**, 476–491, https://doi.org/10.2113/2.4.476

Hutchinson, D. 2015. *Presentation at COST Action TU1202 workshop*. Ljubjiana, Slovenia, October 2015.

Intrieri, E., Gigli, G., Mugnai, F., Fanti, R. & Casagli, N. 2012. Design and implementation of a landslide early warning system. *Engineering Geology*, **147**, 124–136.

IPWEA 2006. *International infrastructure management manual*. Institute of Public Works Engineering Australasia, Sydney, Australia.

Jang, H.S., Kim, C.K., Lee, J.C., Lee, Y.D. & Oh, H.W. 2008. The analysis of road side slopes using RG helicopter photogrammetric system. *Proceedings of the XXIst ISPRS Congress, Beijing. ISPRS Archives*, **XXXVII**(Part B4), 395–398.

Kane, W.F., Beck, T.J. & Hughes, J.J. 2001. Applications of time domain reflectometry to landslide and slope monitoring. *In*: *Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications*. Infrastructure Technology Institute at Northwestern University, Evanston, IL, 305–314.

Kuras, O., Meldrum, P.I., Beamish, D., Ogilvy, R.D. & Lala, D. 2007. Capacitive resistivity imaging with towed arrays. *Journal of Environmental and Engineering Geophysics*, **12**, 267–279.

Lato, M., Hutchinson, J., Diederichs, M., Ball, D. & Harrap, R. 2009. Engineering monitoring of rockfall hazards along transportation corridors: using mobile terrestrial LiDAR. *Natural Hazards and Earth System Sciences*, **9**, 935–946.

Lato, M.J., Diederichs, M.S., Hutchinson, D.J. & Harrap, R. 2012. Evaluating roadside rockmasses for rockfall hazards using LiDAR data: optimizing data collection and processing protocols. *Natural Hazards*, **60**, 831–864.

Lehmann, P., Gambazzi, F., Suski, B., Baron, L., Askarinejad, A., Springman, S. M., Holliger, K. & Or, D. 2013. Evolution of soil wetting patterns preceding a hydrologically induced landslide inferred from electrical resistivity survey and point measurements of volumetric water content and pore water pressure. *Water Resources Research*, **49**, 7992–8004, https://doi.org/10.1002/2013WR014560

Lehtonen, V.J., Meehan, C.L., Lansivaara, T.T. & Mansikkamaki, J.N. 2015. Full-scale embankment failure test under simulated train loading. *Géotechnique*, **65**, 961–974.

Loke, M.H., Chambers, J.E., Rucker, D.F., Kuras, O. & Wilkinson, P.B. 2013. Recent developments in the direct-current geoelectrical imaging method. *Journal of Applied Geophysics*, **95**, 135–156.

Marjanovic, M., Abolmasov, B., Djuric, U., Zecevic, S. & Susic, V. 2013. Basic kinematic analysis of a rock slope using terrestrial 3D laser scanning on the M-22 highroad pilot site. *In*: Kwaśniewski, M. & Łydżba, D. (eds) *Rock Mechanics for Resources, Energy and Environment*, Taylor & Francis, London, 679–683.

Massey, C.I., Petley, D.N. & McSaveney, M.J. 2013. Patterns of movement in reactivated landslides. *Engineering Geology*, **159**, 1–19.

Miller, P.E., Mills, J.P. *et al*. 2008. Terrestrial laser scanning for assessing the risk of slope instability along transport corridors. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, **37**, 495–500.

Miller, P.E., Mills, J.P., Barr, S.L., Birkinshaw, S.J., Hardy, A.J., Parkin, G. & Hall, S.J. 2012. A remote sensing approach for landslide hazard assessment on engineered slopes. *IEEE Transactions on Geoscience and Remote Sensing*, **50**, 1048–1056.

Millis, S.W., Ho, A.N.L., Chan, E.K.K., Lau, K.W.K. & Sun, H.W. 2008. Instrumentation and real time monitoring of slope movement in Hong Kong. The 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG), 4563–4576.

Morin, G., Hassall, S. & Chandler, R. 2014. Case study – the real life benefits of geotechnical building information modelling. *In*: Toll, D.G., Zhu, H. *et al*. (eds) *Information Technology in Geo-Engineering*. IOS Press, Amsterdam, 95–102.

Network Rail 2015. *Climate change adaptation report 2015*. www.networkrail.co.uk/publications/weather-and-climate-change-resilience [last accessed 5 June 2016].

O'Kelly, B.C., Ward, P.N. & Raybould, M.J. 2008. Stabilisation of a progressive railway embankment slip. *Geomechanics and Geoengineering: An International Journal*, **3**, 231–244.

Perpetuum 2016. www.perpetuum.com [last accessed 30 March 2016].

Petley, D. N., Mantovani, F., Bulmer, M. H. & Zannoni, A. 2005. The use of surface monitoring data for the interpretation of landslide movement patterns. *Geomorphology*, **66**, 133–147, https://doi.org/10.1016/j.geomorph.2004.09.011

Powrie, W. 2014. On track: the future for rail infrastructure systems. *Proceedings of the Institution of Civil Engineers: Civil Engineering*, **167**, 177–185.

Reid, M.E., Baum, R.L., Lattusen, R.G. & Ellis, W.L. 2008. Capturing landslide dynamics and hydrologic triggers using near-real-time monitoring. *In*: Chen, Z., Zhang, J. *et al*. (eds) *Landslides and Engineered Slopes*, Vol. 1. Taylor & Francis, London, 179–191.

Richards, D.J., Chandler, R.J. & Lock, A.C. 2003. Electronic data transfer systems for field monitoring. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, **156**, 47–55.

Ridley, A.M., Dineen, K., Burland, J.B. & Vaughan, P.R. 2003. Soil matrix suction: some examples of its measurement and application in geotechnical engineering. *Géotechnique*, **53**, 241–254.

Sadler, J., Griffin, D., Gilchrist, A., Austin, J., Kit, O. & Heavisides, J. 2016. GeoSRM – online geospatial safety risk model for the GB rail network. *IET Intelligent Transport Systems*, **10**, 17–24, https://doi.org/10.1049/iet-its.2015.0038

Scaioni, M., Longoni, L., Melillo, V. & Papini, M. 2014. Remote sensing for landslide investigations: an overview of recent achievements and perspectives. *Remote Sensing*, **6**, 1–26.

Silvast, M., Nurmikolu, A., Wiljanen, B. & Levomaki, M. 2013. Identifying frost-susceptible areas on Finnish railways using the ground penetrating radar technique. *Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit*, **227**, 3–9.

Smethurst, J.A. & Powrie, W. 2007. Monitoring and analysis of the bending behaviour of discrete piles used to stabilise a railway embankment. *Géotechnique*, **57**, 663–677, https://doi.org/10.1680/geot.2007.57.8.663

Smethurst, J.A., Clarke, D. & Powrie, W. 2006. Seasonal changes in pore water pressure in a grass-covered cut slope in London Clay. *Géotechnique*, **56**, 523–537, https://doi.org/10.1680/geot.2006.56.8.523

Smethurst, J.A., Clarke, D. & Powrie, W. 2012. Factors controlling the seasonal variation in soil water content and pore water pressures within a lightly vegetated clay slope. *Géotechnique*, **62**, 429–446, https://doi.org/10.1680/geot.10.p.097

Smethurst, J.A., Briggs, K.M., Powrie, W., Ridley, A. & Butcher, D.J.E. 2015. Mechanical and hydrological impacts of tree removal on a clay fill railway embankment. *Géotechnique*, **65**, 869–882, https://doi.org/10.1680/geot.14.p.010

Smith, A. & Dixon, N. 2015. Quantification of landslide velocity from active waveguide generated acoustic emission. *Canadian Geotechnical Journal*, **52**, 413–425, https://doi.org/10.1139/cgj-2014-0226

Smith, A., Dixon, N., Meldrum, P. & Haslam, E. 2014*a*. Inclinometer casings retrofitted with acoustic real-time monitoring systems. *Ground Engineering*, October, 24–29.

Smith, A., Dixon, N., Meldrum, P., Haslam, E. & Chambers, J. 2014*b*. Acoustic emission monitoring of a soil slope: comparisons with continuous deformation measurements. *Géotechnique Letters*, **4**, 255–261, https://doi.org/10.1680/geolett.14.00053

Smith, A., Dixon, N., Moore, R. & Meldrum, P. 2017. Acoustic emission monitoring of coastal slopes in NE England, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, **50**, First published online 15 February 2017, https://doi.org/10.1144/qjegh2016-081.

Springman, S.M., Kienzler, P., Casini, F. & Askarinejad, A. 2009. Landslide triggering experiment in a steep forested slope in Switzerland. 17th International Conference on Soil Mechanics & Geotechnical Engineering (ICSMGE), Alexandria, Egypt, Vol. 2, 1698–1701.

Springman, S.M., Askarinejad, A., Casini, F., Friedel, S., Kienzler, P., Teysseire, P. & Thielen, A. 2012. Lessons learnt from field tests in some potentially unstable slopes in Switzerland. *Acta Slovenica Geotechnica*, **1**, 5–29.

Stähli, M., Sättele, M. *et al*. 2014. Review article: Monitoring and prediction in Early Warning Systems (EWS) for rapid mass movements. *Natural Hazards and Earth System Sciences (NHESS)*, **2**, 7149–7179.

Steelman, C.M., Endres, A.L. & Jones, J.P. 2012. High-resolution ground-penetrating radar monitoring of soil moisture dynamics: field results, interpretation, and comparison with unsaturated flow model. *Water Resources Research*, **48**, 1–17, https://doi.org/10.1029/2011WR011414

Thévenaz, L. 2010. Brillouin distributed time-domain sensing in optical fibers: state of the art and perspectives. *Frontiers of Optoelectronics in China*, **3**, 13–21, https://doi.org/10.1007/s12200-009-0086-9

Toll, D.G., Lourenco, S.D.N. *et al*. 2011. Soil suction monitoring for landslides and slopes. *Quarterly Journal of Engineering Geology and Hydrogeology*, **44**, 23–33, https://doi.org/10.1144/1470-9236/09-010

Toll, D.G., Lourenço, S.D.N. & Mendes, J. 2013. Advances in suction measurements using high suction tensiometers. *Engineering Geology*, **165**, 29–37, https://doi.org/10.1016/j.enggeo.2012.04.013

Topp, G., David, J. & Annan, A. 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research*, **16**, 574–582.

Uhlemann, S.S., Sorensen, J.P.R. *et al*. 2016. Integrated time-lapse geoelectrical imaging of wetland hydrological processes. *Water Resources Research*, **52**, 1607–1625.

Utili, S., Castellanza, R., Galli, A. & Sentenac, P. 2015. Novel approach for health monitoring of earthen embankments. *Journal of Geotechnical and Geoenvironmental Engineering*, **141**, 3, https://doi.org/10.1061/(ASCE)GT.1943-5606.0001215

Vesterberg, B., Bertilsson, R. & Löfroth, H. 2017. Monitoring of negative porewater pressure in silt slopes. *Quarterly Journal of Engineering Geology and Hydrogeology*, **50**, First published online 24 March 2017, https://doi.org/10.1144/qjegh2016-083.

Wang, E.F., Wang, G. *et al*. 2008. Displacement monitoring on Shuping landslide in the Three Gorges Dam Reservoir area, China from August 2004 to July 2007. *In*: Chen, Z., Zhang, J. *et al*. (eds) *Landslides and Engineered Slopes*. Taylor & Francis, London, **2**, 1321–1327.

Wasowski, J., Bovenga, F., Dijkstra, T., Meng, X., Nutricato, R. & Chiaradia, M. T. 2014. Persistent scatterers interferometry provides insight on slope deformations and landslide activity in the mountains of Zhouqu, Gansu, China. Proceedings of World Landslide Forum, **3**, 2–6 June 2014, Beijing.

Westerberg, B., Bertilsson, R., Prästings, A., Müller, R. & Bengtsson, P.E. 2014. *Negative pore water pressures and stability of silt slopes*. Swedish Geotechnical Institute, Publication, **9** [in Swedish].

Wilkinson, P.B., Chambers, J.E., Meldrum, P.I., Gunn, D.A., Ogilvy, R.D. & Kuras, O. 2010. Predicting the movements of permanently installed electrodes on an active landslide using time-lapse geoelectrical resistivity data only. *Geophysics Journal International*, **183**, 543–556.

Wilkinson, P.B., Uhlemann, S., Chambers, J.E., Meldrum, P.I. & Loke, M.H. 2015. Development and testing of displacement inversion to track electrode movements on 3-D electrical resistivity tomography monitoring grids. *Geophysics Journal International*, **200**, 1566–1581, https://doi.org/10.1093/gji/ggu483

Zhu, H.-H., Shi, B., Yan, J.-F., Zhang, J. & Wang, J. 2015. Investigation of the evolutionary process of a reinforced model slope using a fiber-optic monitoring network. *Engineering Geology*, **186**, 34–43.