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The Growing Risk of Slope Failure to Strategic Infrastructure – Risk Mitigation and the Role of Intelligent Monitoring Solutions

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Abstract

Strategic infrastructure assets such as roads and railways in many parts of the world are built on embankments or adjacent to steep slopes. Climate change has brought increasingly frequent extreme weather events and slope failures have become more common. Failures can manifest in gradual settlement and disruption, or sudden landslides or rockfalls and significant threat to human life.

The authors aim to describe the challenges facing infrastructure owners, different approaches to inspection, monitoring and risk management and focus on the development of wireless remote condition monitoring. The adoption and large scale deployment of the technology by rail operators, specifically Network Rail, is described and data are presented from a landslip event affecting the railway.

The emergence of internet of things (IoT) technologies has enabled the development of wireless intelligent monitoring solutions (IMS), which detect and respond to ground movement and provide early warning to geographically dispersed stakeholders.

The core element of such a system is a network of long-life movement sensors connected to each other and the internet via a wireless radio platform. Such systems display many IoT attributes: they are cost-effective; small; easy to install and need little or no maintenance over their ultra-long (>10 years) lives. They do not need mains power and operate as a self-healing system that can sustain damage to individual components. Wireless systems can integrate movement sensors with automated cameras and geotechnical logging instruments for added insight.

The authors conclude that the technology provides a solution that is sufficiently responsive and robust for large-scale deployment, and that it can provide users with a means of slope risk mitigation relating to remote and vulnerable assets.

Keywords: Slope Stability, Embankments, Monitoring, Rail.

1. Introduction: Risks & Challenges

Railways in many parts of the world are built on embankments or adjacent to natural or man-made slopes. The safe and efficient use of these assets can be adversely affected by movement of soil, rock or vegetation in such a way as to block or de-stabilise the route. Failures can manifest in gradual settlement and deformation giving rise to disruption and the need for expensive engineering intervention, or to sudden landslides, rockfalls or washout failures that pose a significant threat to operations and to human life.

Factors that contribute to growing concern about slope failure risk include:

- an increase in extreme weather events associated with climate change, including more frequent episodes of prolonged heavy rainfall – a key factor in reducing ground stability (Bracegirdle, 2007)
- increasing levels of rail traffic, which increases the risk that an event will have an impact on people, and the potential severity of that impact
- the age of many man-made earthworks, which pre-date design standards, are poorly drained, and are overly steep by modern standards (Martinovic, 2016)
- a more risk averse culture, where asset managers face pressure to predict and prevent events rather than fix them retrospectively.

With this background, we consider historic practice and examine the use of IMS based on wireless remote condition monitoring technology to mitigate the risks of slope failure by detecting ground movement and warning stakeholders.

In particular, we describe the use of intelligent monitoring solutions by Network Rail on UK railways.

2. Asset Management – Historic Practice

Historically, asset managers have inspected and monitored slopes where and when there is particular concern, but the established tools available to them were labour-intensive and often ineffective in providing stakeholders with useful warning.

Determining the optimal monitoring approach for a rail site is usually based on a risk assessment taking into consideration factors including the history of the site, the traffic using the route and visual inspections. Network Rail categorize the risk of slope failure depending on the speed of the event. Their categories are Slow, such as the gradual settlement of an embankment; Rapid, such as a landslip and Instantaneous, such as rockfall (Network Rail, 2018). Historically, slope management practice has been based on periodic visual examination and attended surveys. Where particular concern about slope failure risk has arisen, geotechnical (subsurface) monitoring, for example using borehole piezometers, inclinometers and extensometers may be undertaken. This is expensive, requires periodic site visits and manual logging and is not only labour-intensive, but ineffective at predicting rapid slope failure, or notifying users quickly following a failure. A better way of mitigating the risks is needed and wireless remote monitoring is an option with a number of attractions (Mair, 2021).

But the use of this type of solution in this application is challenging. Sites are mostly rural and often located at the bottom of steep slopes or perched on embankments; they therefore sometimes have poor cellular coverage. Very few sites have electrical power supply, and gaining access to transport and install equipment is often difficult. Most significant though, is the challenge of assuring all parties that a system will deliver the level of reliability and repeatability needed to provide an effective warning system.

3. Wireless Monitoring Solutions

Asset managers and engineers responsible for at-risk slopes near railways have a number of options in terms of gathering data relating to failure detection. These have advantages and disadvantages summarised in Figure 1 below. In general, methods that rely on human attendance on site can provide a rapid response, but are considered impractical for anything more than emergency monitoring. Methods that operate in "always-on mode" such as CCTV require fixed power supply and may still require a person to monitor the data off-site. Devices that are usually asleep but take samples at fixed intervals such as automated total stations may be effective in detecting incremental ground movement but not sudden movement such as landslips. Manual monitoring methods such as logging borehole instruments are labour-intensive and provide sparse sampling. Faced with these choices, infrastructure owners such as Network Rail have explored alternative approaches – one of which is the type of intelligent remote monitoring systems discussed in this paper.

The aim of development work over the last five years has been to deliver a reliable ground movement detection system that can operate in low-power mode until an event such as sudden movement triggers them to wake up; such a system would be able to provide long-term monitoring that is highly responsive to the type of events that could bring disruption or danger to the railway or road operator.

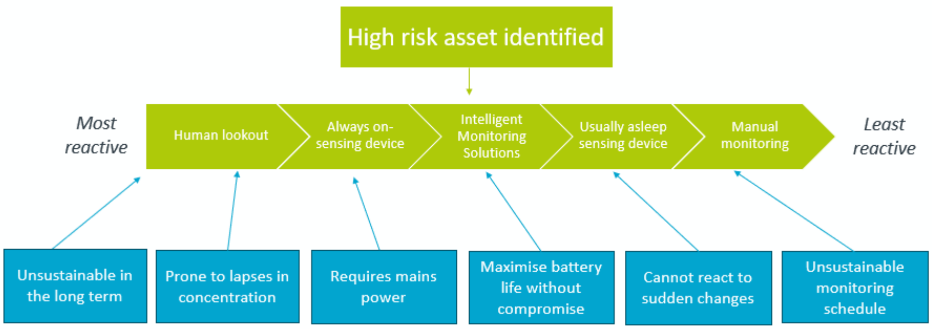


Figure 1: Relative merits of monitoring approaches applied to high-risk assets.

The emergence of robust, reliable, connected technologies associated with the internet of things (IoT) has enabled the development of wireless intelligent monitoring systems (IMS) that can be effective in remote locations. They are able to detect and respond to ground movement and provide early warning to geographically dispersed stakeholders.

The core element of such a system is a network of long-life MEMS tilt sensor nodes connected to each other and the internet via a wireless radio platform. Sensor data are collated at a gateway and relayed to an online user interface (WebMonitor™) via either the HSPA+ (3G) or LTE (4G) communication technologies.

Such systems display many of the attributes associated with IoT devices: they are relatively inexpensive; small; easy to install and need little or no maintenance over their ultra-long (>10 years) lives. They communicate with users without wired connections for power or communications and operate as a self-healing system that can sustain damage to individual components.

The characteristics described above are common to many wireless remote condition monitoring systems. The focus of this paper is a more sophisticated version i.e. the InfraGuard™ intelligent monitoring system as developed for use on railway earthworks.

A number of key attributes are present in a monitoring system that can be defined as an IMS. These relate principally to automation/self management and responsiveness.

The InfraGuard™ solution is built around a network of intelligent sensors that communicate with the internet via a mesh-networked wireless communication platform (FlatMesh™). This was developed over the last decade by Senceive with its roots traceable to research at University College London initiated in 2005. A version launched in 2013 was the first to incorporate edge computing and built-in intelligence in the sensor nodes. By 2015, variable reporting rates, automated event triggering and an integrated camera were added, along with improvements to power consumption giving a typical node life of more than a decade between battery changes.

Intelligent processing of data at the sensor node and automatic decision-making capability has benefited remote geotechnical condition monitoring applications. Sampling is normally set at fixed intervals of 15 to 60 minutes, but this is automatically accelerated in the event of a sudden movement event in order to send alerts in near real-time. The detection of movement will also trigger other nodes in the network to wake up and the camera node to capture an image. Where critical conditions arise, the network gateway automatically allows the override of communication protocols to enable immediate data transmission to the server.

Examples of tilt nodes used as part of a wireless IMS are the Senceive IX and Nano families of tilt sensor which measure rotational movement at a resolution of 0.0001° (0.0018 mm/m). The computational capability built into the tilt node is a factor in making the mesh sufficiently robust to withstand short or long-term damage without systematic loss of performance. In the event of a short-term outage, data can be stored on board the node and forwarded when network coverage is resumed. If a node is subject to long-term damage (for example by impact with construction equipment) the neighbouring nodes will automatically adjust by finding the most efficient transmission pathway to the gateway.

4. Precision, Durability, Repeatability and Latency

Key considerations for a system that fulfils a safety-related role on the rail network include precision, durability, repeatability and latency.

The precision of tilt meter readings measuring soil movement on slopes has been compared with measurements from robotic total stations at a site in Austria (Berger, 2021). Tilt sensors and prisms were mounted on the same metal stakes inserted into the ground.

Figures 2a and 2b below present a comparative dataset where data are presented as longitudinal displacement in the x-axis. It is evident that there is a high degree of correlation between the two datasets, indicating that tilt meters provide a comparable degree of precision in this application.

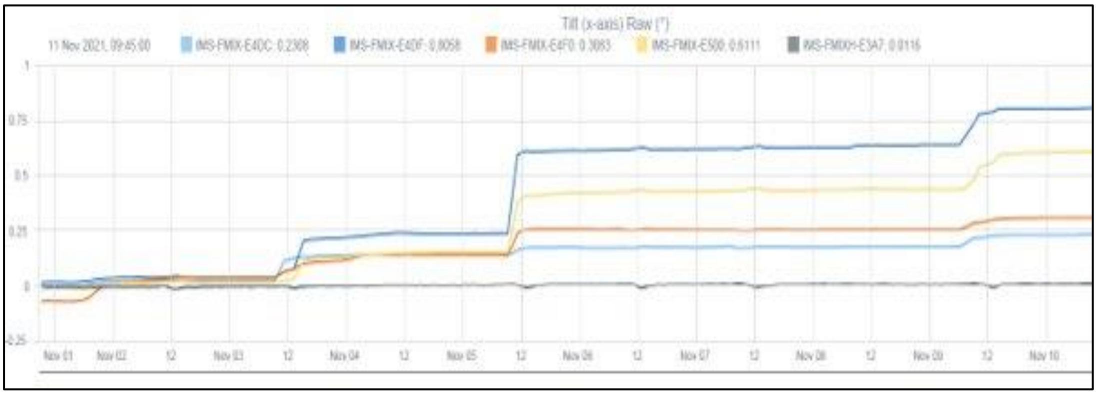


Figure 2a. Movement data (cm) from tiltmeters on stakes

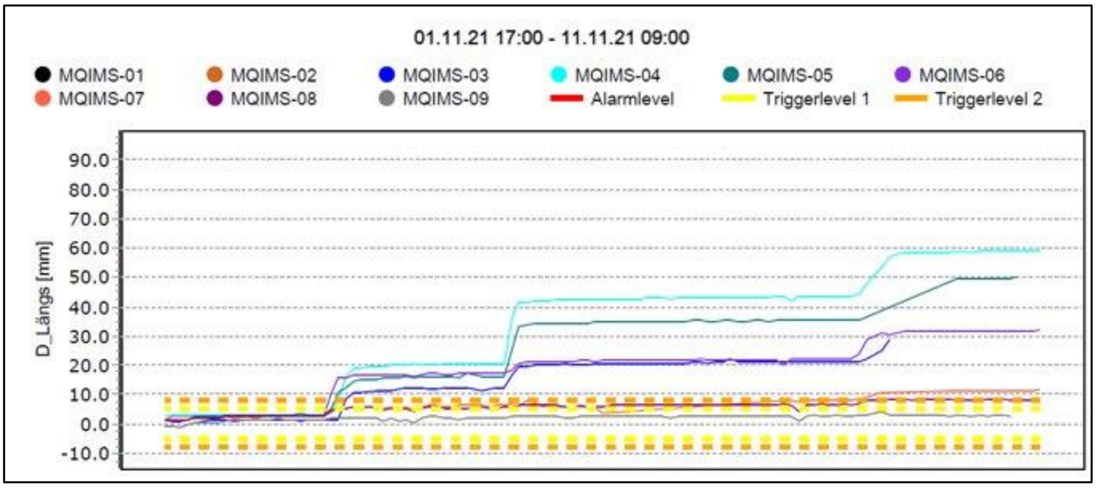


Figure 2b. Movement data (mm) of prisms measured by robotic total station readings

In terms of durability, the intention is that the monitoring system will operate in all weather and light conditions for many years without significant human intervention. The hardware elements are designed and built to operate in environmental conditions beyond any likely to be experienced in Europe or the USA. The tilt sensors, for example, are specified to operate in a temperature range of -40°C and +85°C. Battery life of the tilt sensors is 12 to 15 years at the typical reporting frequency. The cellular communications hub and cameras are powered by a solar panel.

A small degree of human interaction is required, however. There is a need to selectively clear vegetation to prevent it making contact with the tilt sensors or obstructing the cameras, and there is a need to clean the solar panels in areas prone to tree sap or other precipitation.

The term latency relates to the lag between a measurement being taken and sent. For the camera, latency refers to the lag between receipt of a trigger to activate the camera, to the picture being available in the web gallery. The typical latency is 1 minute 30 seconds. For the tilt node, latency is defined as the time from receipt of a request to take a measurement to an alert being sent to the WebMonitor™ portal. The typical latency is 2 minutes and 41 seconds.

A further key requirement of a monitoring system is ensuring that the instruments deliver a level of repeatability to minimize spurious readings and misleading alerts that could disrupt end-users and reduce confidence in the system. Repeatability is defined by the Bureau International des Poids et Mesures as measurement precision under a set of repeatability conditions. For IX tilt sensors, the value is ±0.0005°, equating to ±0.0087 mm/m.

At present the only sensors that can be used to automatically trigger an alert are triaxial tilt sensors. Other sensors can, however, be incorporated into the same wireless monitoring programme, including a laser extensometer sensor node referred to as an optical displacement sensor, crack sensors, a camera and vibrating wire Millivolt/Volt integrator nodes that connect to third party sensors.

5. Network Rail and Slope Failure Risks

Network Rail owns and maintains the mainline rail network in the UK. The core elements of this network are mostly more than 130 years old, including most of the 190,000 earthworks.

Figure 3. *Steep cutting slopes are prone to landslide after heavy rain (left) and track damage can be caused by flooding and damage to supporting materials (right)*

Several routes include a combination of attributes that combine to generate a relatively high level of risk of disruption associated with slope failure. Factors include the presence of steep slopes, unstable geology, increasingly frequent periods of extremely wet weather and high traffic levels.

The busy commuter lines to the south of London through Kent, Sussex and Wessex are prime examples, and the asset managers responsible for them have chosen to implement widespread monitoring of the cuttings and embankments to mitigate the effects of the types of failure shown in Figure 3.

5.1 Large-scale monitoring in Network Rail Southern Region

A decision was made to invest approximately £6 million on earthworks monitoring in an initial large-scale rollout of wireless monitoring in Kent and Sussex within Southern Region, with the intention of commissioning the system before the winter storm season of 2020/21. In order to make the deployment efficient and simple enough to be performed by non-specialists, a standardised approach was taken for every location. Each site was divided into blocks of 100 m (equating to five chains on the traditional UK rail system). Within each block, 50 tilt sensor nodes, two cameras and one solar-powered cellular communications gateway were installed.

In Sussex, the tilt sensors were installed at four metre centres in a pair of staggered rows at the foot of the slope and two metres up the slope. The team in Kent opted to install one row at the bottom of the slope, and one row at the top. In all cases the sensors were fixed to vertical metal poles driven 500 mm into the ground.

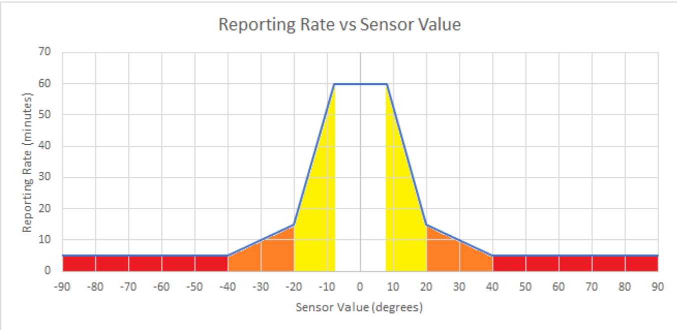
The shortest sites have just one of these blocks, whereas longer sites have several. The longest, at Haywards Heath has 20 blocks comprising 20 gateways, 40 cameras and 996 tilt sensors. In the initial phase of work a total length of 9.7 km was instrumented in Sussex, and 12.7 km in Kent.

The Southern Region programme has subsequently grown to a total of 39 km across the Kent, Sussex and Wessex routes. Equipment installed includes more than 10,000 tilt nodes, 500 cameras and 200 gateways.

Figure 4. *Left - installing Edgehub Gateway, 4G camera and solar panel. The Edgehub collates sensor and image data and transfers to stakeholders via the cellular network. Right - installing tilt nodes on metal stakes.*

Installation (Figure 4) on this scale has enabled significant efficiency gains. Towards the end of the project, an entire 100 m installation could be completed in a single shift that only provided four or five working hours at the worksite. This included ecological, topographic and buried utility surveys, selective vegetation clearance, installing nodes, cameras and the gateway with its solar panel, and completing an as-built survey. The monitoring installation was done by contractors with no prior experience. Most of the work was done without line closures.

A standard workflow was developed for the project. The system was functioning before the team left site. Full configuration and signoff took place typically within 48 hours of completion on site, with camera optimization being the most demanding aspect. The data feed and documentation were then checked and approved by the Network Rail route asset manager and pushed through to Route Control once signed-off. The system employs a standardised series of alerts based on the scale of movement recorded. These are summarised in Figure 5 below, together with the dynamic reporting rates which provide increased sampling as the level of concern grows.



Alert	Alert Threshold	Reporting Rate
Red	-40 degrees	5 minutes
Amber	-20 degrees	15 minutes
Yellow	-8 degrees	1 hour
None		1 hour
Yellow	8 degrees	1 hour
Amber	20 degrees	15 minutes
Red	40 degrees	5 minutes

Figure 5. *Left: reporting rate versus sensor value: Right: alert thresholds and dynamic reporting rates*

Most of the system commissioned in Kent and Sussex was operational through the winter of 2020/2.

Figure 6. *Example of images from 4G Camera, left image taken at Midday, right image at Midnight.*

Figure 6 shows examples of images from one of the 4G solar-powered cameras, demonstrating the capability to see the track both in daylight and in dark overnight conditions.

The intelligent monitoring solution described here is intended to detect surface movement of slopes and provide timely warning to remote stakeholders. In addition to the tilt sensors used to detect movement, the wireless monitoring platform at the core of the system can incorporate a range of other sensors, including subsurface geotechnical instruments. The Network Rail project described above included a limited number of borehole piezometers installed in the same system as the tilt sensors and cameras. Although not included within the project described, other instruments that have been incorporated in wireless monitoring systems include vibrating wire rod extensometers, in-place inclinometers (IPI) and vibrating wire piezometers.

6. Results

This type of intelligent monitoring technology has been installed on slopes in Network Rail Southern Region since 2019. An examples of landslide detection at one of these sites is summarised below.

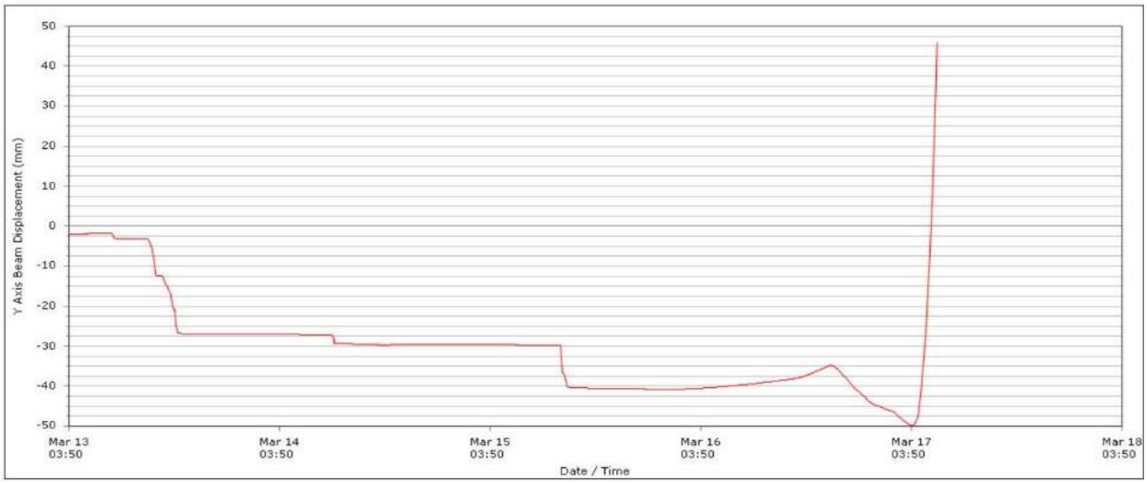


Figure 7a. *Wadhurst Slope Failure Graph – 4 days*

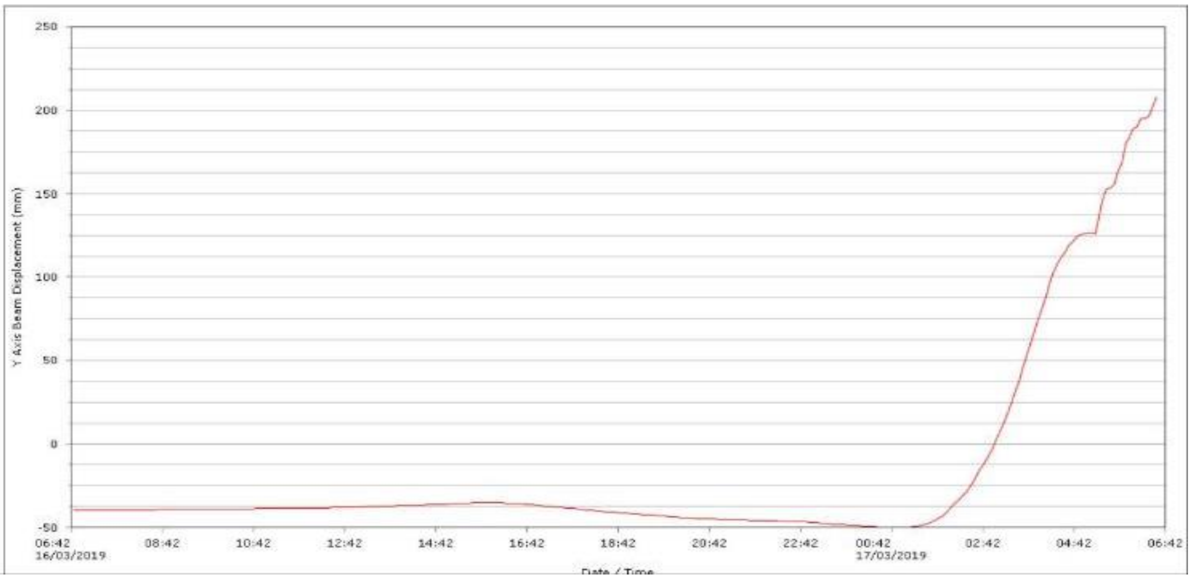


Figure 7b. *Wadhurst Slope Failure Graph - 24 hours*

The steep slope over the southern tunnel portal at Wadhurst on the Hastings Line had been identified as an at-risk site early in the monitoring program and was selected as a priority area. Tilt nodes mounted on stakes were installed to the sides of the track and on the steep slope overlying the portal.

Data presented in Figure 7 above show Y axis beam displacement of a single tilt node located in the area above the tunnel portal. Figure 7a shows movement data over a four day period and Figure 7b shows a 24 hour view. A pattern of incremental movement can be observed in the data from March 13th up to March 17th 2019, at which point a sudden large-scale event occurs. The extent of that event can be seen in the aerial view in Figure 8. It was estimated that more than 60 tonnes of loose earth had slipped towards the track.

Figure 8. *Aerial view of slope failure above Wadhurst Tunnel*

7. Conclusions

Advantages over geodetic based monitoring or human observation/inspection have been found to be significant. The most obvious advantage is more effective early warning of slope failures due to enhanced temporal and spatial sampling. Other benefits include a significant reduction in site visits needed, for example to inspect slopes visually or clean prism reflectors where optical monitoring systems are installed. Datasets based on more frequent sampling provide greater assurance that significant events will be detected, and the ability to validate alerts using remote cameras cuts the need for unnecessary site visits and reduces the risk of false alerts.

The Wadhust data presented here demonstrate the ability to detect incremental ground movement as well as sudden large-scale slope failure. This is significant in the context of wireless monitoring in this application because, while earlier systems would be effective in detecting the small incremental movements, they would not realistically be capable of detecting and alerting stakeholders of the sudden movement events sufficiently quickly to send alerts and stop train traffic.

Further developments are expected to include greater integration of data streams to better predict slope failure and network disruption. Integration of ground movement data with highly localized rainfall data is the most obvious candidate.

The intelligent monitoring system described here was developed explicitly for use on earth slopes adjacent to railways. It would be less effective where the main concern is rockfall, because a significant-sized individual rock could fall in a path between the sensors and remain undetected. There are other rail applications where the same type of system could be applied, however. Examples include embankments and flood defence levees and bridges regarded as being at-risk of sudden failure due to impact with vessels or damage by scour.

Acknowledgements

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