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Intelligent Monitoring Solution to manage slope risk on Network Rail earthworks: large scale deployment in Kent, Sussex and Wessex

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Abstract

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.

Historic management practice has been based on manual inspection and attended survey. More recent technological development has brought automated survey instruments, remote sensing and better data management, e.g. improved weather forecasting. All have limitations, however, such as limited spatial and temporal sampling and the need for frequent site visits and associated costs and risks.

Internet of things (IoT) technology 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.

Over the last decade this technology has moved from the laboratory to become widely adopted by users such as the UK’s Network Rail, who installed more than 10,000 smart sensors in 2020. The same remote condition monitoring platforms have now been approved in a growing list of countries including Germany, France, Canada and the USA.

Keywords: IoT, Embankments, Slope failures, Monitoring.

1. Introduction

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 rail corridor. 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 et al)
- 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 et al)
- 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.

1.1 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 categorise 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 landslide and Instantaneous, such as rockfall (Network Rail). 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 et al).

But the use of this type of solution in this application is challenging. Sites are mostly rural and often 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.

2 Wireless monitoring solutions

2.1 Monitoring options

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 operator.
2.2 Intelligent monitoring systems

The emergence of robust, reliable, connected technologies associated with the internet of things (IoT) has enabled the development of wireless (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 Limited, 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. 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.

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). Tilt sensors and prisms were mounted on the same metal stakes inserted into the ground. Figure 3 below presents 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 2: Comparison of data from tiltmeters on stakes (left) and robotic total station readings (right).](image)

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.

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 the IX tilt sensors deployed on this project, 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 mV/V integrator nodes that connect to third party sensors. It is not possible to operate an IMS on the LoRaWAN point to point radio communications network that is used by much of the wireless monitoring industry due to lack of bandwidth and issues relating to synchronisation and communication.

3. 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.

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 5.

3.1 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 (Figure 6), 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.

![Figure 3: Map showing Network Rail Southern Region, indicating the Wessex, Sussex and Kent routes](image)

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. This level
of insertion has been found to be optimal both terms of detecting rotational movement in the upper soil and in
terms of the ability to withstand accidental impact – such as deer using the posts for scratching.

Large-scale installation (Figure 4) 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.

![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.](image)

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 optimisation
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.
The system employs a standardised series of alerts based on the scale of movement recorded. These are summarised in Table 1, together with a description of the management actions triggered at each level.

<table>
<thead>
<tr>
<th>Response level</th>
<th>Scale of movement</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 Green</td>
<td>10 mm</td>
<td>Flight engineer determines whether the results are genuine, informs asset management team, carries on monitoring.</td>
</tr>
<tr>
<td>Level 2 Yellow</td>
<td>30 mm</td>
<td>Flight engineer determines whether results are genuine, informs asset management team and sends someone out to check the site.</td>
</tr>
<tr>
<td>Level 3 Red</td>
<td>60 mm</td>
<td>All of the above, plus they will let the asset management team know whether to impose an emergency speed restriction and trigger any work.</td>
</tr>
<tr>
<td>Level 4 Black</td>
<td>90 mm</td>
<td>All of the above, plus stop or caution the train.</td>
</tr>
</tbody>
</table>

**Table 1**: Trigger levels and actions

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

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. It is important to note that, whilst data can be reported periodically to remote stakeholders, these instruments cannot currently form a dynamic part of the IMS (which relies solely on detection of near-surface ground movement).
4. Results

This type of intelligent monitoring technology has been installed on slopes in Network Rail Southern Region since 2019. Examples of landslip detection at two sites are summarised below.

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 programme 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 below show Y axis beam displacement of a single tilt node located in the area above the tunnel portal. The graph on the left shows movement data over a four day period and the graph on the right 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 11. It was estimated that more than 60 tonnes of loose earth had slipped towards the track.

A second example of monitoring detecting a landslide in this early phase of the wireless monitoring programme was at Barnehurst on the Bexleyheath Line. This had also been classed as a high-risk site due to a history of instability affecting the steep cutting slopes. A monitoring system comprising 250 stake-mounted tilt sensors and 10 solar-powered cameras was installed to give warning of further failures (Wordsworth).

Following a prolonged period of heavy rainfall, a single node generated a red (>60 mm) alert on the 7th February 2019, followed by a single node black (>90 mm) alert the next day. This triggered an inspection by the Earthworks Examiner and was followed by multiple node alerts in the early hours of the 11th February. A camera overlooking the affected area was triggered and images showed that earth and trees had slipped down the slope and onto the track. Notifications were sent to Route Control and trains were stopped – preventing a potentially dangerous incident.

Figure 9 shows an example graph of X axis beam displacement from one of the nodes giving rise to a black alert during the landslide. Movement of more than 90 mm is apparent over a period of less than one hour.
5. 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 and automated alerting. 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 Wadhurst 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 wireless 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 movements.

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 localised 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.

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References


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