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Sensor Networks for Monitoring Major Infrastructure and Pre-Emptive Activity to Avoid Catastrophic Failures

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ABSTRACT

The application of autonomous sensors to monitor major pieces of infrastructure has been well understood for over 15 years. During this time, sensors have become lower powered, easier to install and with more efficient data flows. This has democratised the act of monitoring across a wider range of end users, allowing more time-sensitive and data-supported decisions. This paper outlines the application of sensors in monitoring rail and tunnel infrastructure whilst also demonstrating instances where the use of sensors has led to actions preventing a potential catastrophic failure. In the rail sector, the use of biaxial (now triaxial) sensors to measure lateral trackbed deformation (cant) led to the correlation of longitudinal tilt with manually surveyed settlement. Tilt sensors are now widely deployed in the rail environment, negating the need for manual survey and the line-of-sight requirement for an optical measurement. The application of sensors can measure tunnel convergence, settlement or ovalisation. Similarly in tunnels, line of sight for traditional total station measurements can often be limited or ongoingly obstructed. A key feature of the use of sensors and cloud reporting is the configuration of thresholds and alerts to notify key personnel that an underlying structure is approaching non-conformance or, in some instances, failure. This paper demonstrates the data that led to key decisions being made to avert potential failures. The use of autonomous sensors has the potential to increase data collection, analysis and cost efficiencies whilst also keeping the workforce and community safe.

KEYWORDS: *Rail, tunnel, sensor, alert, failure*.

1 INTRODUCTION

Monitoring is a key activity primarily undertaken by surveyors and often requires interaction with other professions such as engineers and geotechnicians. Often, the success of a monitoring program is not simply reliant on the taking of measurement but also the ability to take this measurement repetitively and ensure results are distributed efficiently. As urban populations typically become denser, the interaction between social infrastructure and construction activities increasingly become unavoidable. Monitoring is inevitably mandated statutorily or, if not, undertaken by the constructor as a means of maintaining positive community relations.

This paper reflects on the application of sensor-based monitoring systems and shows not only the data leading up to a failure but how the effective application of a system has led to the avoidance of potentially damaging failures. It should be noted that the sensors discussed in this paper have been independently verified against conventional surveying and measuring techniques by the Monash Institute of Rail Technology (Muthuraj and Naidoo, 2021) and the

Transportation Technology Center Inc. (TTCI) in the United States (Wilk, 2021). In the interest of focusing this paper on applications, their results will not be discussed here.

2 MONITORING SYSTEMS

2.1 Definition

This paper refers to monitoring as being a system as opposed to the act of taking a measurement, albeit very precisely. A key element of a monitoring system is that the autonomous nature of monitoring produces results with high levels of precision with minimal human and instrument error. Not only is the act of taking a single measurement autonomous, but tasks such as taking confirmation measurements, increasing measurement frequency based on a threshold exceedance, transforming raw data and the emission of alerts should also be autonomous.

A sensor-based system relies on low-powered Micro-Electromechanical Sensors (MEMS) that utilise largely solid-state componentry to measure a variety of parameters including but not limited to tilt, displacement, temperature, current and vibration.

2.2 System Architecture

A sensor-based monitoring system will consist of a series of MEMS instruments classified as part of the ‘internet of things’ (IoT) category of equipment. These instruments are typically internally powered and communicate wirelessly to a central gateway via either direct communication or by meshing through adjacent sensors. From the gateway, data is transferred to the internet primarily over cellular networks or alternatively hardwired directly. All interactions with the sensors and data are undertaken over a web-based portal, although systems can be constructed on isolated, local networks if required.

3 APPLICATIONS

3.1 Rail

During the time of rail works, significant levels of disturbance may be imposed on the track area, with the imperative that public transport and private rail networks remain operating with a high degree of surety. As such, monitoring systems are required to ensure track geometry is preserved within certain tolerances and a near-real-time system is often specified.

Track disturbance monitoring specifications typically call for an optical method to be utilised (Transport for NSW, 2016). Factors including poor line of sight, availability of personnel, accuracy and safety often render the use of optical instrumentation, either by manual methods or Autonomous Total Stations (ATS), impractical. Sensor-based systems do not rely on system-wide line of sight and can be installed rapidly by non-specialists. A crew of three can install 200 sensors in around four hours, covering over 500 linear meters of track.

In the context of trackbed monitoring, there are generally three variables which must be kept within tolerance: track cant, track twist and track displacement in both the vertical (settlement) and horizontal (slew) directions (Figure 1).

Figure 1: Typical trackbed installation.

3.1.1 Cant and Twist

The cant on a railway track is the rate of change in elevation between the two rails. The tilt sensors will measure any change in angle of the sleeper. For this to work effectively, the sleeper must be mechanically rigid and firmly attached to the rail via the shoes and clips. The high-precision tilt sensors measure changes in the cant, as reflected by changes in the angle of the sleeper, which is recorded by the sensor and transmitted back via the gateway.

The sensor records an absolute reading of angle, relative to horizontal. There are of course many factors that can affect this, such as the mounting, the current tilt angle of the sleeper, thickness of adhesive and so on. The sensors are digitally baselined and subsequent readings are presented online relative to this baseline.

The change in displacement of one rail relative to the other is then computed as:

$$\delta = sin\alpha \cdot l \tag{1}$$

where δ is the vertical displacement of one rail relative to the other, α is the measured change in angle of the sleeper measured in the lateral direction (Y axis) and l is the track gauge.

3.1.2 Longitudinal Settlement

Settlement is calculated by using a virtual beam chain whereby the rail acts as a proxy for the actual beam (Figure 2). The start and end of the virtual beam chain should ideally be located outside the zone of influence. There is a qualification of the displacement at each location – if the displacement is out of an expected range, then it is assumed to be disturbed and not included in the cumulative calculation. Calibrations can be made between the actual settlement, if known, and the indicative settlement.

The vertical displacement at each chainage location can be computed as:

$$\Delta Z_n = L \cdot sin\ (\theta_n) \tag{2}$$

where ΔZ is the vertical displacement from one sensor to another, L is the sensor spacing and θ is the sleeper angle measured by the sensor in the longitudinal direction (X axis). The accumulated vertical displacement for each chainage location may then be expressed as:

$$accumulated\_\Delta Z_n = \sum_{i=0}^{n} \Delta Z_i \tag{3}$$

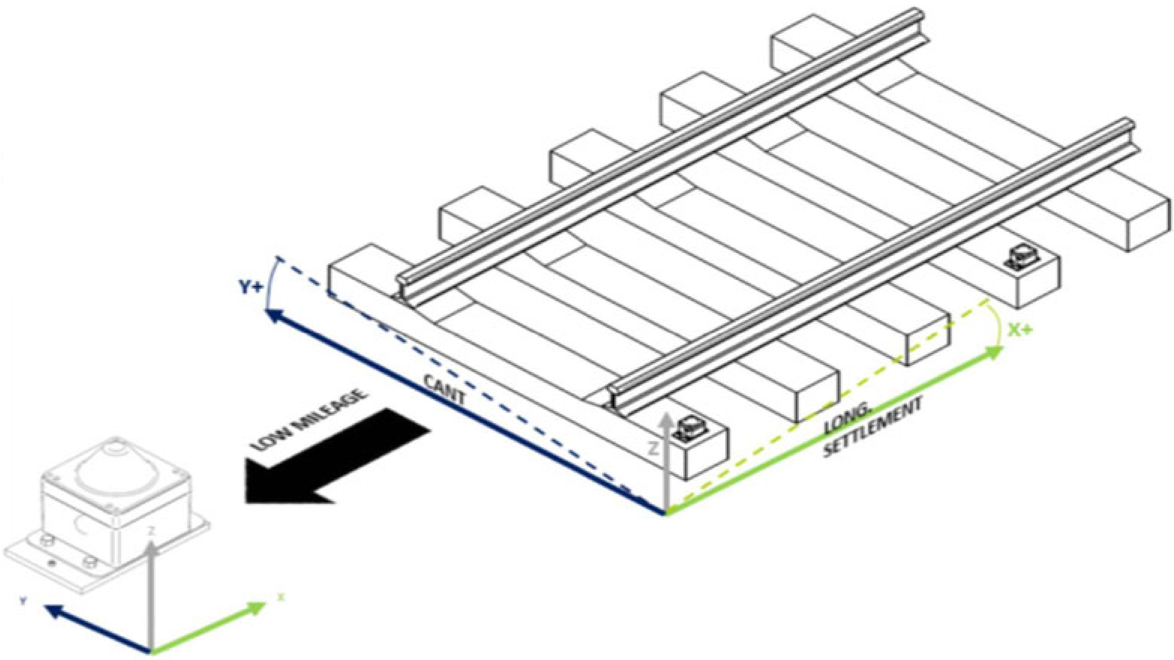

Figure 2: Sensor location and axes orientation.

3.1.3 Slew

An Optical Displacement Sensor (ODS) can be used to measure track slew, i.e. horizontal displacement (Figure 3). The node is installed past the track cess in a stable location and will point towards the rail web. No reflective target is required. The integrated tilt sensor will indicate sensor movement and the displacement must be disqualified until repositioned. Alternatively, the sensor can be track-mounted and measure out to a fixed object or to an adjacent track to measure relative slew. In this instance, as the sensor is tilt-integrated, the sensor will perform the previously described displacement measurements.

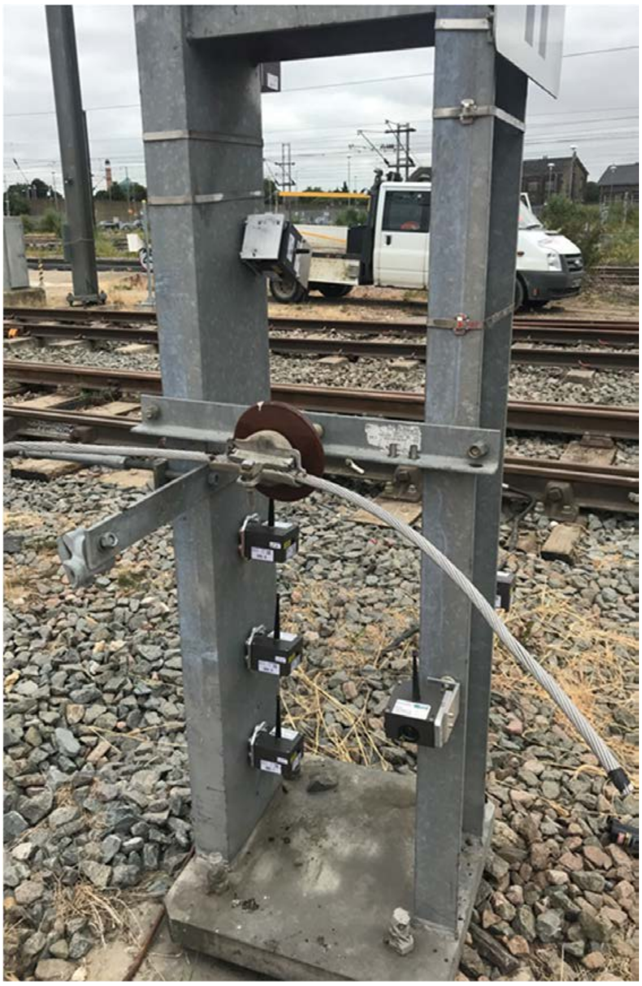

Figure 3: Stanchion-mounted sensors measuring track slew.

3.2 Tunnels

A common parameter in tunnel monitoring is convergence as observation of changes of the tunnel profile perpendicular to the alignment. This can be conducted as life cycle monitoring of ageing masonry tunnels as well as temporary observation of deformation induced by adjacent construction measures or even advance and construction of the tunnel itself (Rennen, 2022).

Autonomous monitoring systems are routinely deployed during the construction cycle to overcome disruptions to the tunnelling process and remove personnel from confined spaces. ATS systems have been a widely used monitoring method whereby the biggest share of investment is with the total station, and efficiencies are gained by monitoring multiple points from a single location. Drawbacks occur when the quality of observations decreases over distance with likely obstructions from dust, construction infrastructure or machinery. Furthermore, as distances increase, resolving targets with small relative incidence angles can become problematic. The ATS itself may also present as a 'high-profile' object within the tunnel, increasing the likelihood of damage.

3.2.1 ODS Monitoring

The ODS nodes include a 3-axes MEMS tilt sensor enabling observation of rotational movement at each location regardless of the node orientation, as well as measuring the distance to a reflective target (Figure 4). Achieving the nominal sub-millimetre accuracy not only depends on the environmental conditions, e.g. the medium the laser beam has to travel through, but also the quality and orientation of the target. Aiming at rough and/or oblique surfaces decreases accuracy as the incidence point might shift inadequately. Very short windows of installation can also be achieved with four sections of sensors in an hour being achievable (Rennen, 2022).

Figure 4: Installed ODS convergence monitoring system.

ODS data can be presented in either relative or absolute figures. Results can be presented in schematic format whereby the last reading is displayed or can be displayed in a graphical time series by individual sensor or in multiples of relevant sensors (Figure 5).

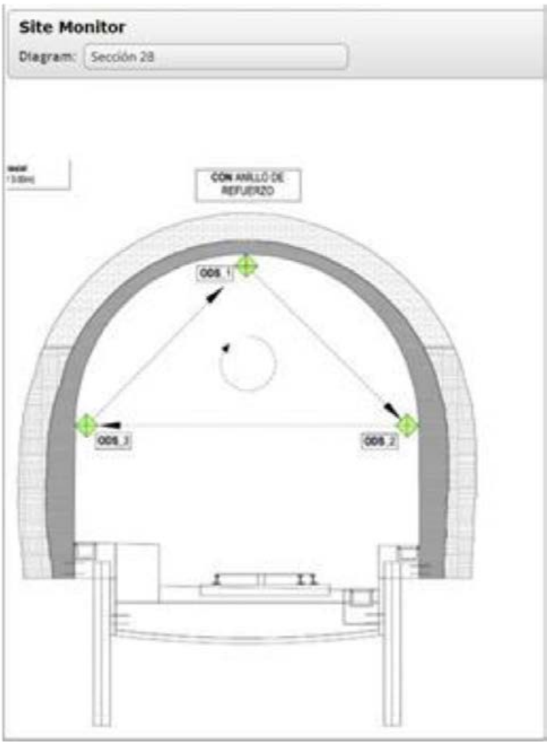

Figure 5: Section diagram of ODS convergence monitoring installation (Rennen, 2022).

3.2.2 Beam Chain Monitoring

An ODS array may not be practical, or the tunnel deformation may require a higher definition of data points to define the profile of a tunnel. In this instance, a sensor beam chain may be installed around the profile of the tunnel to provide a more granular monitoring profile. The application of low-profile sensors may reduce the risk of impinging a kinematic envelope (Figure 6).

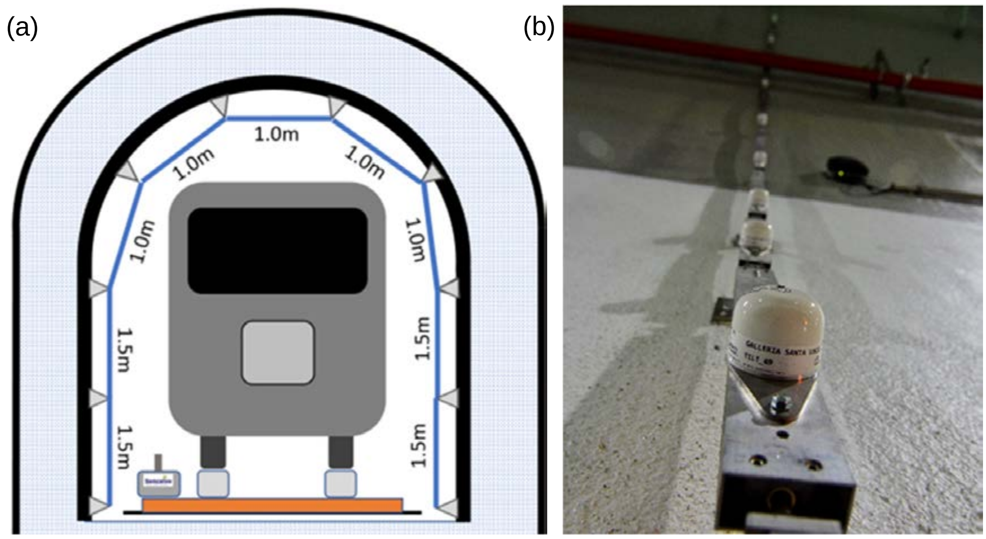

Figure 6: (a) Schematic sectional representation of a tilt beam monitoring installation (Rennen, 2022), and (b) low-profile sensors installed in a tunnel beam chain.

3.2.3 Virtual Beam Chain Monitoring

Particularly in tunnels generated by a Tunnel Boring Machine (TBM), the installation of a 360° physical beam chain may not be feasible. The deployment of low-profile tilt sensors in profile sections can be coupled with the application of virtual beam lengths. This length would represent each side of the virtual polygon created if lines were extended from each sensor. The sensor would be located at the mid-point of each side (Figure 7).

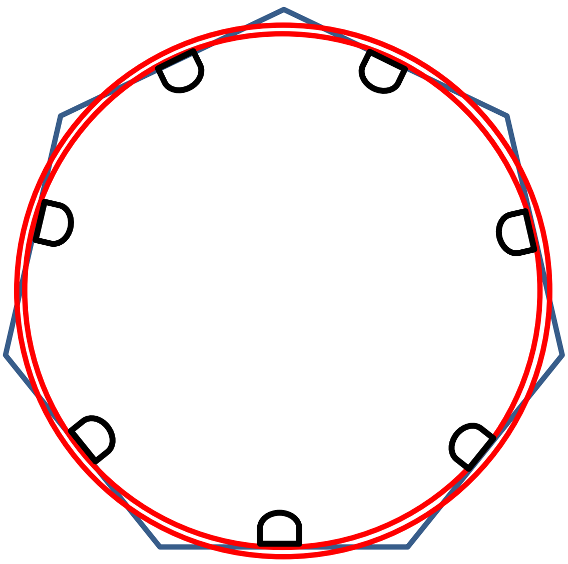

Figure 7: Section diagram of virtual beams (blue) within a TBM generated tunnel.

The virtual beams would be of a known length, based on the diameter of the tunnel. Tilt measurements generated by the sensors would show how the vertexes of the virtual polygon are deforming, and convergence calculations could be performed along the diagonals accordingly.

3.3 Slope Stability

Slope stability monitoring can cover applications for unconsolidated embankments through to road and rail cuttings. Geotechnical failures can impact infrastructure and can happen suddenly, particularly if located in areas susceptible to high rainfall or seismicity. Sensor systems producing numerical data can be enhanced with the addition of integrated cameras that can be triggered to take a photo if a sensor moves through predefined thresholds. Furthermore, these systems can autonomously increase their measurement frequency to provide confirmation readings or the rate of deformation (Figure 8).

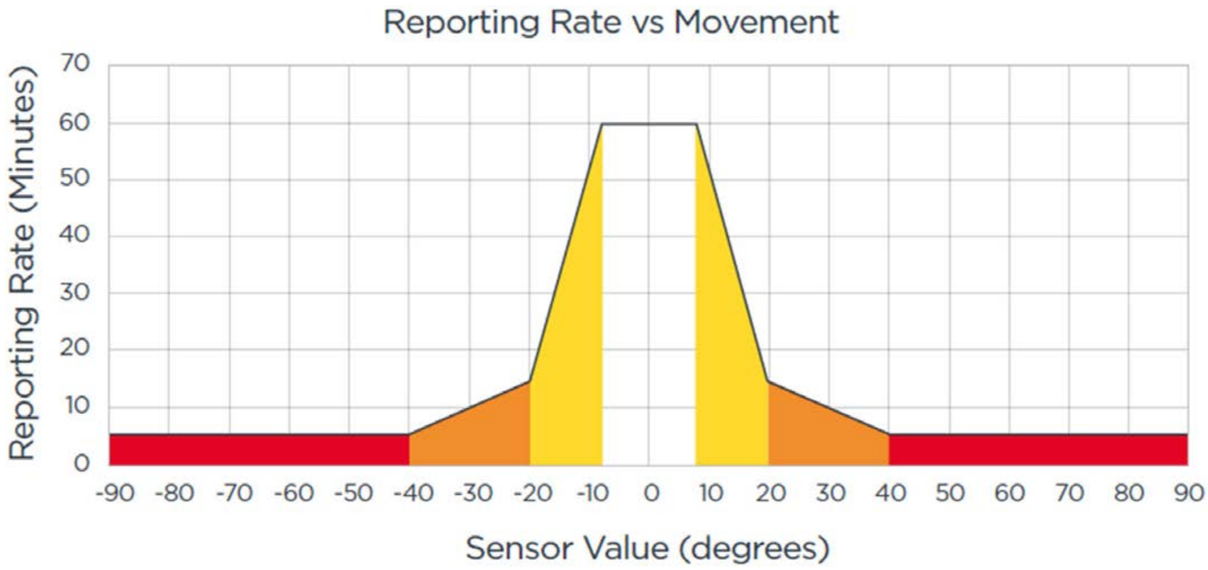

Figure 8: Charted representation of a user-defined autonomous monitoring regime (Senceive, 2022).

Sensor monitoring systems can provide rapid response times, even from dense sensor networks. Sensors are programmed to wake up from cyclic sampling when movement is detected, and the gateway will switch to low-latency reporting rates. Sensor networks can self-heal and recover in the event of individual nodes being damaged (Senceive, 2022).

3.4 Pre-Failure Scenarios

3.4.1 Brick Tower

A client had a system of low-profile sensors installed on a heritage-era brick tower. The 30-minute measurement intervals show the diurnal trend of movement that correlates with the temperature profile. The low temperatures in February represent a period of unseasonably high rainfall, which contributed to a shift in the underlying structure (Figure 9). Whilst the structure did not continue to deform, the risk of failure was deemed high enough to have the structure significantly remediated.

Figure 9: Online analysis package, showing sensor performance after low temperatures and high rainfall.

3.4.2 Rock Cutting

A monitoring system had been installed on a rock cutting since 2018. The system was configured to generate displacement data in millimetres by factoring in the measured tilt with the dimensions of each hazard the sensors were mounted on. The site went into a higher level of awareness when the first threshold was exceeded during March 2021, and alerts were sent accordingly (Figure 10). The hazard continued to deform for next the week until the higher threshold was exceeded, and alerts were sent to cease all activities in the area. At this point, the hazard was removed by a specialist team and made safe. The sensor was then redeployed in the same area.

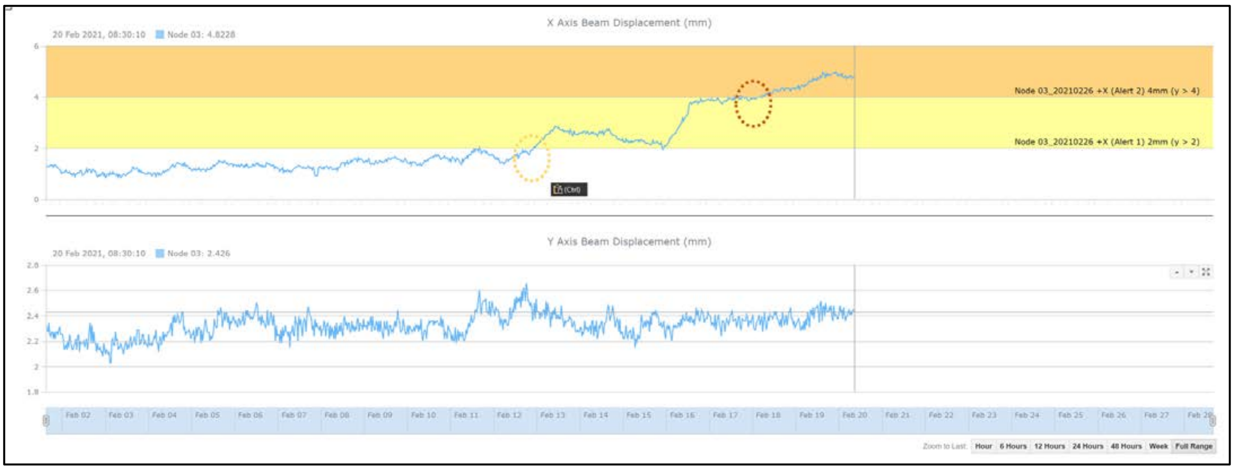

Figure 10: Online analysis package, showing sensor performance and threshold exceedances highlighted in orange and red.

3.4.3 Slope Failure

In contrast to the previous scenarios, remediation activities may not always be practical. In the instance of the slope failure shown in Figures 11 & 12, the sensors showed the deformation in the days leading up to the slope failure, allowing the correct procedures to be followed to ensure personnel and equipment could be made safe.

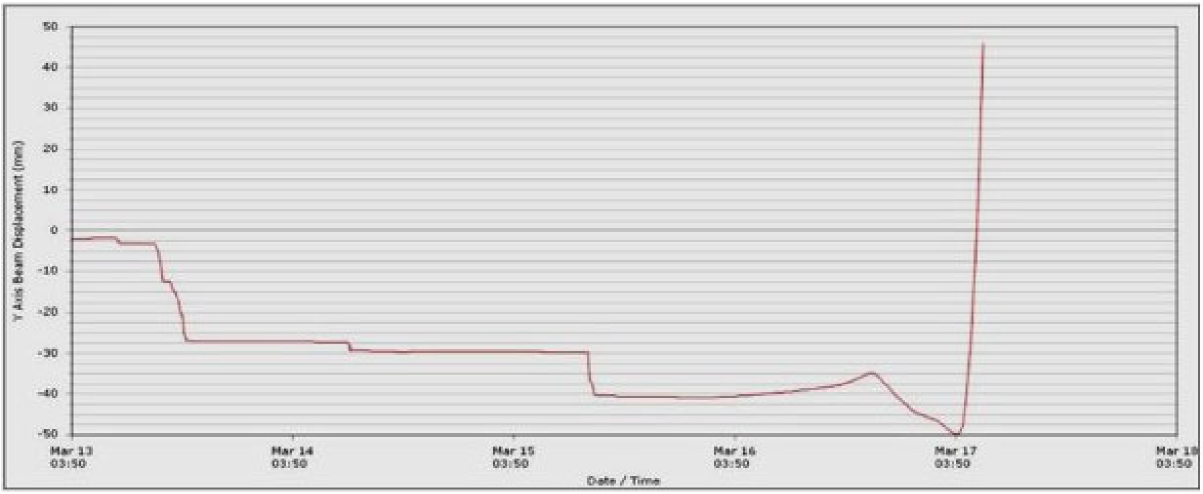

Figure 11: Online analysis package, showing the incremental deformation in the 5 days leading to the slope failure.

Figure 12: Monitoring system layout with outlined slope failure.

4 CONCLUDING REMARKS

This paper has demonstrated that sensor-based monitoring systems provide advantages over manual processes and, in some applications, autonomous total stations. These advantages are associated with increased productivity and safety, reduced size and space limitations. When a structure has exceeded a threshold, the autonomous monitoring system is able to efficiently leverage its own architecture to increase its observation rate, whilst a manual process requires duplication of effort. Furthermore, beyond monitoring the spatial characteristics of a structure, systems can be expanded to structural, geotechnical and environmental parameters within the same hardware ecosystem. This functionality also enhances productivity and stakeholder interaction. As with any system, applications need to be carefully assessed within the limitations of the hardware prior to implementation.

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