Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-244

Landslide monitoring: comparative analysis of long-term automated systems in Brazil and the UK

Surveillance des glissements de terrain: analyse comparative des systèmes automatisés à long terme au Brésil et au Royaume-Uni

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ABSTRACT: Long-term landslide monitoring is essential for understanding landslides and implementing mitigation strategies. Case studies in Brazil and the UK used automatic systems for this purpose. In Brazil, since 2013, a geotechnical sensor system has been monitoring soil movement, water pressure, and rainfall. In the UK, a project since 2012 has been using various instruments to monitor a highway's slope slippage. Both systems allow for early warnings and corrective actions. The current paper will also discuss the challenges and advantages of implementing such systems and also show the benefits of using the right instruments to provide long term monitoring of unstable assets in different regions and contexts.

RÉSUMÉ: La surveillance à long terme des glissements de terrain est essentielle pour comprendre ces phénomènes et mettre en œuvre des stratégies d'atténuation. Des études de cas au Brésil et au Royaume-Uni ont utilisé des systèmes automatiques à cet effet. Au Brésil, depuis 2013, un système de capteurs géotechniques surveille les mouvements du sol, la pression interstitielle et les précipitations. Au Royaume-Uni, un projet utilise divers instruments depuis 2012 pour surveiller le glissement de pente d'une autoroute. Les deux systèmes permettent des alertes précoces et des actions correctives. Le présent document exposera également les défis et avantages de la mise en œuvre de tels systèmes et montrer également les avantages de l'utilisation des bons instruments pour assurer le suivi à long terme des actifs instables dans différentes régions et contextes.

Keywords: Geotechnical monitoring; instrumentation; observational method; inclinometers; piezometers.

1 INTRODUCTION

Continuous monitoring systems aid risk management by understanding landslides and enabling timely responses to reduce casualties. They enhance risk reduction strategies and ensure infrastructure safety by using advanced technology for data acquisition and analysis. Monitoring enables informed decisions and timely interventions to mitigate landslide impacts.

Long-term monitoring of landslides is essential in regions like UK and the Brazil for understanding their dynamics and implementing mitigation measures. Both countries have adopted automatic systems for this purpose. For instance, a project in Lancashire, UK, initiated in 2012, employs ShapeArrays, water level recorders, rain gauges, and tiltmeters to monitor slope movements on a highway. Likewise, in Campos de Jordão, Brazil, a geotechnical sensor system has been operational since 2013, gathering real-time information on soil movement, water pressure, and rainfall. This system aids in early warnings and taking timely corrective actions. The current paper will expose the challenges and advantages of both long-term monitoring case studies.

The objective of the paper is not to provide an analysis and description of the failure mechanisms, or to undertake a back analysis of the data, but to stress the benefits of using the right instruments to provide long term monitoring of unstable assets in different regions and contexts.

2 UK CASE STUDY – SOUTHBOUND HIGHWAY

The United Kingdom has an extensive road network totalling approximately 400,000 km. The Strategic Road Network of England is the economic core of the country's road network and is made up of motorways and major A-roads, with a length of over 15,000 km. 80% of these (approx. 13,000 km) are comprised of cuttings and embankments.

An ageing infrastructure (mostly built in the 1960s and 1970s) and an increased volume of traffic (up approximately 80% between the 1980s and the early 2000s) have continuedly contributed to the deterioration of a significant number of geotechnical assets along the network.

The site presented in this paper is in Lancashire, United Kingdom and comprises a cutting approximately 250m long along the Southbound carriageway of a dual carriageway road part of the Strategic Road Network. The cutting features a sheet piled retaining wall spanning approximately 90m at the toe of the slope, raising approximately 1m above ground level, with a layer of rockfill behind it.

A ground investigation campaign was carried out in the Summer of 2011 which was used to install monitoring along the slope, comprised of piezometers and inclinometers. Initial readings of inclinometers were taken end of September 2011. In a manual monitoring campaign carried out early January 2012, cumulative displacements of up to 80mm had already been recorded, with a shear zone clearly identified in all the instruments. As it can be seen in Figure 1, the inclinometer measurements allow not only to understand the cumulative displacement of the slope, but also the rate of displacement and the width of the "shearing zone" within the soil; in the case of Figure 1, it is apparent how the soil deformation is concentrated within a "band" which is approx. 3m thick.

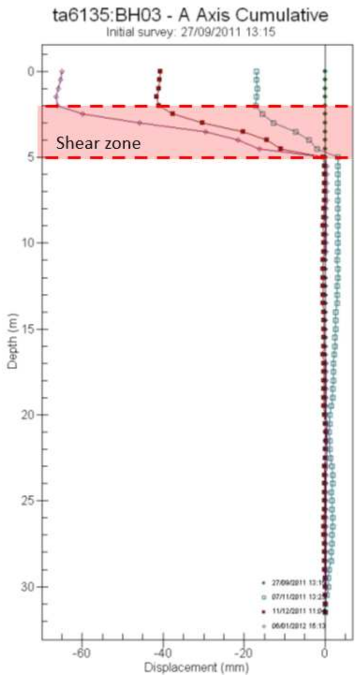


Figure 1. Manual inclinometer results for BH03 Jan/2012.

2.1 Automation monitoring

In April 2012, given the rate of displacement and the fact it wasn't possible to traverse the inclinometer casings with an inclinometer probe due to excessive bending, the slope monitoring was automated with ShapeArrays (Figure 3) and water level recorders. To complement this, a rain gauge was also installed on site in June 2012 and wireless tiltmeters were installed on the sheet pile wall in August 2012 (Figure 2).

Figure 2. Wireless tiltmeter in a sheet pile wall.

Data was collected using four independent networks of dataloggers connected via radio link. On each network, a main hub with a mobile network modem allows for remote data collection, with data being made available to the asset owner automatically via a web-based data visualisation and analysis platform.

Figure 3. Automatic inclinometers (ShapeArray) installation.

Since the installation of the automated monitoring in 2012, displacements have been registered up to a maximum of 995mm downslope, with an average displacement of ~86mm/year (Figure 4).

Based on the continuous monitoring of the asset, over the last 10 years, the client was able to assess the stability of the slope, implement any required safety measures, and guarantee the safety for the road users throughout the year.

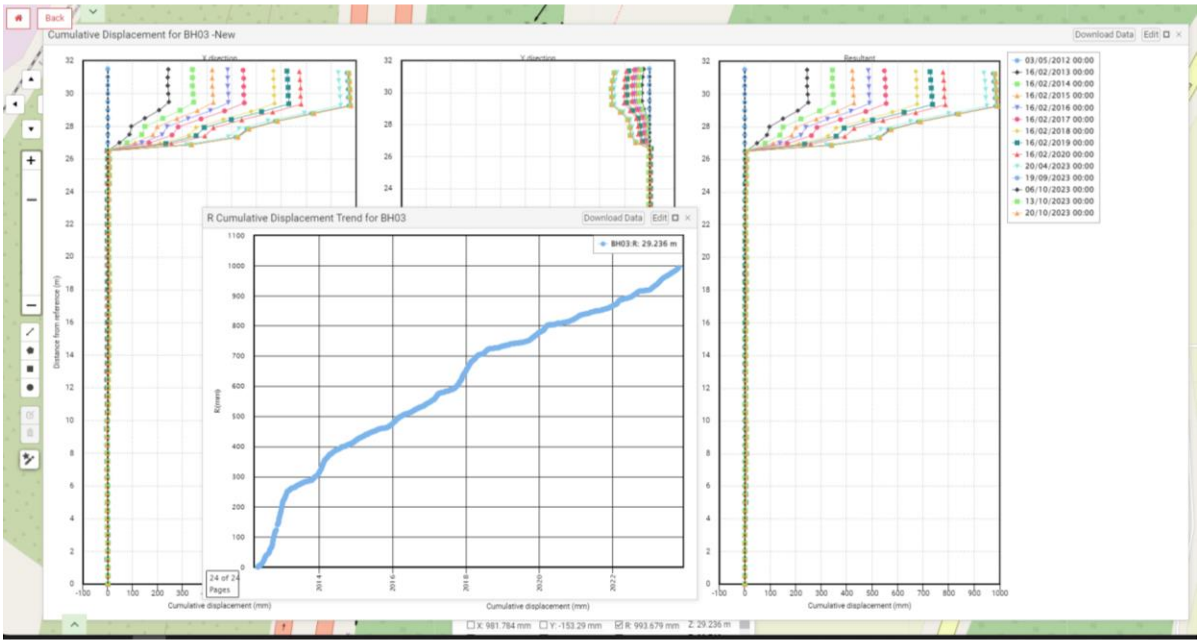


Figure 4. Cumulative displacement at BH03 in October 2023 and cumulative displacement trend.

The automation of the site allowed the monitoring to continue without costly re-drilling works, with increased frequency of data acquisition if/when required, reducing the presence of staff on site with only one/two maintenance visits throughout the year required to keep the system running.

Figure 5 shows how the thickness of the soil “band” interested by the deformations has been keeping consistent during the monitoring period. This kind of information could crucially inform the back analysis and the (consequent) optimisation of the maintenance strategy and maintenance interventions on the slope.

The slope stability analysis and any potential stabilisation/remedial works have been and are being carried out by a specialist engineering consultancy employed by the client. The authors are not involved in this process.

Recently, works were carried out to improve the drainage along the slope and the sheet pile wall was extended North for approximately 100m. The client and the engineering consultant are now assessing the impact of these works in the overall stability of the slope.

Over the years some of the equipment (mainly piezometers) started failing, which prompted the client to consider a refurbishment of the monitoring system. The ShapeArrays continued performing over the years, even when measuring significant deformations over very short lengths.

Due to the rate of movement over the years, manual data acquisition with an inclinometer probe and the required additional works to keep the monitoring going would render this option unsustainable. The ability to retrofit ShapeArrays into existing inclinometer casings that had suffered extreme bending proved to be a game changer for this project, allowing the monitoring of the slope to continue without costly additional works or disturbance of the slope with heavy drilling equipment.

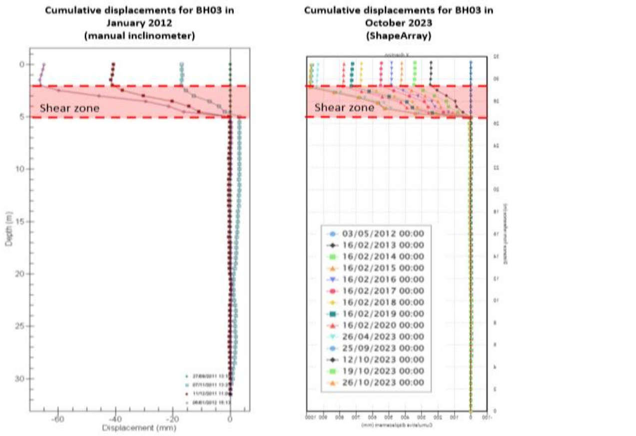


Figure 5. Comparison of cumulative displacement profiles between Jan/2012 and Oct/2023.

3 BRAZIL CASE STUDY – CAMPOS DO JORDÃO PILOT PROJECT

Brazil annually contends with floods and landslides affecting over 4 million people across 14,000 highly susceptible areas. During the rainy season (December-March), catastrophic events claim lives and cause substantial damage. In January 2023, flooding and landslides in São Paulo killed 65 and displaced 3,500. In the previous year, Petropolis saw 235 fatalities and 4,000 displaced due to intense rainfall. Despite recognizing the importance of geotechnical instrumentation, its inadequate implementation persists.

In 2013, a pilot project was initiated to monitor a slope in São Paulo, Brazil, using two ShapeArray inclinometers and two vibrating wire piezometers. The fully automated system has been operational for around 10 years with hourly data collection. The project aims to:

- Establish a remote monitoring system.
- Measure key variables.
- Ensure reliable, continuous data delivery.
- Enhance risk management in an area prone to landslides.

3.1 Geometric, geological, and geotechnical characterization

The slope is about 50m long and 10m wide from the top to its base. The water table varies between 2m from the surface at the base of the slope and about 5m at the top of it (Figure 6).

The stratigraphy obtained through the boreholes provided indicates the existence of a surface landfill stratum (brown clay silt) and an underlying layer with low, predominantly clayey resistance characteristics (Gray organic clay with 1 to 2 blows Nspt), followed by a saprolite soil (young residual soil) to saprolite (transition from residual soil to altered rock) typical of tropical regions.

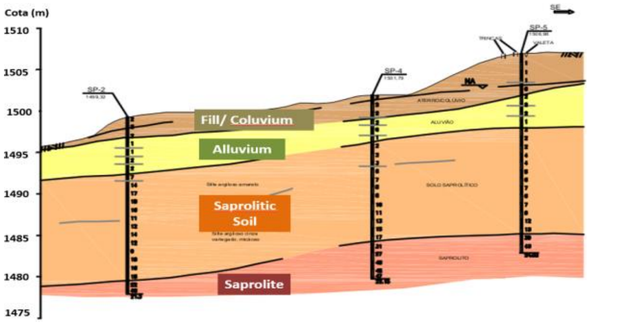
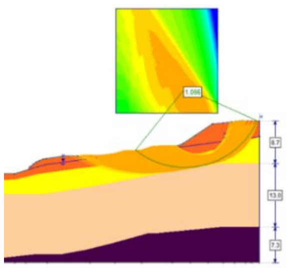


Figure 6. Geological profile of the study area (from top to bottom – Fill/Coluvium, Alluvium, Saprolitic soil, Saprolite.

Before installation, a Morgenstern-Price Method limit equilibrium analysis assessed slope stability (Figure 7). Despite moderate steepness, geological and hydrogeological factors favour mass movement. The analysis highlighted the importance of the alluvial layer (yellow layer in Figure 6 and Figure 7) in slope stability, with its characteristics directly influencing the overall safety factor. Rupture surfaces with safety factors near 1 are concentrated in this layer, indicating deeper landslide potential. Furthermore, stability worsens with heavy rainfall and loads on the upper slope. This limit equilibrium analysis was useful to understand the potential failure mechanism and define the instrumentation plan such as: type of instruments, location and data collection frequency.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kN/m2)	Phi
Aterro de Colúvio		18	Mohr-Coulomb	5	30
Aluvião		16	Mohr-Coulomb	10	16
Solo Saprolítico		18	Mohr-Coulomb	10	30
Saprolito		20	Mohr-Coulomb	10	35

Figure 7. Results of the stability analysis (Morgenstern-Price Method - FS [1 to 1.5]. Material names translation from top to bottom: Fill/Colluvium, Alluvium, Saprolitic soil, Saprolite).

3.2 Instrumentation plan

The instrumentation project involved integrating two ShapeAccelArrays (SAAs) and two vibrating wire piezometers at a geological site. They were strategically placed based on-site features. A detailed assessment identified critical factors including horizontal displacements and pore pressures. Two SAAs (18m and 22m) measured displacements at various depths, while two piezometers (at 5m and 8m depths) monitored pore pressures. The data collection occurred at one-hour intervals.

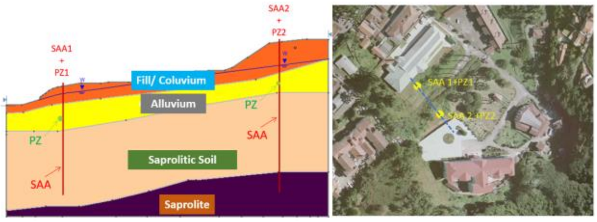


Figure 8. Cross-section with the location of the instruments (from top to bottom – Fill/Coluvium, Alluvium, Saprolitic soil, Saprolite.

As illustrated in Figure 8 there was a concern about anchoring the automated inclinometers in competent locations of the saprolitic or saprolite layers. The piezometers in the middle of the alluvial layer to verify the possible change in the pore pressure regime in this soft clay soil were identified as critical in the limit equilibrium stability analysis.

3.3 Analysis and data interpretation

It is important to note that although the monitoring has been taking place since 5/10/2013, there is a gap without data due to the lack of project funding funds that prevented the data from continuing to be transmitted, being only kept in the physical datalogger. However, due to the frequency adopted, the datalogger's ring memory was filled every three months, and the older data were overlaid as new data were collected. Continuous data collection resumed in July 2022. Even so, after diagnostic tests and sensor integrity checks, the equipments remain in good working condition.

Automated inclinometers demonstrate displacements in the shallowest strata of colluvium and alluvium. In SAA1, a clear-cut surface is defined about 3.5 m from the surface, while for SAA2, this surface is delineated from the surface 6 m, as illustrated in Figure 9. The results are consistent with the geological profile of the site, showing a creep phenomenon (Figure 11) that mobilizes slowly the surface layer of colluvium and part of the alluvium due to its characteristics of magnitude and velocity (1mm/year), with the latter showing more variation of around 2mm in periods of greater rainfall (Figures 9B and 10B).

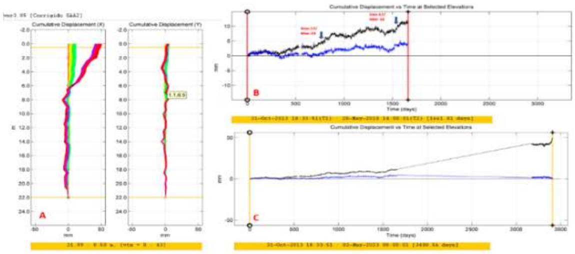


Figure 9. A) Cumulative displacements in the X (preferred direction of displacement) and Y axes of SAA2; B) Cumulative displacements in X (black) and Y (blue) axes over time at 1.0m depth, emphasizing acceleration during heavy rainfall; C) Cumulative displacements in X (black) and Y (blue) axes over time at 1.0m depth from 2013 to 2023.

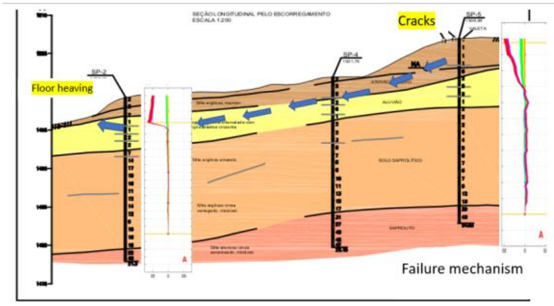


Figure 10. Illustration of the cumulative displacements in both ShapeArrays (left/right) according to the geological profile and installation site. Pathologies (cracks at the top and school floor heaving at the bottom). Location of vibrating wire piezometers and assumed position of the water table (NA) according to piezometric results. Understanding of the failure mechanism. (blue arrows).

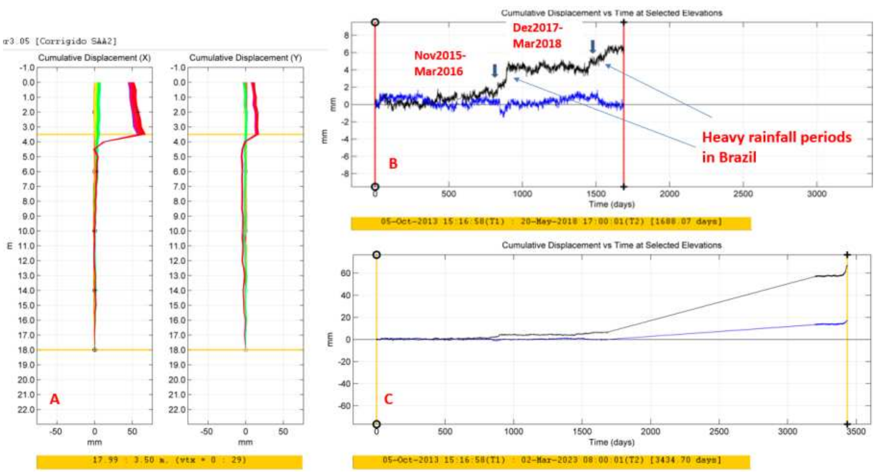


Figure 11. A) Cumulative displacements in the X (preferred direction of displacement) and Y axes of SAA1; B) Cumulative displacements in X (black) and Y (blue) axes over time at 3.5m depth, emphasizing acceleration during heavy rainfall; C) Cumulative displacements in X (black) and Y (blue) axes over time at 3.5m depth from 2013 to 2023.

3.3.1 Vibrating wire piezometers

The vibrating wire piezometers had a brief operational period due to technical issues. Data collected during this time was accurate. PZ1 and PZ2 showed consistent values with assumed groundwater levels from geotechnical investigations (Figure 12). Despite the short period, PZ1 detected minor variations during the initial high rainfall period (Nov/2013 to Mar/2014), indicating increased pore pressures during peak rainfall and subsequent decrease. This is likely due to colluvium layer saturation, increasing self-weight and loading on adjacent alluvium layer.

Barometric variations may also influence these changes.

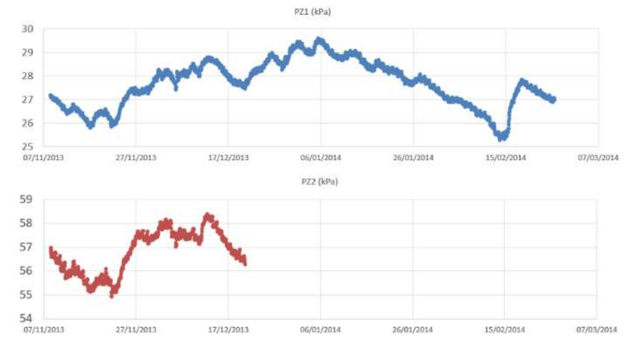


Figure 12. Pore pressure data recorded by vibrating wire piezometers (while operational).

3.3.2 Rain gauges

Rain gauge data from CEMADEN, a governmental institute tracking environmental data and natural disasters nationwide, was integrated with geotechnical monitoring from the pilot project. This enhanced landslide risk forecasting by correlating rainfall with soil stability. The data reveals annual rainfall and temperature patterns over 30 years (Figure 13), aiding in identifying regional wettest/driest and hottest/coldest periods.

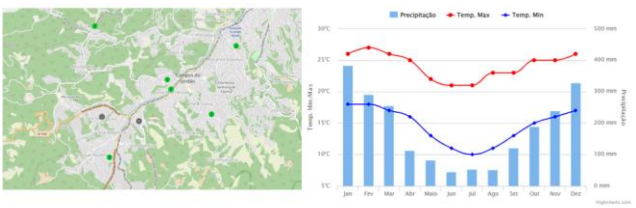


Figure 13. Left- Rain Gauge location (Green circles); Right - the average behaviour of rainfall (blue histogram) and temperature (min-blue line/max- red line) throughout the year at Campos de Jordão city– Source: CEMADEN.

4 CONCLUSIONS

1. Geological Behaviors in Brazil and the UK: Despite similar monitoring principles, distinct geological responses and context were observed.
    - Brazil: Revealed slow, 'creep' type landslide characterized by discrete movements.
    - UK: Showed high-magnitude displacements and faster landslide evolution.
2. Role of Automated Monitoring: Automated systems efficiently correlate rainfall with displacement rates, crucial in both cases.
    - Correlation with Rainfall: established over multiple seasonal cycles, illustrates the critical role of prolonged and intense rainfall as triggers for landslides.
3. Decision-making between Manual and Automated Monitoring: Hinges on project-specific factors.
    - Cost-effectiveness of Automation: Automated monitoring emerged as more cost-effective despite challenges faced (importation fees and taxes in the Brazilian case)
4. Integration of Geotechnical and Meteorological Data: Enhances effectiveness of preventive and corrective actions.
    - Improvement in Data Collection: Facilitates better correlation with rainfall, surpassing limitations of manual methods.
5. Challenges and Maintenance: Vulnerability of instruments and financial constraints emphasize the need for ongoing management.
6. Importance of Integrated Data for Understanding Geological Events: Integration of geotechnical and meteorological data crucial for comprehending slope stability dynamics.
    - Advancement in Research: Enables further exploration of rainfall, infiltration, and soil suction dynamics, expanding understanding of slope stability.
7. Contribution to Risk Management and Future Projects: Insights gained contribute significantly to risk management in slope stability, informing approaches for future projects in different regions and scenarios.