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Lynch, K., Hughes, D., Karim, M. R., Harley, R., Bell, A., McKinley, J., ... Bergamo, P. (2015). Evolving techniques for characterising and monitoring the stability of infrastructure slopes. Paper presented at XVI European Conference on Soil Mechanics and Geotechnical Engineering, Edinburgh, United Kingdom.

Document Version:
Peer reviewed version

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Evolving techniques for characterising and monitoring the stability of infrastructure slopes

Le développement de techniques pour la caractérisation et la surveillance de la stabilité des talus

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ABSTRACT: Landslides and debris flows, commonly triggered by rainfall, pose a geotechnical risk causing disruption to transport routes and incur significant financial expenditure. With infrastructure maintenance budgets becoming ever more constrained, this paper provides an overview of some of the developing methods being implemented by Queen's University, Belfast in collaboration with the Department for Regional Development to monitor the stability of two distinctly different infrastructure slopes in Northern Ireland. In addition to the traditional, intrusive ground investigative and laboratory testing methods, aerial LiDAR, terrestrial LiDAR, geophysical techniques and differential Global Positioning Systems have been used to monitor slope stability. Finally, a comparison between terrestrial LiDAR, pore water pressure and soil moisture deficit (SMD) is presented to outline the processes for a more informed management regime and to highlight the season relationship between landslide activity and the aforementioned parameters.

RÉSUMÉ : Les glissements de terrain et des coulées de débris, déclenchés par les précipitations, généralement présentent un risque géotechnique qui perturbe voies de transport et engager des dépenses financières importantes. Avec des budgets d'entretien des infrastructures deviennent de plus en plus contraint, ce document donne un aperçu de quelques-unes des méthodes innovantes mis en œuvre par l'Université Queen de Belfast, en collaboration avec le Ministère du développement régional pour surveiller la stabilité des deux infrastructures pentes très différentes en Irlande du Nord. En plus des, sol intrusive méthodes d'essai d'investigation et de laboratoire traditionnelle, LiDAR aérien, LiDAR terrestre, techniques géophysiques et différentielles systèmes mondiaux de positionnement ont été utilisés pour mesurer la stabilité des pentes. Enfin, une comparaison entre LiDAR terrestre, la pression interstitielle de l'eau et le déficit d'humidité du sol (SMD) est présenté pour décrire les processus pour un régime de gestion plus éclairées et à mettre en évidence la relation de saison entre les glissements de terrain et les paramètres mentionnés ci-dessus.

1 INTRODUCTION

Slope instabilities such as landslides and debris flows, commonly triggered by rainfall, pose a geotechnical risk causing disruption to transport routes and incur significant financial expenditure. With infrastructure maintenance budgets becoming ever more constrained, geotechnical engineers have been required to adapt existing geotechnical monitoring approaches and develop new methods to ensure the continued resilience of assets.

This research details the various methods being implemented by Queen's University, Belfast and the Department for Regional Development to character-

ise and monitor slope stability on two higher risk infrastructure slopes in Northern Ireland.

2 RESEARCH SITES

The research sites at Loughbrickland and Straidkilly Point have been identified as slopes that have a higher risk of failure and therefore have been the subject of this characterisation and monitoring campaign. Fig. 1 illustrates the location of the sites within Northern Ireland. Straidkilly Point lies on the A2 Coast Road, one of the most spectacular roads in Europe (Day, 2006).

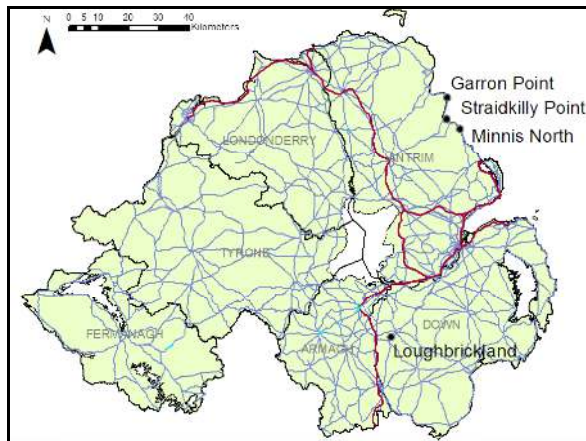


Fig. 1. Site Location Map

The 15m high, natural slope at Stridkilly Point has experienced frequent instances of instability resulting in large volumes of debris being deposited onto the carriageway, forcing road closures. The stratigraphy at Stridkilly Point is comprised of Triassic Mercia Mudstone overlain by the Waterloo Mudstone Formation (Lias Clay) comprising of medium to dark grey calcareous mudstone, pale grey siltstone and thick beds of nodular limestone (Mitchell, 2004). A thin layer of highly permeable, intermittent Hibernian Greensand overlies the Lias Clay. The Cretaceous Ulster White Limestone Formation overlies the Hibernian Greensand, which is subsequently overlain by the Palaeogene Lower Basalt Formation.

The second slope at Loughbrickland was excavated in 2004 as part of a major infrastructure upgrade to link the cities of Belfast and Dublin. The 25m high slope is composed of a weathered Greywacke overlain by a stiff glacial lodgement till. The upper layer of the till is heavily weathered. During excavation flowing artesian conditions occurred at the toe of the slope, due to the upper bedrock surface acting as a confined aquifer (Clarke, 2007).

3 SLOPE CHARACTERISATION METHODS

In addition to the traditional boreholes and laboratory tests, a number of other techniques were deployed to effectively and efficiently characterize the slopes. The methods are discussed in the succeeding sections.

3.1 Aerial LIDAR Scanning (ALS)

The Natural Environment Research Council (NERC) Airborne Research and Survey Facility provided LiDAR data of Stridkilly Point. The raw georeferenced aerial LiDAR data was imported into Lastools (2013) for the removal of above ground objects. Lastools is a powerful set of LiDAR analysis tools. Tools are available in standalone modules or ArcGIS (ESRI, 2012) toolbox extension. Within the suite of Lastools, lasground.exe is a tool for bare earth extraction. Following the extraction of above ground objects, post processed LiDAR point cloud data was imported into ArcGIS. Inverse distance weighting (IDW) with 32 neighbours and a power of 2, were used as the interpolation approach for the generation of the Digital Elevation Model (DEM), with cell size 0.1m.

A hillshade map (Fig. 2) was then generated from the DEM to aid with the identification of geological features such as the extents of large rotated blocks.

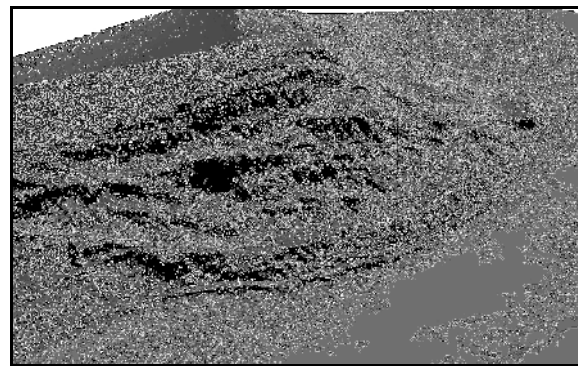


Fig. 2. Hillshade of Stridkilly Point generated from the DEM

3.2 Electrical Resistivity Tomography (ERT)

ERT is used to calculate the electrical resistivity distribution of the subsurface by measuring a large number of electrical potential differences for different combinations of surface electrodes. The electrical resistivity of soil is controlled by a combination of factors including saturation, porosity, clay content, temperature and pore-fluid. A number of researchers have recently used resistivity measurements to investigate landslides and slope stability problems. These include investigations into the properties of the

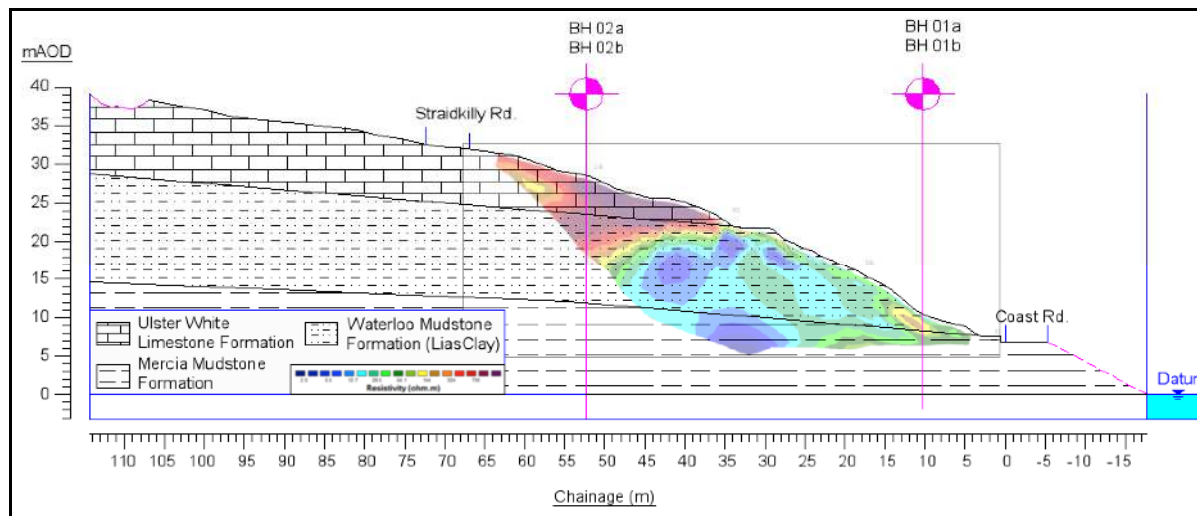


Fig. 3. ERT Results, Straidkilly Point (Survey: July 13)

landslide body (e.g. Donohue *et al.* 2012), location of the failure surfaces (e.g. Caris and Van Asch 1991), and investigate the effects of rainfall infiltration (e.g. Friedel *et al.* 2006).

ERT data was acquired for both sites using a multi-electrode Syscal Proswitch resistivity meter with 32 conventional stainless steel electrodes. A Dipole-Dipole array configuration was used with an electrode spacing of 2 m. Inversion of the apparent resistivity data was carried out with the software Res2Dinv using the L_2 norm inversion optimisation method. Due to the large subsurface resistivity contrast present at the site the Gauss-Newton method was selected for the first 2 or 3 iterations, after which the quasi-Newton method was used (deGroot-Hedlin and Constable 1990). The inverted ERT profile from Straidkilly (Fig. 3) shows a significant contrast in resistivity exists between the upslope and downslope areas of the site. The high resistivity zone at the top of the slope is likely to be the Ulster White Limestone. The low resistivity material (generally $< 50 \Omega\text{m}$) found beneath the lower half of the slope corresponds to Lias Clay (Waterloo Mudstone Formation), within which the majority of slope movement occurs. The information gained from the ERT survey correlated well with the borehole data and facilitated the interpolation of any spatial variability between the boreholes.

3.3 Seismic Surveys

Seismic surveys, including Multichannel Analysis of Surface Waves (MASW) and P-wave refraction tomography, involve the recording the vibrations of soil generated by an active source. Vibrations are generally detected by means of a set of vertically polarized geophones placed at the top surface of the subsoil.

The MASW technique records the propagation of surface waves (Rayleigh Waves) in the shallow subsurface. The waves propagate through a portion of subsurface to a depth approximately equal to one wavelength. As the wavelength depends on the frequency, different frequency components propagate through different layers and hence exhibit different phase velocities. The acquired seismic section is therefore processed to provide information about the dispersion characteristics of Rayleigh Waves. As the phase velocity of Rayleigh Waves depends predominantly on the S-wave velocity (V_s) model of the subsoil, surface wave dispersion data can be inverted to reconstruct the V_s profile of the near-surface zone below the recording array (Socco and Strobbia, 2004). V_s profiles were obtained by applying the Monte Carlo inversion approach introduced by Maraschini and Foti (2010). From the retrieved S-wave velocity profile (Fig.4) it is possible to derive the distribution of G , the shear modulus (Fig. 5), and there-

for the small strain shear modulus of the subsoil (Foti, 2003).

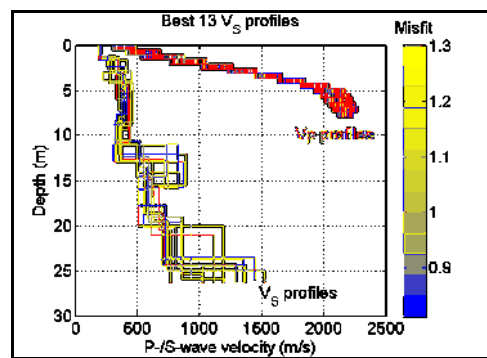


Fig. 4. Best fitting V_s profiles and V_p section (Survey: May 14)

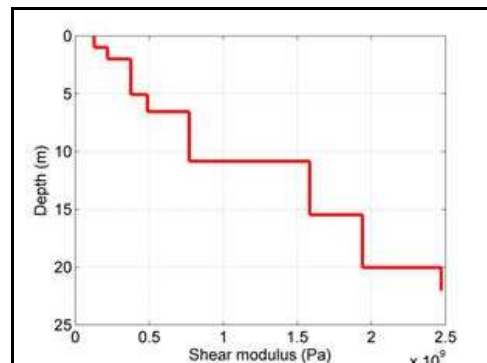


Fig. 5. Distribution of shear modulus with depth (Survey: May 14)

MASW and P-wave refraction surveys are currently being used to determine the mechanical/geotechnical properties of the subsoil. These seismic acquisition campaigns are repeated over time to track changes in the geotechnical behaviour due to climatic effects (e.g. progression of seasons, alteration in precipitations patterns and changes in soil moisture deficit).

4 MONITORING METHODS

Blight (2003) stated that geotechnical engineers have for too long considered only a snapshot in time of soil water conditions, pore water pressure (PWP) and water content, when considering the stability of geotechnical assets. To overcome this shortcoming a multifaceted continuous monitoring approach was implemented at both sites. For illustrative purposes

the succeeding sections describe and present the results of the continuous monitoring techniques that have been implemented at Straidkilly Point.

4.1 Weather Measurement

A Davis Vantage Pro2 Weather Station was installed to obtain regular weather data. The station records weather variables including temperature, wind speed, wind direction, precipitation, solar radiation and barometric pressure at hourly intervals. Soil moisture deficit (SMD) values were calculated using this weather station data to loosely account for seasonal changes in rates of evapotranspiration. The method used to calculate SMD was the hybrid model based on existing models used by Teagasc and Met Éireann (Schulte et al. 2005).

4.2 Pore Water Pressure Measurement

In order to determine the PWP on site the Casagrande Standpipe method was implemented. A 50mm \varnothing standpipe with a 1m-slotted section at a specific depth was installed in each of the 4 boreholes. The area between the 1m-slotted section of standpipe and the borehole was backfilled with granular fill, which had a hydraulic conductivity (K) value of 1×10^{-3} m/s, much larger than that of the surrounding soil (1×10^{-7} m/s) to ensure that the K of the fill did not restrict the flow of water into the standpipe. Above and below the granular fill, bentonite plugs were used to hydraulically seal the slotted section of the standpipe to ensure that the standpipe did not act as a drain and only water that entered via the slotted section of the standpipe would register. Vibrating wire piezometers were installed within each of the standpipes, these were subsequently connected to a logging unit. As the Casagrande Standpipe arrangement does not facilitate the recording of rapid fluctuations in pore pressure, readings were recorded at hourly intervals. The PWP measurements were then corrected for variations in barometric pressure using the weather station data to a datum of 900mb.

Soil moisture probes and tensiometers were also installed at varying depths up 1m to investigate the role of vegetation and the climate boundary condition on soil moisture and matric suction. However the magnitude of the landslide movement on-site rendered these inoperable.

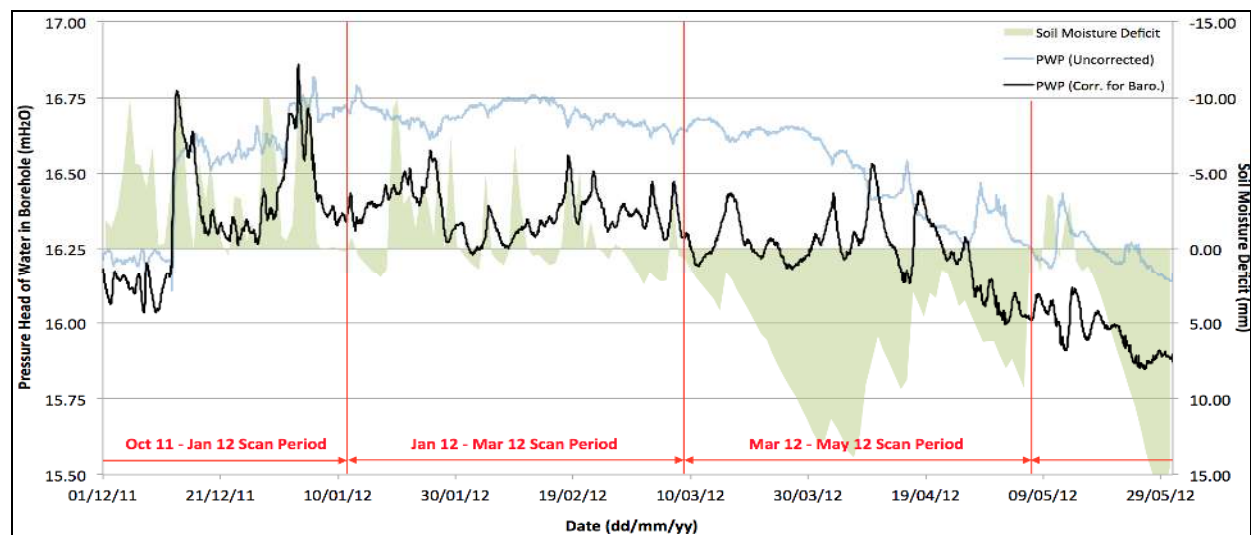


Fig. 6. Comparison between rainfall, SMD and PWP at Straidkilly Point; 1st December 2011 to 31st May 2012.

4.3 Terrestrial LiDAR Scanning (TLS)

Terrestrial LiDAR data were acquired from a Leica Terrestrial LiDAR Scanner, HDS3000 Scan Station. Field operations were carried out on approximately a 2 monthly basis. Two scan positions were used and registered with targets placed on the slope. A site-specific geodetic network of survey nails installed using a differential Global Positioning System (dGPS) provided geo-referencing. This site-specific geodetic network enabled all scans to be recorded within the same co-ordinate system, essential when analyzing temporal changes. Scan registration errors were less than 6mm. The terrestrial LiDAR data was post processed using the same process previously outlined for the aerial LiDAR data. By comparing subsequent DEMs, a Digital Elevation Model of Difference (DOD) was created to chart the movement and evolution of the slope.

4.4 Differential Global Position System (dGPS)

A Leica AS10 differential GPS receiver was also deployed on site to provide a real-time warning system for gross movements via a real-time coordinate analysis summary generated by Leica SpiderQC. This has been installed with an alarm system to provide the Department with a warning if gross movements exceed predetermined thresholds.

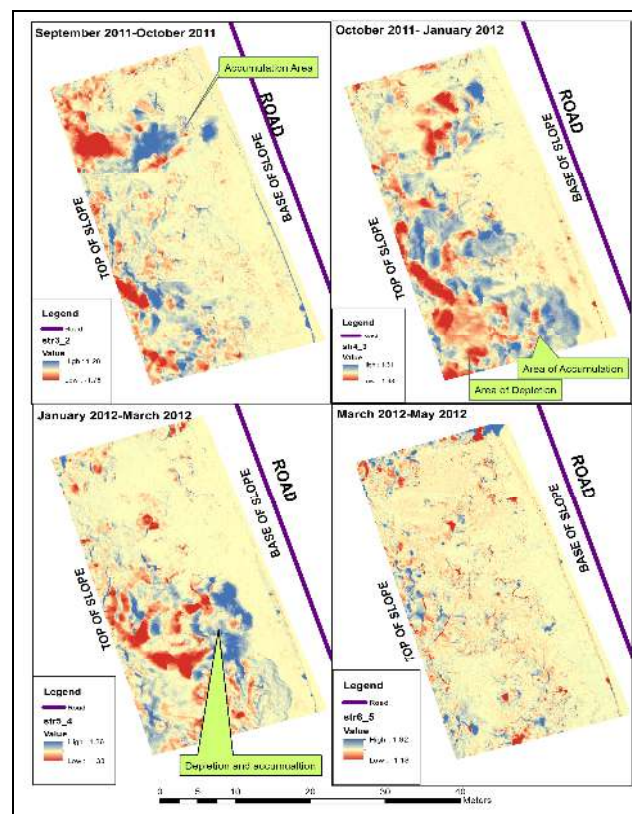


Fig. 7. Progression of slide (changes in elevation); September 2011 to May 2012.

4.5 Monitoring Results

Fig. 6 illustrates the correlation between SMD and PWP at Straidkilly Point between 1st December 2011 and 31st May 2012. The data generally confirms what would be expected. In the winter the SMD value is low and the PWP is high due to the increased precipitation and decreased evapotranspiration. Moving into the spring and early summer, the decrease in precipitation and the increase in evapotranspiration results in an increase in SMD and a decrease in PWP.

Fig. 7 illustrates DODs created from scans taken at regular intervals between September 2011 and May 2012; blue and red illustrate areas of accumulation and depletion, respectively. Between October 2011 and January 2012, there are two notable peaks in PWP and extremely low SMD values, which correspond to 76m³ of transient landslide material. Between January 2011 and March 2012 the SMD begins to increase and the PWP begins to decrease, corresponding to a reduction in the observed quantity of trans-located material (32m³). Finally between March 2012 and May 2013, the PWP continues to fall and the SMD continues to rise, resulting in only 4m³ of slope movement.

5 CONCLUSION

This paper describes some of the contemporary techniques being used to compliment traditional ground investigative and geotechnical monitoring techniques on one manmade and one natural infrastructure slope in differing geological settings.

Electrical resistivity and seismic geophysical surveys have been successfully used to determine the spatial variability of geological features and infer in-situ geo-mechanical properties.

Periodic aerial and terrestrial LiDAR scans have also been successfully combined using spatial analysis techniques to create Digital Terrain Models of Difference illustrating the main areas of depletion and accumulation. A dGPS receiver was also used to provide real-time slope movement data. A volumetric analysis of the DOD was used to quantify the magnitude of the slope movement, which was correlated with SMD and PWP, as key drivers of slope instability, to provide the basis for a more informed, cost-effective approach to the management of geotechnical risk by the Department. Finally the study also

highlights the seasonal relationship between SMD and slope movement.

ACKNOWLEDGEMENTS

The authors would like to thank the Department for Regional Development, Northern Ireland for funding and supporting this on-going research, being undertaken as part of iSMART, an Engineering and Physical Sciences Research Council funded project.

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