The 6th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
Hong Kong | 9-11 December 2013

GEOTECHNICAL MONITORING USING A COMBINATION OF LIDAR, REAL-TIME DGPS, AND ELECTRICAL TOMOGRAPHY TO ASSESS GEOTECHNICAL RISK OF A COASTAL LANDSLIDE

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ABSTRACT

The Antrim Coast Road stretching from the seaport of Larne in the East of Northern Ireland has a well-deserved reputation for being one of the most spectacular roads in Europe (Day, 2006). However the problematic geology; Jurassic Lias Clay and Triassic Mudstone overlain by Cretaceous Limestone and Tertiary Basalt, and environmental variables result in frequent instances of slope instability manifested in both shallow debris flows and occasional massive rotational movements, creating a geotechnical risk to this highway. This paper describes how a variety of techniques are being used to both assess instability and monitor movement of these active slopes near one site at Straidkilly Point, Glenarm. An in-depth understanding of the geology was obtained via boreholes, resistivity surveys and laboratory testing. Environmental variables recorded by an on-site weather station were correlated with measured pore water pressure and soil moisture infiltration data.

Terrestrial LiDAR (TLS), with surveys carried out on a bi-monthly basis allowed for the generation of Digital Elevation Models (DEMs) of difference, highlighting areas of recent movement, accumulation and depletion. Morphology parameters were generated from the DEMs and include slope, curvature and multiple measures of roughness. Changes in the structure of the slope coupled with morphological parameters were characterised and linked to progressive failures from the temporal monitoring. In addition to TLS monitoring, Aerial LiDAR datasets were used for the spatio-morphological characterisation of the slope on a macro scale. A Differential Global Positioning System (dGPS) was also deployed on site to provide a real-time warning system for gross movements, which were also correlated with environmental conditions. Frequent electrical resistivity tomography (ERT) surveys were also implemented to provide a better understanding of long-term changes in soil moisture and help to define the complex geology.

The paper describes how the data obtained via a diverse range of methods has been combined to facilitate a more informed management regime of geotechnical risk by the Northern Ireland Roads Service.

KEYWORDS

Geotechnical health monitoring; landslides; dGPS; LiDAR; electrical resistivity tomography; slope stability; geotechnical risk.

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 resources. Recent technological advances in geomorphological studies of slopes, such as ground based Terrestrial LiDAR Scanning (TLS) has enabled an effective means of monitoring and characterising slopes (Oppikofer et al., 2009). TLS has been used in a number of studies including structural monitoring of geomorphological units (Dunning et al. 2009; Nguyen et al. 2011), monitoring mass movements (Avian et al. 2009; Oppikofer et al., 2009; Baldo et al., 2009) and landslide characterisation (Jaboyedoff et al., 2009; Kasperski et al., 2010). The advantage of LiDAR is that it has resulted in the generation of high resolution Digital Terrain Models (DTM) enabling highly detailed classification of slope features and units (Ventura et al., 2011).

LiDAR can be used to supplement ground survey data, such as rainfall data (Bull et al., 2010) or geotechnical measurements (Corsini et al., 2006), enabling detailed quantifiable assessment of an area. Multi-temporal Digital Elevation Models (DEM) have been used in a number of studies for the assessment of changes over time of landslides and slope failures (Mitasova et al., 2009; Dewitte et al., 2008; Prokop and Panholzer, 2009). DEM's of difference (DOD) were obtained from topographic changes of DEM's and are an effective means for determination of areas where the landscape is evolving or failing. Multi-temporal DTMs were used to understand how a landform or feature of the landscape evolves over time (Avian et al., 2009; Corsini et al., 2009; Ventura et al. 2011).Changes in slope morphology can now be monitored by comparing ground survey data supplemented by TLS and correlating measured slope geotechnical parameters with these morphological changes. This has provided a unique insight into the monitoring of slope processes.

Recent trends in slope stability studies have shown an increased reliance on multi-level assessments of areas using a number of different data acquisition methods. With these different acquisition techniques come the potential for errors to arise and inaccurate conclusions to be drawn. Mitasova et al. (2009: pp.507) suggest that analysis carried out to date needs; "To address the issues of accurate data integration because the rapid evolution of LiDAR technologies during the past decade has produced datasets with different accuracies, scanning patterns and point densities". Heckmann et al. (2012) assessed the integration of ALS, TLS and geotechnical datasets for studying rockfalls. Bremner and Sass (2012:50) illustrated the advantages of the high spatial resolution of laser scanning and integration of Terrestrial and Airborne systems benefitting and becoming a 'powerful tool for the quantification of geomorphic extreme events.' They conclude that a gap in knowledge remains in relation to the combination of the Aerial and Terrestrial systems stating that 'the application of combined approaches is a challenging task and has rarely been performed to date' (pp.50).

This research illustrates a combined monitoring approach using TLS and geotechnical observations for a flowslide in Co. Antrim, Northern Ireland. TLS monitoring and site specific geotechnical parameters are incorporated for analysis of an active flowslide. These parameters include DTMs of difference, Pore Water Pressure (PWP), Soil Moisture Deficit (SMD) and rainfall. This results in the spatial representation of non-spatial geotechnical parameters illustrating how slope morphological changes can relate to underlying superficial geology.

RESEARCH SITE

The Antrim Coast Road stretching from the seaport of Larne in the East to the famous Giant's Causeway in the North has a well-deserved reputation for being one of the most spectacular roads in Europe (Day, 2006). Despite the scenic location, since construction in the 1830's there have been a number of locations along the road that have experienced instances of geotechnical instability, including rock falls at Garron Point and mudflows at Minnis North (Prior et al. 1974). This study is primarily focused on a small (6000m^2) active flowslide at Straidkilly Point, North of Glenarm Village, on the A2 coastal road. More recently Straidkilly Point has experienced increased instance of instability, which has resulted in large volumes of debris being deposited onto the A2 Coast Road, forcing road closures. Figure 1 illustrates one such failure event on 25th January 2010.

Figure 1. Landslide debris on A2 Coast Road, 25th January 2010

Figure 2 details the stratigraphy at Straidkilly Point, with the 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 (GSNI, 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 Palaogene Lower Basalt Formation. However, within the study area between the Straidkilly Road and the A2 Coast Road the geology differs significantly, as this is the point at which products of erosion from further back on the escarpment have been deposited. To determine the extent of this debris four boreholes were installed; two next to the Straidkilly Road and two next to the Coast Road. From the borehole data a cross section of the study area was accurately determined (Figure 3), illustrating the competent Mercia Mudstone overlain by a much less competent, thin layer of Lias Clay, which increases in thickness with distance from the sea. This is then overlain by debris mainly comprising of a matrix of chalk boulders and Lias Clay.

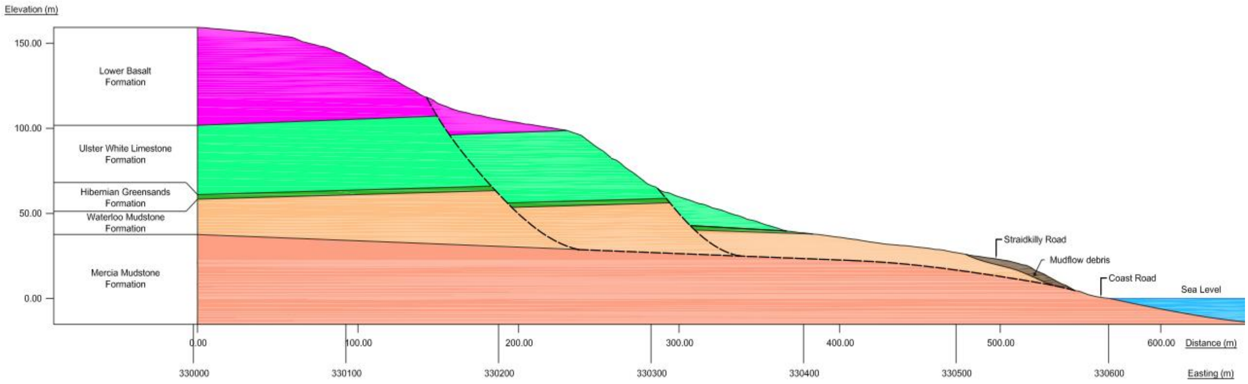

Figure 2. Geological cross section at Straidkilly Point

The mechanism of slope failure on the North Antrim Coast has been well documented, Prior et al. (1974), concluded that the mudflows on the North Antrim Coast could be loosely correlated with values of antecedent precipitation and that the depth of the slip plane was a maximum of 16ft. below ground level, which corresponds to the interface between the Mercia Mudstone and the Lias Clay, hence intense periods of precipitation cause a peak in pore water pressure which results in slope failure. Hutchinson et al. (1974) postulated that the undrained loading of debris from small scale feeder slides caused by increases in pore water pressure initiated larger progressive failure events. This research will attempt to further investigate both these failure mechanisms.

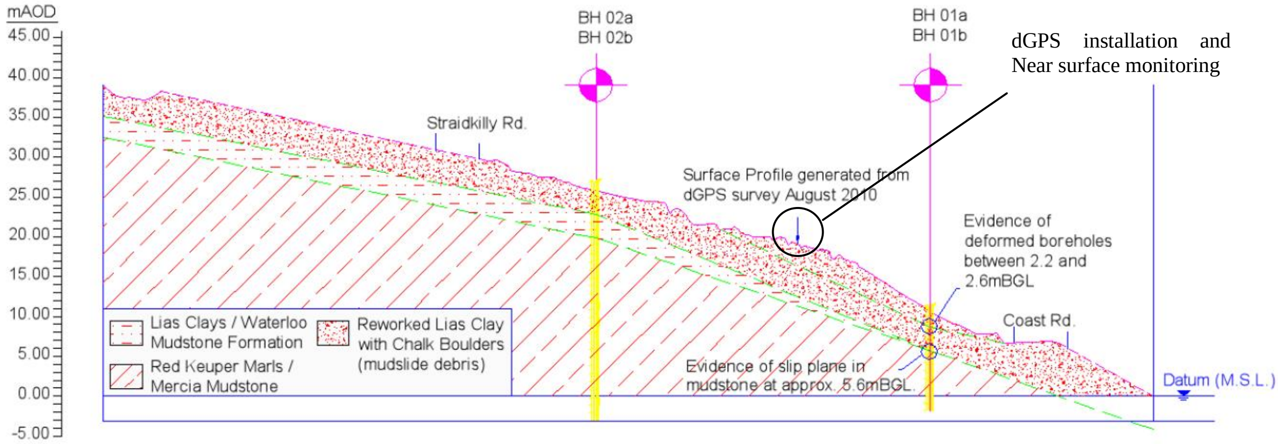

Figure 3. Inferred cross section from borehole data

MONITORING METHODS

Aerial LiDAR Scanning (ALS)

LiDAR data were provided by Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF, 2012)[1]. Aerial LiDAR was post processed and a DTM generated using the same approaches as the Terrestrial LiDAR. DTMs were developed with a 0.1m cell size using Inverse Distance Weighted (IDW) interpolation. For comparison between Aerial LiDAR and Terrestrial LiDAR a DOD was developed to illustrate where the biggest difference are on the slope at Straidkilly. This was carried out using the raster calculator in ArcGIS with the Terrestrial LiDAR, as the higher accuracy surface, being subtracted from the Aerial LiDAR.

[1] http://www.arsf.nerc.ac.uk

Terrestrial LiDAR Scanning (TLS)

This study presents a series of ten Terrestrial LiDAR Data acquisitions over an 18 month period (August 2011 to February 2013). The LiDAR data were acquired from a Leica Terrestrial LiDAR Scanner, HDS3000 Scan Station. Field operations were carried out on approximately a six weekly basis, weather permitting. Two different scan positions were used and registered with targets placed in the field. Georeferencing and positioning were achieved by a site-specific geodetic network of survey nails. Total Station surveying of the targets and survey nails into the site-specific network was carried out. Subsequent georeferencing from dGPS data was undertaken after scan registration. This enabled all scans to be within the same co-ordinate system, essential when analyzing temporal changes between the scans. Scan registration errors were all less than 6mm, within the tolerance of the LiDAR scanner. Survey nails were placed on stable surfaces outside of the slope.

DTM analysis and slope morphological characterisation

Once the Terrestrial LiDAR data were registered and post processed the raw LiDAR data were imported into *Lastools* (2013) for removal of above ground objects. Lastools[2] is a powerful set of LiDAR analysis tools. Multiple tools are available for batch scriptable, multicore command line processing of LiDAR data. Tools are available in standalone modules or ArcGIS (ESRI, 2012) toolbox extension. Within the suite of Lastools, lasground.exe[3] is a tool for bare earth extraction. Following extraction of above ground objects, post processed LiDAR point cloud data were imported into ArcGIS. Inverse distance weighting (IDW) with 32 neighbours and a power of 2, was used as the interpolation approach for the generation of the Digital Terrain Model (DTM), with cell size 0.1m.

This study implements GRASS GIS (GRASS Development Team, 2010) for the spatio-morphological roughness assessment of slopes. *r.roughness* commands (Grohmann 2006) were used to generate Area Ratio Roughness maps from DTMs. Area ratio roughness is the ratio of the real surface to the orthogonal projection, therefore it is sensitive to local variation of slope (Grohmann 2004; Gallay et al. 2010). In addition to roughness parameters, morphological maps of slope, aspect and curvature (profile and plan) are also generated.

Weather and Geotechnical Monitoring

A Davis Vantage Pro2 Weather Station was installed at Straidkilly 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. SMD values were calculated using this weather station data to loosely account for seasonal changes in rates of evapotranspiration. The method used to calculate soil moisture deficit was the SMD hybrid model based on existing models used by Teagasc and Met Éireann (Schulte et al., 2005).
In order to determine the pore water pressure on site the Casagrande Standpipe method was implemented. A 50mm Ø standpipe with a 1m-slotted section at a specific depth was installed in each of the four boreholes.

The area between the 1m-slotted section of standpipe and the borehole was backfilled with granular fill, which had a permeability value of $1x10^{-3}$m/s, much larger than that of the surrounding soil ($1x10^{-7}$m/s) to ensure that the permeability 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 standpipe ensuring 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. Pore water pressure readings were recorded at hourly intervals, as the Casagrande Standpipe arrangement does not facilitate the recording of sudden fluctuations in pore pressure. To record sudden fluctuation in pore water pressure a sizable intake volume and a narrow riser-pipe diameter would be necessary additions (Hvorslev, 1951). The pore water pressure measurements were then corrected for variations in barometric pressure using the weather station data to a datum of 900mb.

Near surface monitoring was also deployed on the site at 2 locations, one of these beside the dGPS installation for correlation of spatial and geotechnical data. Soil Moisture Profile probes was installed to determine soil moisture content and it is also temperature sensitive with sensors at varying depths. Tensiometers were monitored to determine soil moisture tension in the vadose zone, which is directly linked to the effect of vegetation on the site.

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[2] http://www.cs.unc.edu/~isenburg/lastools/

[3] http://rapidlasso.com/lastools/lasground/

Differential GPS (dGPS)

Differential GPS was recently deployed on site to provide a real-time warning system for gross movements via a real-time coordinate analysis summary generated by Leica SpiderQC[1]. A single reference station has been installed; Figure 3 outlined the location of the installation, just above the mudflow. A Leica AS10[2] is installed on top of a 1.5m stainless steel post to monitor 3D real-time spatial deformations. This has been installed with an alarm system to provide a warning if gross movements exceed predetermined thresholds.

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, pore-fluid and matrix resistivity. A number of authors have recently used resistivity measurements to investigate landslides and slope stability problems. These include investigations into the properties of the landslide body (e.g., Lapenna *et al.* 2003; Donohue *et al.* 2012), location of the failure surfaces (e.g. Caris and Van Asch 1991; Göktürkler *et al.* 2008), and investigation of the effects of rainfall infiltration (e.g., Suzuki and Higashi 2001; Friedel *et al.* 2006). Permanently installed ERT arrays have also recently been used for monitoring temporal variations of electrical resistivity within slopes, thereby enabling variations in soil moisture (Chambers et al. 2013) and slope movement be predicted (Wilkinson et al. 2010). If calibrated appropriately, this approach could provide a useful means of assessing unstable slopes, potentially providing an early warning for rainfall induced landslips.

RESULTS AND DISCUSSION

The evolution of the slope at Straidkilly is presented as Figure 4 illustrating the cumulative changes in elevation over the monitoring period. Changes in the elevation of the temporal DTMs show distinct changes in slope morphology. There is a propagation of the material processes on the slope. Failures occur and can be progressively mapped downslope with the source area further up the slope clearly evident. Further losses of material and gain downslope can be tracked to originate from the top of the slope in a number of areas. A large area of accumulation can be seen at the base of the slope. Spatial variation was observed in the main units of failure and areas of terrain evolution.

Temporal changes in the DTMs relating to changes in height (Figure 5) can be characterised into boxplots of incremental changes in height split into the seasons of change. The largest changes in height were in Autumn 2011 and Spring 2012. There is a sinusoidal (wave-like) nature to the changes in height on the slope as a direct result of failure events on the slope. Most changes occured during the winter and spring months, with least change in the summer months. Changes in height were also reflected by morphological change as indicators of movement. Roughness illustrates spatial and temporal variation relating to the changes in terrain and failures in the slope. The highest roughness values (Figure 6) were observed in March 2012 and May 2013. Temporal variation in roughness decreased during the summer months followed by increases in the winter months. These relate to failures on the flowslide which leave behind scarps and areas of steeper rougher terrain.

Figure 7 illustrates the correlation between rainfall, SMD and pore water pressure at Straidkilly between 1st December 2011 and 31st May 2012. These data generally confirm what would be expected, in the winter months the SMD value is low and the pore water pressure is high due to the increased precipitation and the decrease in evapotranspiration. Moving into the spring and early summer months, the decrease in precipitation and the increase in evapotranspiration resulted in an increase in SMD and a decrease in pore water pressure.

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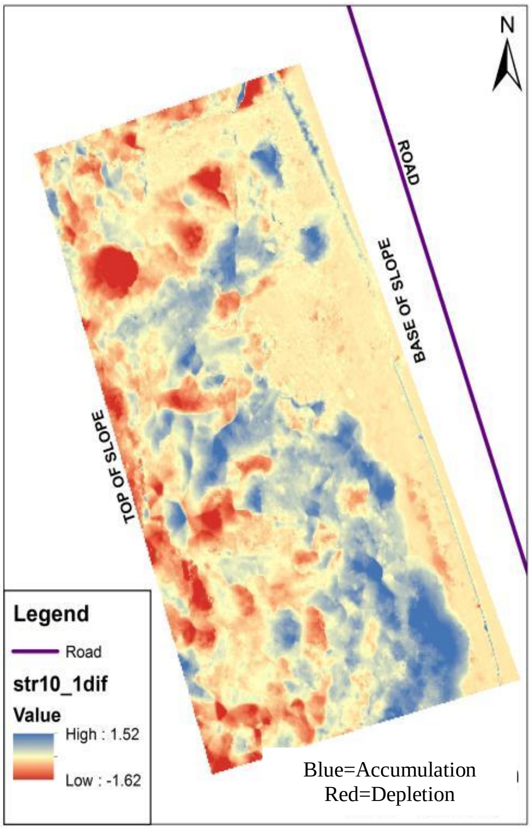
[1] http://www.leica-geosystems.com/en/Leica-SpiderQC_83496.htm Leica SpiderQC, a product from Leica Geosystems, is a multi-purpose GNSS data analysis tool which is currently employed for Network Real Time Kinematic (RTK) performance monitoring at Straidkilly Point.

[2] http://www.leica-geosystems.com/en/Leica-AS10_5549.htm Leica AS10 is a high performance multi-GNSS compact antenna for single reference stations, RTK and monitoring networks.



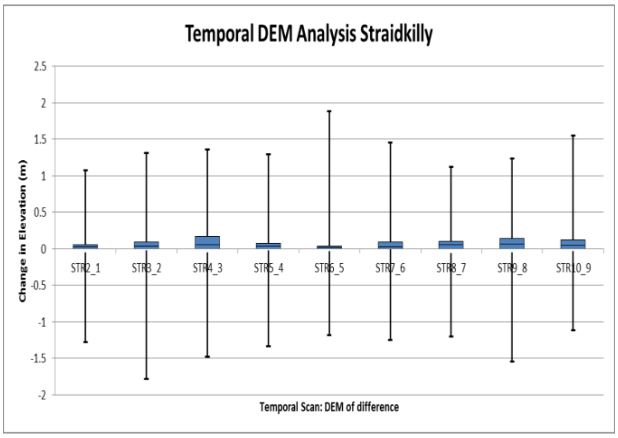


Figure 5. Temporal DTM analysis, boxplots of change in elevation (m) for the temporal monitoring period; August 2011 to February 2013

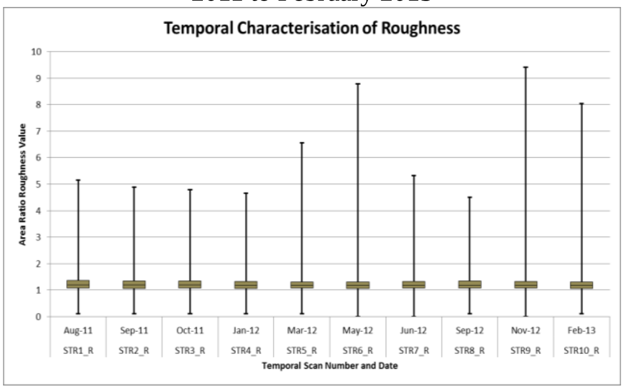


Figure 4. Cumulative DTM of difference for the Terrestrial LiDAR monitoring period at Straidkilly

Figure 6. Temporal changes in Area Ratio Roughness over monitoring period; August 2011 to February 2013

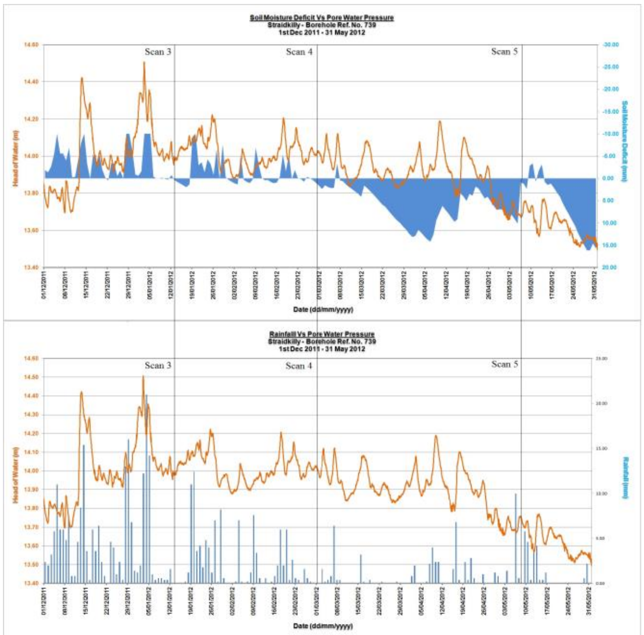


Figure 7. Comparison between rainfall, SMD and pore water pressure at Straidkilly Point; December 2011 to May 2012

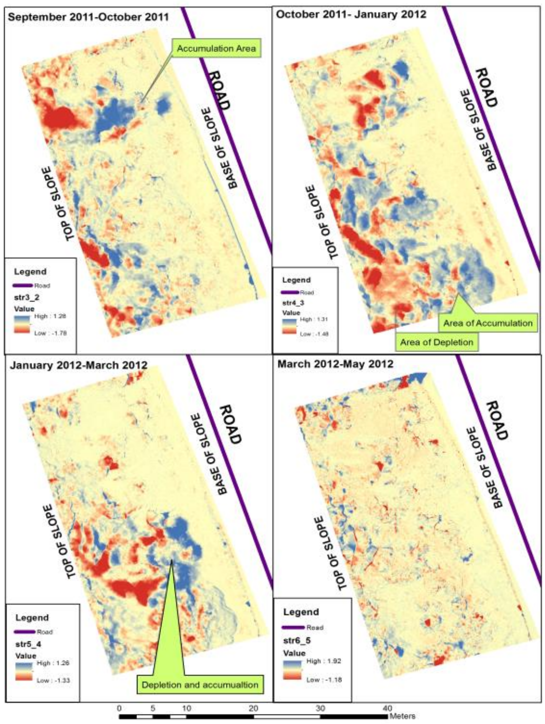


Figure 8. Incremental changes in elevation; terrain evolution and progression of flowslide, Straidkilly Point; September 2011 to May 2012

Figure 8 details the evolution of the slope due to flowslide activity over approximately the same period of time as the geotechnical and weather data presented in Figure 8. Between October 2011 and January 2012, there are two notable peaks in pore water pressure and extremely low SMD values, which correspond to large volumes of transient landslide material. Between January 2011 and March 2012 the SMD begins to increase and the pore water pressure begins to decrease, corresponding to a reduction in the observed quantity of trans-located material. Finally between March 2012 and May 2013, the pore water pressure continues to fall and the SMD continues to rise resulting in almost no observed slope movement.

Figure 9 illustrates the difference between Aerial and Terrestrial LiDAR at Straidkilly with maximum difference on the slope of 5.64m. There are higher areas of difference between the two monitoring approaches, as the slope at Straidkilly gets higher, the difference between the Aerial and Terrestrial LiDAR gets higher. Figure 10 shows a slope map of the slope at Straidkilly. The majority of the slope has lower differences in height, with flatter areas being comparable with no error introduced. Negative differences relating to an under sampling of the Terrestrial LiDAR are evident in some sections of the slope, as low as -1.02m.

This study highlights the need for the application of Terrestrial LiDAR for higher accuracy monitoring of the slope. This is down to the higher spatial density of point. One should be wary of Aerial LiDAR data studies of smaller study areas as the spatial density of point and interpolation to a regular grid fort analysis may produce error and spatial autocorrelation which may not be indicative of the true ground surface.

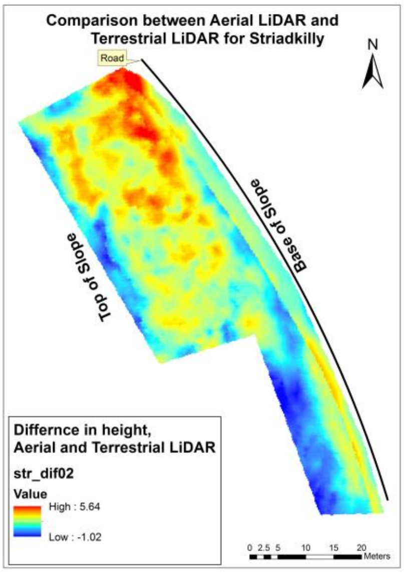


Figure 9. Comparison between ALS and TLS for Straidkilly

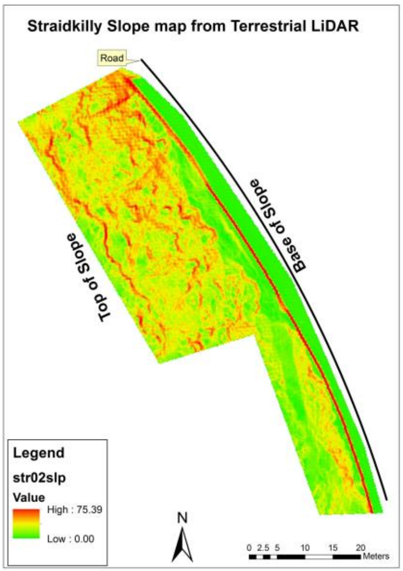


Figure 10. Straidkilly Slope Map from TLS

ERT data for the Straidkilly slope was acquired 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 (Loke 2004) using the L_2 norm inversion optimisation method. Due to the large subsurface resistivity contrast present at the site the quasi-Newton least squares method (Loke and Barker 1996) was not deemed appropriate, instead the Gauss-Newton method (Sasaki, 1989; deGroot-Hedlin and Constable 1990) was selected for the first 2 or 3 iterations, after which the quasi-Newton method was used. In many cases, this provides the best compromise between computational time and accuracy even at sites with large resistivity contrasts (Loke and Dahlin 2002). For this dataset the inversion converged to a normalised root-mean-squared (RMS) error of 8 % within 5 iterations. The inverted ERT profile from Straidkilly (Figure 11) shows a significant contrast in resistivity exists between the Western/ upslope and Eastern/ downslope areas of the site. The high resistivity zone at the top of the slope is likely to be the Ulster White Limestone (Figure 2 & 3). The low resistivity material (generally < 50 Ωm) found beneath the lower half of the slope corresponds to Mudstone, within which the majority of slope movement is occurring. The relatively high resistivity values observed close to the surface of this layer is related to debris, predominantly comprising a matrix of high resistivity chalk boulders and Lias Clay. A permanent ERT array will shortly be installed at Straidkilly in order to monitor the spatial and temporal variations of electrical resistivity within the slope. Once calibrated, this will enable variations in moisture and slope morphology to be continually monitored.

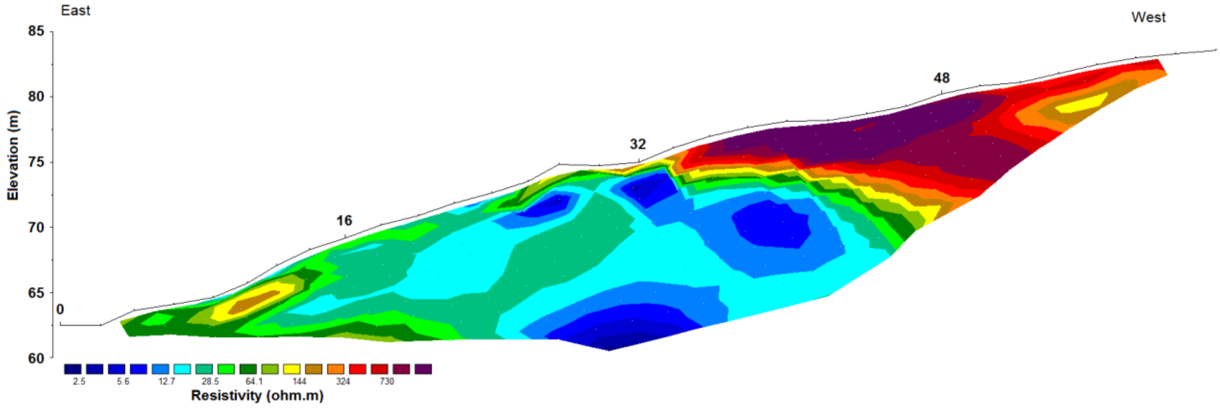


Figure 11. Electrical Resistivity Tomography profile for Straidkilly

CONCLUSION

Terrestrial LiDAR has successfully been applied for the monitoring of Straidkilly Point. Spatial analysis approaches to the monitoring of the slope allow morphological change to be characterised with DTMs of difference, illustrating the main areas of depletion and accumulation between scans. These give a spatial context and understanding for the mechanisms of SMD and PWP as drivers of slope instability. The volumetric analysis and characterisation of main areas of change elucidate the findings of the geotechnical observations. Supplementary non-spatial geotechnical observations are parameterized, when given a comparative spatial context in terms of slope morphological change.

This study indicates the potential for the combined approach of geotechnical and TLS monitoring for the characterisation and classification of slope stability issues. This research shows the application of spatial and volumetric analysis depicting main morphological units of change over a particular survey period. In-situ, non-spatial ground based geotechnical measurements give an indication of the site-specific rainfall regime, soil moisture deficits and pore water pressures. These factors have a seasonality intrinsically linked to evapotranspiration and climatological forcings. Linked to TLS monitoring of the site, parameters given a spatial context, accurately reflect changes in the slope morphology. The progressive failing nature of the flowslide is effectively characterised by a combination of TLS monitoring and geotechnical parameter analysis.

The deployment of dGPS on site provides a real-time warning system for gross movements allowing these movements will be correlated with slope and environmental conditions. Frequent electrical resistivity tomography (ERT) surveys provide a better understanding of long-term changes in moisture in the slope and help to define the complex geology and mechanism of failure at Straidkilly Point. This multi-faceted approach will facilitate a more informed management of the geotechnical risk by the Northern Ireland Roads Service.

ACKNOWLEDGEMENTS

The authors would like to thank the Department for Regional Development, Roads Service NI, Northern Ireland Rail and University of Saskatchewan for their support and funding of this research.

REFERENCES

Avian, M., Kellerer-Pirklbauer, A and Bauer, A., 2009,
LiDAR for monitoring mass Movements in permafrost environments at the cirque Hintres Langtal, Austria, between 2000 and 2008, Natural Hazards and Earth System Sciences, 9, 1087-1094

Baldo, M., Bicocchi, C., Chicchini, U., Giordan, D. and
Lollino, G. 2009, LIDAR Monitoring of mass wasting processes: The Radicofani landslide, Province of Siena, Central Italy, Geomorphology, 105: 193-201

Bull, J.M., Miller, H., Gravely, D.M., Costello, D.,
Hikuroa, D.C.H. and Dix, J.K., 2010, Assessing debris flows using LiDAR differencing: 18th May 2005 Matata event, New Zealand, Geomorphology, 124: 75-84

Caris J.P.T. and Van Asch T.W.J. 1991. Geophysical, geotechnical and hydrological investigations of a small landslide in the French Alps. *Engineering Geology* 21: 249–276.

Carvalli, M. and Marchi, L., 2008, Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR, Natural Hazards and Earth System Sciences, 8, 323-333

Chambers, J.E., Gunn, D.A., Wilkinson, P.B., Meldrum, P.I., Haslam, E., Holyoake, S., Kirkham, M., Kuras, O., Meritt, A. and Wragg, J., 2013. 4D electrical resistivity tomography monitoring of soil moisture dynamics in an operational railway embankment, *Near Surface Geophysics*,doi:10.3997/1873-0604.2013002

Corsini, A., Borgatti, L., Caputo, G., De Simone, N., Sartini, G. and Truffelli, G., 2006, Investigation and monitoring in support of the structural mitigation of large slow moving landslidesL an example from Ca'Lita (Northern Apennines, Regiio Emilia, Italy), Natural Hazards and Earth System Sciences, 6: 55-61

Corsini, A., Borgatti, L., Cervi, F., Dahne, A., Ronchetti, F. and Sterzai, P., 2009, Estimating mass-wasting processes in active earth slides – earth flows with time series of High-resolution DEMS from photgrammetry and airborne LiDAR, Natural Hazards and Earth System Sciences, 9: 433-439

Day, C. 2006. *Ireland*. 6th ed. London: Cadogan Guides. p375.

Dewitte, O., Jasselette, J.-C., Cornet, Y., Van Der Eeckhaut, M., Collignon, A., Poesen, J., and Demoulin, A., 2008, Tracking landslide displacements by multi-temporal DTMs: A combined aerial stereo photogrammetric and LiDAR approach in western Belgium, Engineering Geology, 99: 11-22

Donohue, S., Gavin, K. and Tolooiyan., A. 2011. Geophysical and geotechnical assessment of a railway embankment failure, *Near Surface Geophysics*, 9 (1): 33-44.

Dunning, S.A., Massey, C.J. and Rosser, N.J., 2009, Structural and geomorphological features of landslides in the Bhutan Himalaya derived from Terrestrial Laser Scanning, Geomorphology, 103: 17-29

ESRI 2010, ArcGIS Desktop: Version 10, Environmental Systems Research Institute Redlands, CA.

Friedel S., Thielen A. and Springman S.M. 2006. Investigation of a slope endangered by rainfall-induced landslides using 3D resistivity tomography and geotechnical testing. *Journal of Applied Geophysics* 60: 100–114.

Glenn, N.F., Streuker, D.R., Chadwick, D.J., Tackray, G.D. and Dorsch, S.J., 2006, Analysis of LiDAR-derived topographic information for the characterizing and differentiating landslide morphology and activity, Geomorphology 73: 131-148

Göktürkler G., Balkaya C. and Erhan Z. 2008. Geophysical investigation of a landslide: The Altındağ landslide site, İzmir (western Turkey). *Journal of Applied Geophysics* 65: 84–96.

Heckmann, T., Bimbose, M., Krautblatter, M., Hass, F., Becht, M. and Morche, D., 2012, From geotechnical analysis to quantification and modeling using LiDAR data: a study on rockfall in the Reintal catchment, Bavarian Alps, Germany. Earth Surfaces Processes and Landforms, 37: 119-133

Jaboyedoff, M., Demers, D., Locat, J., Locat, J., Locat, A., Locat, P., Oppikoffer, T., Robitaille, D. and Turmel, D., 2009 , Use of terrestrial laser scanning for the characterization of retrogressive landslides in sensitive clay and rotational landslides in river banks, Canadian Geotechnical Journal, 46: 1379-1390

Jackson, P.D., Northmore, K.J., Meldrum, P.I., Gunn, D.A., Hallam, J.R., Wambura, J., Wangusi, B., and Ogutu, G. 2002. Non-invasive moisture monitoring within an earth embankment - a precursor to failure. *NDT&E International* 35: 107-115.

Kasperski, J., Delacourt, C., Allemand, P., Potherat, P., Jaud, M. and Varrel, E., 2010, Application of Terrestrial Laser Scanner (TLS) to the study of the Sechilienne Landslide, (Isere, France), Remote Sensing, 2: 2785-2802

Lapenna V., Lorenzo P., Perrone A., Piscitelli S., Sdao F. and Rizzo E. 2003. High-resolution geoelectrical tomographies in the study of the Giarrossa landslide (southern Italy). *Bulletin of Engineering Geology and the Environment* 62: 259–268.

Lastools, 2013, Lastools suite of LiDAR processing tools, Open source license, Martin Isenberg, http://rapidlasso.com/lastools/, Last Accessed: 26th April 2013

Mitasova, H., Overton, M.F., Recalde, J.J., Bernstein, D.J., and Freeman, C.W., 2009, Raster Based Analysis of Coastal Terrain Dynamics from Multi-temporal LiDAR Data, Journal of Coastal Research, 25 (2): 507-514

Nguyen, H.T., Fernandez-Steeger, T.M., Wiatr, T., Rodrigues, D. and Azzam, R., 2011, Use of terrestrial laser scanning for engineering geological applications on volcanic rock slopes – an example from Maderia island (Portugal), Natural Hazards and Earth System

Sciences, 11: 807-817

Oppikofer, T., Jaboyedoff, M., Blikra, L., Derron, M-H. and Metzger, R., 2009, Characterization and monitoring of the Aknes rockslide using terrestrial lidar scanning, Natural Hazards and Earth System Sciences, 9: 1003-1019

Prokop, A., and Panholzer, H., Assessing the capability of terrestrial laser scanning for monitoring slow moving landslides, Natural Hazards and Earth System Sciences, 9: 1921-1928

Scheidl, C., Rickenmann, D. and Chiari, M., 2008, The use of airborne LiDAR data for the analysis of debris flow events in Switzerland, Natural Hazards and Earth System Sciences, 8: 1113-1127

Suzuki, K., and Higashi, S., 2001, Groundwater flow after heavy rain in landslide-slope area from 2-D inversion of resistivity monitoring data. *Geophysics 66:733-743.*

Trevasani, S., Cavalli, M. and Marchi, L., 2009, Variogram maps from LiDAR data as fingerprints of surface morphology on scree slopes, Natural Hazards and Earth System Sciences, 9: 129-133

Ventura, G., Vilardo, G., Terranova, C. and Sessa, E. B., 2011, Tracking and evolution of complex active landslides by mutli-temporal airborne LiDAR data: The Montaguto landslide (Southern Italy), Remote Sensing of the Environment, 115, 3237-3248

Wilkinson P.B., Chambers J.E., Meldrum P.I., Gunn D.A., Ogilvy R.D. and Kuras O. 2010a. Predicting the movements of permanently installed electrodes on an active landslide using time-lapse geoelectrical resistivity data only. *Geophysical Journal International* 183(2), 543–556.