Using geotechnical and LIDAR spatial monitoring to determine key environmental slope instability thresholds of a Jurassic coastal landslide: Straidkilly Point, Northern Ireland, UK.

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Using geotechnical and LiDAR spatial monitoring to determine key environmental slope instability thresholds of a Jurassic coastal landslide: Straidkilly Point, Northern Ireland, UK

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ABSTRACT

The Antrim Coast Road stretching from the seaport of Larne in the East of Northern Ireland 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). At various locations along the route, fluid interactions between 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 within the vadose zone. During such instances of instability, debris flows and composite mudflows encroach on the carriageway posing a hazard to road users. This paper examines the site investigative, geotechnical and spatial analysis techniques currently being implemented to monitor slope stability for one site at Straidkilly Point, Glenarm, Northern Ireland. 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 dynamic data.

Terrestrial LiDAR (TLS) was applied to the slope for the monitoring of failures, with surveys carried out on a bi-monthly basis. TLS monitoring allowed for the generation of Digital Elevation Models (DEMs) of difference, highlighting areas of recent movement, erosion and deposition. 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 are characterised and linked to progressive failures from the temporal monitoring. In addition to TLS monitoring, Aerial LiDAR[i] datasets were used for the spatio-morphological characterisation of the slope on a macro scale. Results from the geotechnical and environmental monitoring were compared with spatial data obtained through Terrestrial and Airborne LiDAR, providing a multi-faceted approach to slope stability characterization, which facilitates more informed management of geotechnical risk by the Northern Ireland Roads Service.

1 INTRODUCTION

Slope stability issues such as landslides and debris flows, commonly triggered by rainfall, can cause damage to infrastructure and blocking of main transport routes. Recently technological advances in geomorphological studies of slopes using ground based Terrestrial LiDAR Scanning (TLS) has enabled slope stability issues to be effectively monitored and characterised (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 the generation of a high resolution Digital Terrain Model (DTM) enabling highly detailed classification of slope features and units (Ventura et al., 2011). The use of LiDAR to supplement ground survey data, such as rainfall data (Bull et al., 2010) or geotechnical measurements (Corsini et al., 2006) enables detailed quantifiable assessment of an area. Ground survey data supplemented by TLS provides a unique insight into slope processes by characterising changes in slope morphology, and correlating measured slope geotechnical parameters with these morphological changes.

Multi-temporal DEMs 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). Topographic change and analysis of DEMs resulting in DEMs of difference are an effective means for the determination of areas where the landscape is evolving or failing. Multi-temporal DTMs enable the characterisation of the landform and identification of changes in the topography. The evolution of the hillslope can then be seen along with any distinct change in slope morphology. Monitoring using Terrestrial LiDAR demonstrates short scale temporal measurement of the responses and changes of the slope.

Previous work into the characterisation of landslide morphology using high resolution DTMs was initially carried out by McKean and Roering (2004), using roughness of the landslide as an indicator of previous movement patterns. Carvalli and Marchi (2008) supplement the analysis with detailed characterisation of landslide morphology using LiDAR sources. Glenn et al. (2006) characterize and differentiate landslide morphology and activity using multiple assessment methods. Trevisani et al. (2009) develop the characterisation of LiDAR coupled with variogram analysis for the characterisation of landslide activity.

Limitations of the current understanding identify a gap in the knowledge for a multi-temporal characterisation of slope morphological change coupled with ground based geotechnical parameters. Characterisation and monitoring of slope stability issues using continued monitoring with multiple spatial parameters leads to better understanding of slope processes. Studies for monitoring and quantifying earth flows and landslides using multi temporal Aerial LiDAR (ALS) have been assessed by Ventura et al. (2011). Corsini et al. (2009) have assessed mass wasting processes. Debris flow analysis using spatial precedents have been carried out by Scheidl et al. (2008). Quantification of rockfalls with the incorporation of geotechnical parameters has been carried out by Heckmann et al. (2012). Geotechnical parameters in this case are the analysis of sliding surfaces for rockfall assessment. These previous studies into slope stability assessment are largely focused on a singular spatial element. The incorporation of site specific geotechnical parameters and monitoring data has been assessed for a landslide in Italy, by Corsini et al. (2006). Mackey et al. (2009) develop a methodology for tracking landslide kinematic units using a combination of LiDAR and soil analysis for identifying main areas of movement.

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 Mositure Defect (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.

2 STUDY AREA

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 this beauty, since construction in the 1830s 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 paper examines 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 on 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

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 think 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

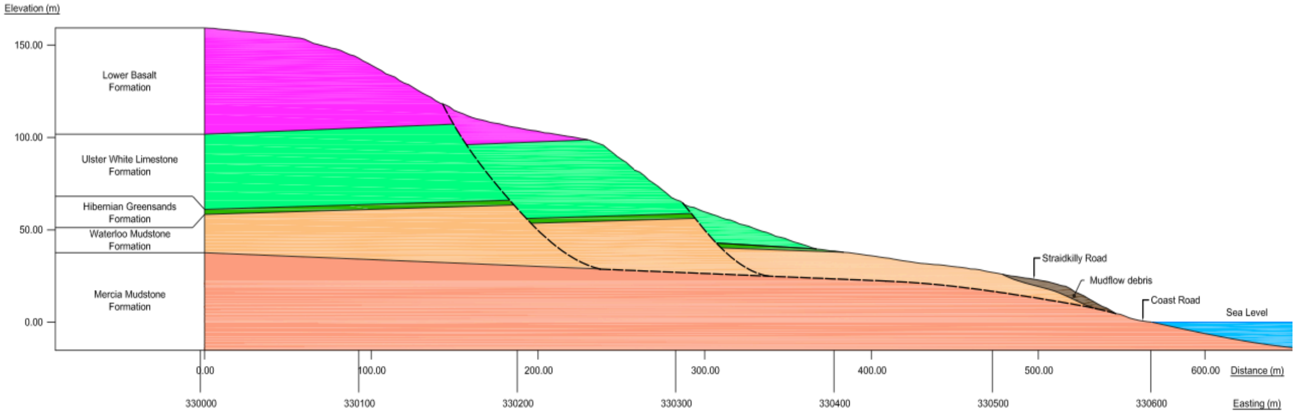

Figure 2 – Geological cross section at Straidkilly point

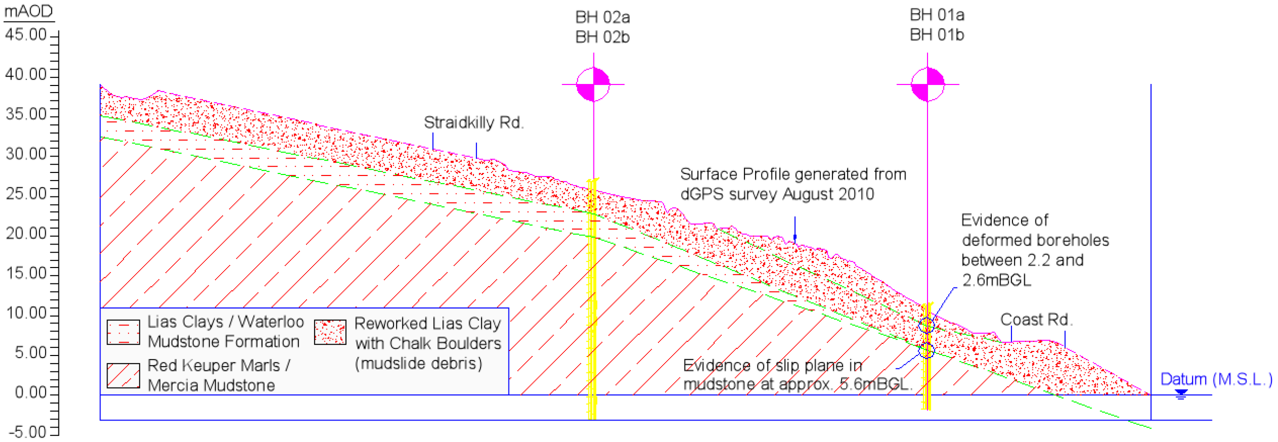

Figure 3 – Inferred local cross section from borehole data

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.

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.

3 METHODS

3.1 Terrestrial LiDAR Monitoring

This study is based on a series of ten Terrestrial LiDAR Data acquisitions over a 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.

Table 1. Straidkilly Point, Scan dates, number and Average point density (m2) from Terrestrial LiDAR scanning

Scan Date	Scan Number	Average Point Density (m^2)
August 2011	1	1042.36
September 2011	2	858.31
October 2011	3	1326.20
January 2012	4	656.25
March 2012	5	837.26
May 2012	6	947.32
June 2012	7	1043.60
September 2012	8	1015.09
November 2012	9	1059.74
February 2013	10	701.12

3.2 DTM Analysis and Slope Morphological Characterization

Once the Terrestrial LiDAR data was registered and post processed the raw LiDAR data was imported into *Lastools* (2013) for removal of above ground objects. Lastools[1] 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

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[1] http://www.cs.unc.edu/~isenburg/lastools/
Lastools is a highly efficient batch processing software suite for viewing, classifying, filtering, tiling and converting LiDAR data. It is based on C++ programming language Laslib from which Lastools is based.

extension. Within the suite of Lastools is, lasground.exe[2], 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, was used as the interpolation approach for the generation of the Digital Terrain Model (DTM), with cell size 0.1m. Multi-temporal DTMs are 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). For the purposes of this study, generated DTMs for each survey period were analysed for changes in elevation relating to morphological changes in the structure of the slope. Characterisation of the temporal change in the DTMs is achieved by changes in elevation, the previous DTM being subtracted from the most recent. This was carried out using the raster calculator in ArcGIS. Temporal changes in elevation maps are generated characterising any movement in the main slope kinematic units. Areas exhibiting a negative change in the elevation are areas of depletion, with a positive change indicating areas of accumulation.

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.

3.3 Weather and Geotechnical Monitoring

A Davis Vantage Pro2 Weather Station was installed at Straidkilly to obtain regular weather data. The station recorded weather variables such as; temperature, wind speed, wind direction, precipitation, solar radiation and barometric pressure at hourly intervals. Soil moisture deficit 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.

4 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 downlsope 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 an number of areas. A large area of accumulation can be seen at the base of the slope. There is a spatial variation in the main units of failure and areas of terrain evolution.

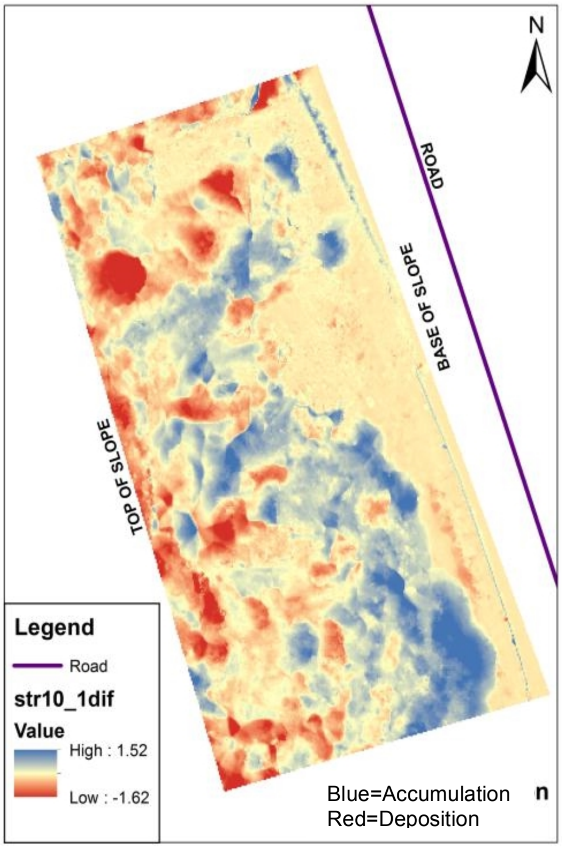

Figure 4 – Cumulative DTM of difference for the Terrestrial LiDAR monitoring period at Straidkilly

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[2] http://rapidlasso.com/lastools/lasground/
Lasground is a tool for bare-earth extraction of LiDAR data. It classifies LiDAR points into ground points and non-ground points.

Figure 5 presents temporal changes in the DTMs relating to changes in height can be characterised into boxplots of incremental changes in height split into the seasons of change. The largest changes in height are in Autumn 2011 and Spring 2012. There is a sinusoidal (wave like) nature behind of the changes in height on the slope as a direct results of failure events on the slope. The peaks and troughs of greater and lower changes in height are down to the climatological and lithological forcing present on the sites resulting in changes in the spatial characterisation of these changes. Most changes occur during the winter and spring months with smaller changes in the summer months.

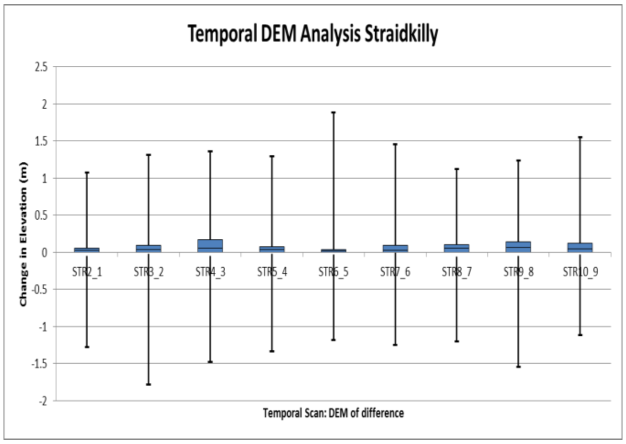

Figure 5 - Temporal DTM analysis, boxplots of change in elevation (m) for the temporal monitoring period; August 2011 to February 2013.

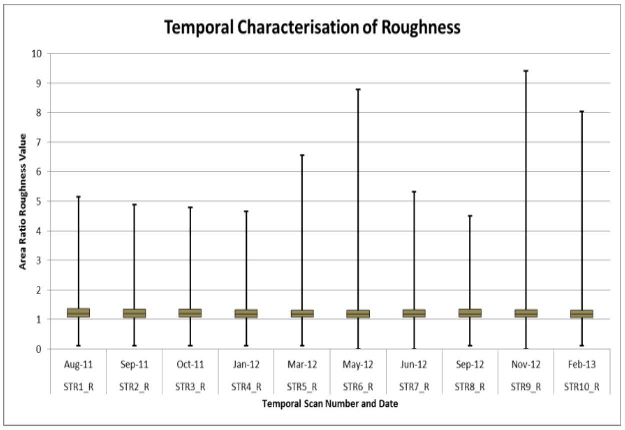

Figure 6 - Temporal changes in Area Ratio Roughness over monitoring period; August 2011 to February 2013.

Changes in height are 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) are found in the March 2012 and May 2013. Temporal variation in roughness can be seen as decreased during the summer months followed by increases in the winter months. These relate to the failures on the flowslide which leave behind scarps and areas of steeper rougher terrain. The failures on the slope result in a restructuring of the spatial structure of the dataset so the roughness will increase and decrease at different areas of the slope depending if they have failed.

Figure 8 illustrates the correlation between rainfall, SMD and pore water pressure at Straidkilly between 1st December 2011 and 31st May 2012. This data generally confirms 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 results in an increase in SMD and a decrease in pore water pressure.

Figure 7 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 observation 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.

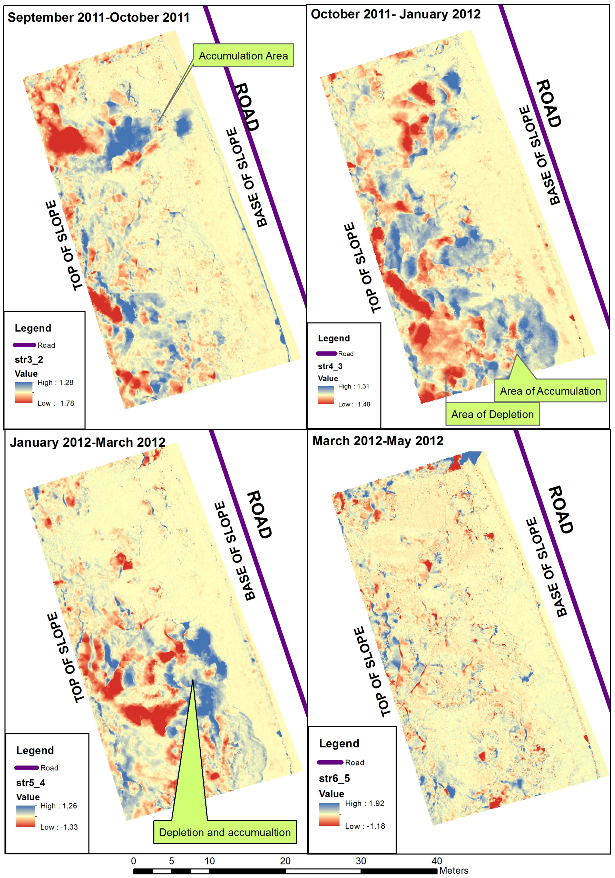

Figure 7 - Incremental changes in elevation; terrain evolution and progression of flowslide, Straidkilly Point; September 2011 to May 2012.

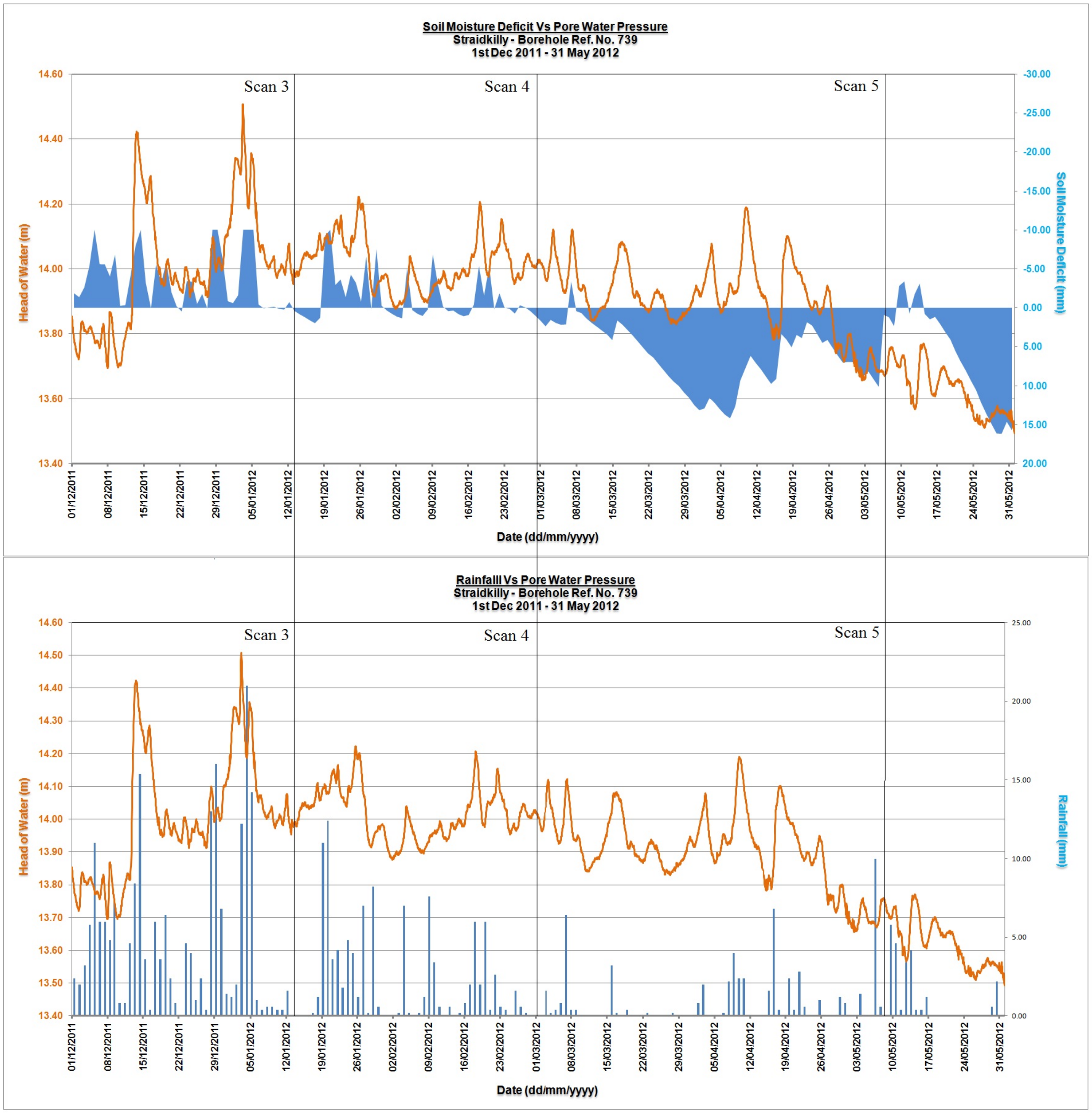

Figure 8 – Comparison between rainfall, SMD and pore water pressure at Straidkilly Point; December 2011 to May 2012.

5 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 erosions and deposition 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, i.e., Slope morphological change.

This study indicates the potential for the combined approach of geotechnical and TLS monitoring for the characterization 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.

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