TERRESTRIAL LASER SCANNING FOR ASSESSING THE RISK OF SLOPE INSTABILITY ALONG TRANSPORT CORRIDORS

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ABSTRACT:

Transport networks play a crucial part in the global economy, with roads and railways being of particular importance at regional and national scales. However, roads and railways are founded on earthworks such as embankments, which can be susceptible to slope failure. Slope instability is a costly problem, which can lead to travel disruption, and injury or loss of life. Earthwork stability assessment is therefore a critical activity for management bodies. However, current approaches are largely limited to hazardous on-foot site inspections. Although high resolution geospatial datasets are becoming increasingly available, there is currently a mismatch between the availability of these datasets, and the ability to use this data in support of decision making. This paper presents one aspect of an integrated methodology for risk assessment in transport corridor environments. The potential of terrestrial laser scanning (TLS) for assessment of slope deformation and failure is examined through application to two test sites in the north of England. The first site is a full-scale test embankment, while the second is a modern highway embankment. Results have shown that for both sites, multi-temporal TLS surveys facilitate the detection of minor changes, such as soil creep and surface runoff. However, vegetation was found to be a complicating factor, contributing to registration errors between individual scans. This was resolved through the use of a least squares surface matching algorithm, which ultimately facilitated detection of change at the centimetric level. These results confirm the potential of TLS for embankment stability assessment, while highlighting some of the practical limitations.

1. INTRODUCTION

Transport networks are fundamental to the effective operation of national and global economies. They facilitate the flow of a diversity of goods and materials, and underpin the mobility of the workforce over a range of scales. At national and regional levels, road and rail networks are of particular importance. Profitability, reliability and safety are crucial, and indistinguishable to the optimal operation of such networks (Mercer, 2002). To this end, it is essential that operating bodies are able to effectively manage and maintain the complex infrastructure which supports these resources. Earthwork structures such as embankments provide the foundations for both roads and railways, and are crucial to the integrity of modern-day transport networks. It is estimated that embankments make up approximately 30 percent of all transport infrastructure, accounting for around 5,000 km of rail routes in the UK, and 3,500 km of trunk road in England alone (Perry et al., 2003). However, like natural slopes, embankments can be susceptible to deformation, and this can have a knock-on impact on the stability of associated assets such as bridges (e.g. Jones et al., 2008). The consequences of embankment deformation and failure can be far-reaching. Local traffic disruption can propagate to other areas of the network, and where remediation is necessary, even relatively short-term road closures can have a detrimental impact on local businesses. In extreme cases, slope failure may be sudden and catastrophic, resulting in serious injury or even death.

Embankments therefore require continuous assessment in order to preserve their stability. However, given the extensive nature of road and rail corridors, this is an immense task which places significant demands on the resources of the bodies responsible. Although highway embankments in the UK are generally constructed to modern specifications, and thus designed to withstand current environmental pressures, there is uncertainty over response to the future impact of climate change. Furthermore, increased volumes of heavier and faster traffic are placing an additional strain on existing infrastructure. UK railways present a more immediate concern. The existing network largely dates from the mid-to-late 19th century, incorporating ageing earthworks, largely composed of poorly consolidated materials (Perry et al., 2003). An increase in extreme rainfall events has renewed concerns over the stability of railway earthworks, with numerous incidences of minor landslides and derailments over recent years.

Currently, earthwork monitoring activities are largely carried out by trained personnel through on-foot site inspections. However, this is a time consuming, hazardous, and costly process, and it can be difficult to ensure that problems are recorded and handled in a consistent manner. There is an increasing trend towards the utilisation of remotely acquired geospatial datasets, for mapping and asset management activities in the engineering sector. As Barnea and Filin (2008) observe, terrestrial laser scanning (TLS) is rapidly asserting itself as a standard 3D measurement technique for surveying and engineering applications. Through TLS, it is possible to acquire mass point cloud data from a remote perspective, in a relatively short period of time. By utilising high precision instruments, and employing rigorous survey control practices, topographic datasets can be collected to a high degree of

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accuracy. In addition, traditional land survey approaches are unable to compete with TLS in terms of dataset resolution and speed of acquisition (Bitelli et al., 2004). The high spatial resolutions achievable facilitate analysis of terrain features to unprecedented levels of detail. This offers potential for identification of subtle expressions of slope deformation and instability, thereby facilitating early-warning of failure. Although TLS remains largely unexplored in terms of earthwork monitoring for engineering applications, a number of scientists have successfully demonstrated the value of this technique for landslide and geohazard monitoring in natural terrain (e.g. Bitelli et al., 2004; Scaioni et al., 2004).

This paper reports on research which has been carried out to investigate the potential of TLS for evaluating slope stability in transport corridor environments. This is one aspect of an ongoing project which is developing an integrated approach to risk assessment in transport corridor environments (refer to Lim et al., 2007). The project utilises a number of remote datasets, including TLS, lidar, and multispectral imagery in order to provide multi-scale characterisation of embankment conditions in road and rail corridor environments. Instead of utilising these datasets simply for monitoring of change, the research adopts a proactive approach, by identifying key influences on slope stability, and attempting to recover these from the datasets. TLS is a crucial aspect of this strategy, facilitating detailed assessment of instability over local scales. This will allow for an improved understanding of how slope failure evolves over time, and will help to identify the key controlling parameters. This paper reports on initial investigations into the suitability of TLS carried out at a test embankment and an operational highway embankment. Results are then analysed in the context of local slope conditions.

2. METHODOLOGY

2.1 Evaluation of TLS at a Full-Scale Test Embankment

Prior to implementing TLS at a real-world test site, the potential of the technique was evaluated under controlled conditions. Scanning was carried out at a full-scale test embankment, owned and managed by Newcastle University’s School of Civil Engineering and Geosciences (Figure 1). This 90 metre-long embankment is 6 metres high, with 2 in 1 side slopes, and a 5 metre crest width. Constructed in 2005, the embankment is comprised of four distinct plots. The two central plots offer good compaction control, and were constructed to highway specifications. The two end plots, which are less well compacted, were constructed through end-tipping, and are more representative of UK railway embankments. The embankment is fully-instrumented and is continuously monitored using a range of geotechnical sensors.

A Leica HDS2500 scanner was used to carry out repeated high resolution surveys of the embankment. The HDS2500 is a time-of-flight scanner which offers an optimal range of 50 m, and a precision of ± 6 mm. This is a fixed-head, camera-like instrument, which operates on the 3D resection (indirect georeferencing) control principle. This requires that control points be located within the scan, and avoids centring and levelling of the scanner. The HDS2500 (now superseded by the Leica ScanStation 2) is a popular and flexible instrument, which has been used in a diversity of applications, including structural deformation analysis (Su et al., 2006), and coastal geohazard monitoring (Miller, in press). Results of scans carried out in July 2007 and March 2008 are presented here.

Figure 1. Full-scale test embankment.

2.2 TLS Analysis of a Highway Embankment

The second phase of the research involved TLS monitoring and analysis of an operational embankment. The research is being evaluated at a test site near Haltwhistle, Northumberland. This site offers an 8 km-long corridor which contains a major trunk road (A69) and rail route. These form part of a strategic link across northern England, between Carlisle in the west, and Newcastle upon Tyne in the east. The test site contains a large highway embankment, constructed in 1997 as part of the A69 Haltwhistle Bypass. As illustrated in Figure 2, this provides support for a bridge, which carries the A69 over the railway and a minor road (visible in the foreground).

Figure 2. A69 Haltwhistle highway embankment (western end).

The embankment is approximately 15 metres in height, with a relatively constant slope gradient of 30°. The area of interest stretches for around 100 metres east of the bridge. As Figure 2 illustrates, there is a significant amount of loose scree material over the upper slope. In addition, with the exception of a few bushes at the top and bottom of the embankment, vegetation cover over the western end of the slope is sparse. However, further east (not visible in Figure 2), small saplings have been planted in an attempt to promote vegetation growth and provide increased stability. This paper focuses on the results from TLS surveys which were carried out in late October 2007 and mid-December 2007. This facilitates analysis of the influence of vegetation change and seasonal effects, with the October survey representing 'leaf-on' (vegetated) conditions, and the December survey displaying 'leaf-off' conditions. The HDS2500 scanner was again utilised, with the instrument set up at a number of stations at the foot of the embankment. Control targets were placed on the slope, and their location surveyed by total station. The main purpose of the monitoring surveys was to determine if deformation was occurring over the slope, and whether this could be detected through repeated TLS surveys.

2.3 Data Processing

In terms of data processing, the same approach was employed for the test embankment and the Haltwhistle highway embankment. The raw point clouds were initially processed using Leica's *Cyclone* (v. 5.8.1) software, which facilitates data acquisition, point cloud registration, and basic editing. Following this, a number of different software packages were used in order to determine multi-temporal surface changes. Firstly, the datasets were exported to TerraSolid's *TerraScan* (v. 007.004) software. *TerraScan* is capable of handling both airborne and terrestrial laser scanning datasets, and offers a range of classification and analysis routines. The main task involved classification of ground points. *TerraScan's* ground classification algorithm has been shown to perform favourably in comparison to alternative algorithms, particularly over steep slopes (Sithole and Vosselman, 2003), and therefore was well suited to this application. After classification and production of ground models, the point datasets were exported to McCarthy Taylor's *LSS* (v. 9.60) terrain modelling software. This allowed calculation of vertical surface differences between the multi-temporal survey epochs, while preserving the original high resolution of the datasets. Finally, ESRI's *ArcGIS* (v. 9.2) software was used for visualisation and analysis of the surface differences.

3. RESULTS

3.1 TLS Test Embankment Evaluation Survey

Two TLS datasets, from July 2007 and March 2008, were available for the test embankment. Elevation differences were calculated between the datasets, and plotted using *ArcGIS*. Figure 3 illustrates the differences between the July 2007 and March 2008 surveys for the south side of the embankment. Although no major areas of deformation or failure are apparent, a number of minor differences are visible. The linear features indicated at A in Figure 3 relate to run-off drains which were installed a few weeks prior to the March 2008 survey. As these represent instances of known change, they provide a useful check on the TLS difference results. Although not representative of natural processes, it is clear that TLS monitoring has facilitated successful detection of these features. Feature B highlights the occurrence of erosion at the central plot boundary. This had already been observed visually on-site, and is detectable in the change dataset. Interestingly, adjacent to this central area, positive change appears to have occurred. The cause of this is unclear, although it may be associated with internal bulging of the slope, or perhaps increased vegetation growth. Finally, feature C highlights minor instances of negative change occurring in a distinct lateral pattern across the embankment. These are most likely due to soil creep. Unfortunately it was not possible to determine the accuracy of the results, as no check point datasets were available. However, given the low magnitude changes detectable in Figure 3, it would seem likely that the level of uncertainty is within an acceptable tolerance.

3.2 TLS Analysis of Haltwhistle Highway Embankment

The results presented in Section 3.1 suggested that TLS is suitable for high resolution monitoring of earthwork structures in transport corridor environments. As described in Section 2.2, scans of the Haltwhistle A69 highway embankment were carried out in October 2007 and December 2007. This proved to be a more challenging procedure than in the case of the test embankment. Firstly, it was necessary to identify optimal scanning positions in order to minimise occlusions and gaps between adjacent scans. In total, twelve scans, from four

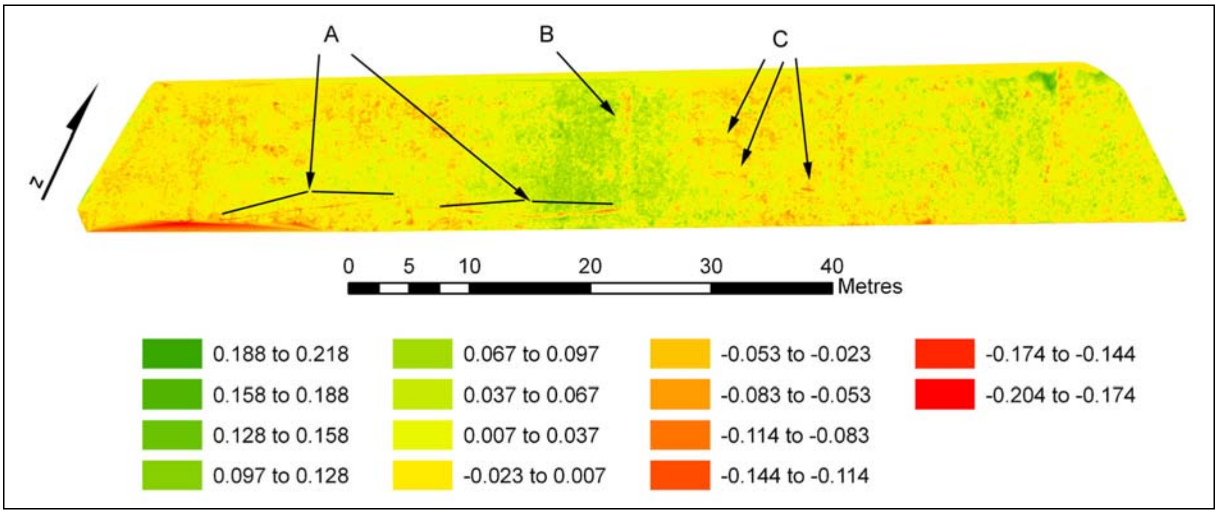

Figure 3. Test embankment elevation differences (metres), July 2007 – March 2008, with key features highlighted.

different positions were required to provide comprehensive coverage of the embankment. This resulted in an average spatial resolution of 1000 points/m^2, and around nine million points per survey. Along the length of the embankment, from west to east, the slope progressed from bare earth, to short grass, to small saplings and bushes, to dense deciduous trees. As a consequence, the site provides an excellent test case for examining the effects of vegetation on slope stability, and evaluating its impact on TLS datasets. However, during data acquisition, the greatest challenge related to locating control markers in visible locations on the vegetated sections of the slope – a highly time-consuming procedure.

During data processing, it became apparent that several of the point clouds contained registration errors. This issue affected both the October and December surveys, and closer investigation revealed that this was largely caused by vegetation having partially obscured some of the control targets. Minor systematic offsets in height were also discovered between a number of the scans. Although in some cases this amounted to little more than 4 cm, clear systematic errors were apparent in the surface difference results. To resolve these problems, a robust least squares surface matching approach was adopted. Surface matching allows poorly-oriented datasets to be matched to a fixed reference surface through least squares minimisation of surface differences. This enables determination of the unknown translation and rotation parameters required to register the matching surface to the fixed reference surface, and removes the requirement for control points. This algorithm, which was developed at Newcastle University, has previously been successfully utilised for matching of both lidar and TLS datasets, and further details can be found in Mills et al. (2005) and Miller et al. (in press). The individual point clouds (23 in total) for the two TLS surveys were matched to a high resolution lidar dataset which had been captured in July 2007. By matching all point clouds to a common, continuous reference surface, it was possible to eliminate systematic error, thus facilitating the detection of relative differences between the two survey epochs. With the datasets now in a common reference system, the individual scans were amalgamated into a single dataset for each epoch. Following the procedure outlined in Section 2.3., it was then possible to directly compare the datasets in order to analyse surface changes.

Figure 4 illustrates the final surface differences between October and December 2007 for the western end of the embankment. Although no major slope deformation is apparent, there are some subtle indications of surface movement. The most obvious differences are the linear features of negative change highlighted at A. Not only do these occur over the steepest section of the embankment, but they also correspond to the area of loose material highlighted in Figure 2. These are most likely erosion tracks caused by runoff of surface water, but may also be partly associated with soil creep. The data gaps indicated at B are caused by two dense bushes, apparent near the bottom of the slope in Figure 2. Due to the terrestrial perspective of the scanner, these have caused a shadow effect in the data. This has also occurred to a lesser extent along the bottom of the slope near the road. This highlights one of the difficulties associated with scanning in vegetated terrain. The area of negative change indicated at C corresponds to a particularly dense clump of bushes and may be associated with a loss of foliage between October and December affecting the corresponding ground models. Further analysis of the more densely vegetated eastern part of the embankment is still to be carried out. However, the effect of the changing vegetation conditions is apparent in Figure 5, which shows a section through the October (leaf-on) and December (leaf-off) point

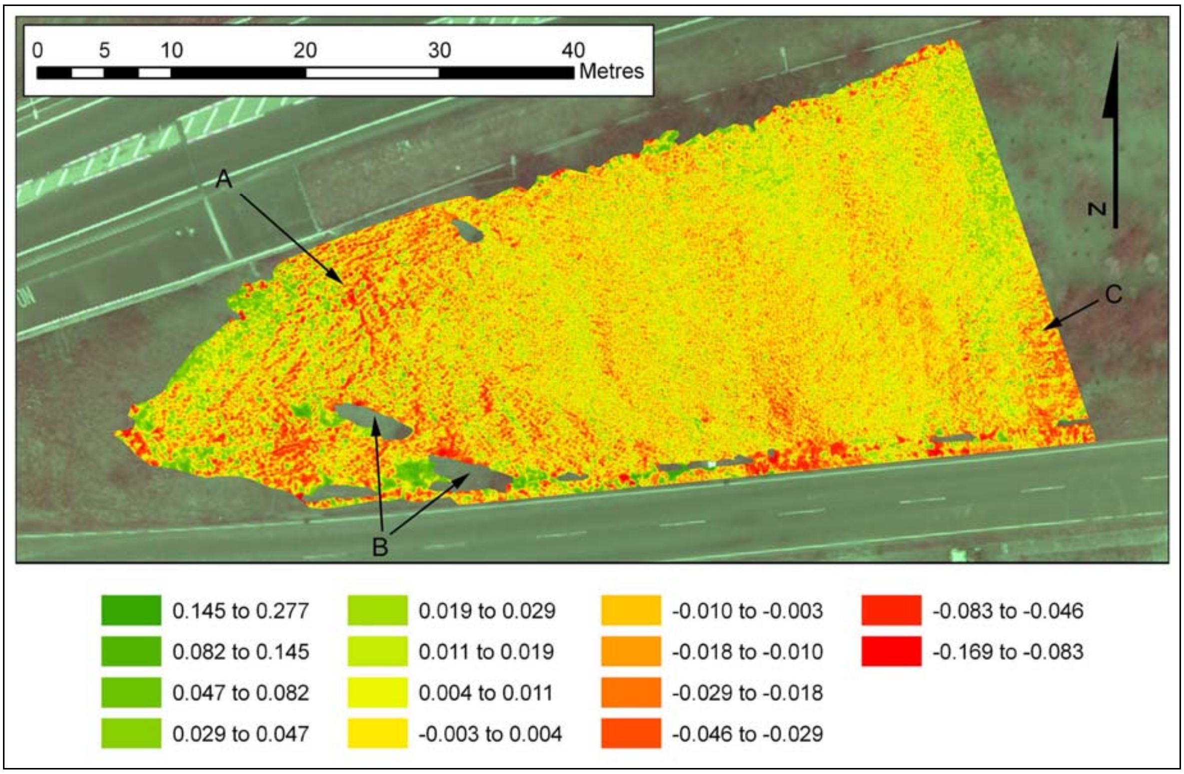

Figure 4. Elevation differences (metres), October - December 2007 for Haltwhistle highway embankment.

Figure 5. Section through TLS datasets during a) leaf-on, and b) leaf-off conditions. Differences are highlighted through combination (c).

clouds for a densely vegetated part of the embankment. It is evident that a significant loss in foliage has occurred over the six week period. This has resulted in an improved representation of the ground surface during leaf-off conditions (Figure 5b), as a greater number of points have penetrated the vegetation canopy.

4. DISCUSSION

The results presented here indicate that TLS is well-suited to the evaluation of embankment stability at local scales. The high spatial and temporal resolutions achievable suggest that TLS would provide a valuable complement to techniques such as lidar and photogrammetry, as part of an integrated risk assessment strategy.

One of the major challenges presented by this application was the requirement to detect low magnitude surface differences which may provide early indications of instability. This places particularly high demands on the quality of the registration solutions, leaving no tolerance for error. However, as demonstrated in this research, when scanning outdoors in a semi-natural environment, it is not always possible to avoid control-related problems. In this application, vegetation was a major complicating factor, which made it difficult to correctly identify targets in the scene. Other difficulties may arise as a result of physical site constraints, poor weather, or scanner battery life. The experiences gained through this research strongly suggest that in order to optimise the magnitude of changes which are detectable through TLS, great care must be taken in locating a sufficient number of targets in the scan. From a surveying perspective, this may seem an elementary requirement, but in terms of TLS, it can be easy to underestimate or overlook the challenges involved. It may be the case that for applications such as this, a direct georeferencing-type scanner may present a more appropriate solution. Direct georeferencing scanners can be oriented, and centred and levelled over a point, thus removing the requirement for control targets to be located in the scan. This presents a completely remote solution and removes the potential for problems associated with target detection. However, ultimately it is likely that the choice of scanner will be dictated by a compromise between range, precision, cost, and availability.

The HDS2500 scanner, with a precision of ± 6 mm, offered an excellent opportunity for detecting low-magnitude surface change. Ultimately, this was achieved through application of a surface matching-based registration approach. This facilitated internal registration of individual point clouds for each epoch, and also enabled the inter-epoch surveys to be registered to a common reference frame. For applications such as this, where sensitivity to change at a threshold of less than 10 cm may be required, surface matching (or point cloud matching) may well offer the most appropriate solution. Indeed, TLS point cloud matching algorithms have been the focus of intensive research effort over recent years (e.g. Gruen and Akça, 2005; Bae and Lichti, 2008). Although it would be useful to establish the absolute accuracy of TLS for this application, for applications involving multi-temporal analysis of change, it is relative differences which are of greatest importance.

While vegetation had a largely detrimental effect on the TLS scans in this case, it is apparent that this technique holds tremendous potential for applications where vegetation is of primary interest. Although impractical to survey entire forests in this manner, TLS has been shown to enable characterisation of forest inventory parameters, through extraction of tree structure and other variables (e.g. Aschoff et al., 2004; Hopkinson et al., 2004). These capabilities may also be of value here, as vegetation is known to directly influence slope stability. Both TLS and lidar may therefore offer a means of extracting key vegetation parameters.

The results presented here have been useful in evaluating potential early characteristics of slope deformation. The evaluation surveys carried out at the test embankment (Section 3.1) identified low magnitude changes such as those due to soil creep. These capabilities were confirmed in Section 3.2, through analysis of differences between the October and December 2007 surveys of the Haltwhistle highway embankment. In this instance, evidence of erosion due to surface runoff was identified. The majority of these changes were of a relatively low level, within a threshold of ± 8 cm. Detection of changes of this magnitude suggests that this approach may be useful for identifying potential pre-cursor surface expressions of embankment instability. It is anticipated that continued TLS monitoring will improve understanding of the underlying factors which contribute to failure, and will allow for refinement of issues such as optimal temporal resolution of surveys. The wider aim of the research is to develop an integrated approach to evaluating risk in transport corridor environments. This implies a more proactive approach to risk assessment than that which would be delivered through monitoring alone. Specifically, the research aims to achieve this goal through evaluating the underlying controls on slope stability. This includes factors such as slope gradient, slope aspect, vegetation influences, and soil moisture conditions. The results of the TLS analysis will allow for an improved understanding of the correlation between these variables and slope deformation.

5. CONCLUSIONS

This paper has evaluated TLS for assessment of embankment stability in transport corridor environments. Initial surveys were carried out at a full-scale test embankment. This enabled identification of minor surface changes, and confirmed the potential of TLS for slope failure monitoring. Subsequent scanning of a modern highway embankment highlighted minor erosion features and possible soil creep over steep sections of the slope. Vegetation was found to be a significant complicating factor. Dense vegetation resulted in shadowing in the datasets, and also obscured some of the control targets, leading to registration difficulties and systematic offsets between scans. These problems were overcome by application of a least squares surface matching algorithm. This enabled detection of low-magnitude (< 8 cm) changes over a six week period. Without adopting the matching-based registration solution, it would have been impossible to resolve such minor changes.

The results presented here have demonstrated the value of TLS for evaluating embankment stability. However, this is only one aspect of a wider research strategy which aims to develop an integrated methodology for assessment of risk in transport corridor environments. This involves the fusion of TLS, lidar, and mutlispectral imagery in order to develop an operational solution which can be applied at the network scale. Future work will concentrate on investigating the correlation between slope deformation and controlling factors such as slope, aspect, vegetation and soil moisture. The research presented here is a crucial aspect of this, as TLS supplies the high spatial and temporal resolutions required to improve understanding of how slope failures develop over time.

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