HIGH RESOLUTION EARTH IMAGING FOR TRANSPORT CORRIDOR SLOPE STABILITY RISK ANALYSIS

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ABSTRACT:

Transport networks are fundamental to economic growth and prosperity, facilitating the nationwide transfer of goods, services and people. Many of the road and railway networks in the UK, and throughout the world, are built on ageing earthwork structures and hence are susceptible to disruption from land instability. This paper describes the use of remotely sensed datasets to analyse the risk of future failures in transport corridor earthworks. High resolution imaging systems such as light detection and ranging (lidar), photogrammetric and multispectral surveys now offer the potential for increasingly detailed earth surface information to be collected. Remotely sensed height and reflectance measurements can be used to provide quantitative records of critical slope characteristics. Although the ability to determine slope variations at a network scale will provide a valuable new tool in asset management, its development requires an extension of conventional error assessments, beyond analysis of the raw dataset to an investigation of the ability to accurately model the desired parameters for slope instability. The results of a preliminary investigation into the performance of the derived slope models are presented and the implications for both earthwork assessments and remote sensing applications for slope studies in general are discussed.

1. INTRODUCTION

This paper presents the results from a preliminary investigation into the derivation of slope measurements at the network scale. The research seeks to improve the assessment of slopes for transport corridors where small variations in gradient may determine the occurrence of localised failures; particularly in poorly compacted and aging earthworks. In order to achieve this, consideration must be given beyond generic indicators of the overall quality in the raw data to the development of new methods with which to assess the ability of each dataset to obtain the required information. The study provides an essential component of a wider aim to extract and integrate slope stability parameters from the fusion of multiple datasets for risk assessment. Through the identification of the conditions and consequently the locations most susceptible to failure the tools developed will guide the more targeted, and therefore more effective, remediation of earthworks.

1.1 Transport corridor assessment

The risks posed by land instability are of particular concern to the management of transport corridors where the costs of remediation and mitigation are both considerable and necessary. As examples, London Underground Limited spent approximately £70M on earth structure assessment between 1994 and 1999, mainly due to the old age of many of the earthworks it comprises. Despite the much younger earthworks found along highways, over £15M was spent on the remedial treatment of earth structures on UK motorways and trunk roads in 1993/94 alone. Increased, faster and heavier traffic is placing higher dynamic loads on earthworks and over the coming years climate change is likely to result in specific changes to precipitation, flooding and vegetation patterns; changes which pose further risks to the reliability of transport infrastructure. It is therefore becoming increasingly important to assess, and where necessary mitigate, the risks posed by hazards that may endanger network users or reduce reliability. Currently engineers must conduct site visits to inspect corridor condition, analysing the risk of failure through qualitative observations or, where necessary, quantitative prediction based on geotechnical models or monitoring instrumentation. The information obtained is essential in planning mitigation measures, in terms of both strategic prioritization and tactical management. However, collecting the required level of detail on the condition of extensive networks is highly time consuming, costly and puts investigators at risk. Furthermore, effective management of transport corridor environments has been limited by a tendency to focus on the identification of past failures rather than assessing the risk of future problems; restricting remediation to reactive rather than proactive practices.

1.2 The importance of slope in earthwork failure

There are many factors which contribute to slope behaviour: vegetation cover, the characteristics of the constituent material, moisture content of the slope and its rheological history can all influence stability. One of the most important determinants on the propensity of a slope to move is the gradient of the slope itself (Al-Homoud and Al-Masri, 1999). Slope gradient has been strongly correlated with mass movements such as landslides (Montgomery and Dietrich, 2004) and debris flows (He *et al*., 2003). With regards to transport corridors, individual earthworks have been designed with relatively consistent gradients based on either construction experience in the case of railways or laboratory calculations that determine the internal angle of friction of highway structures (Highways Agency, 1998). Nevertheless, there is considerable variability both within and between different earthworks, often exacerbated over time due to settlement, degradation and localised remediation of the slope. Therefore the measurement of slope has become an important and commonly applied practice.

1.3 Earth imaging applications to slope studies

Remote sensing data lend themselves to slope modelling because the desired elevation information is collected directly, minimising processing requirements. Once the raw point data is quality assessed and an appropriate surfacing algorithm has been selected slope measurements can be obtained automatically over large areas. However, the methods currently used to assess remote sensing datasets such as lidar and photogrammetry are poorly suited to the quantification of errors on slopes. For example, the American Society for Photogrammetry and Remote Sensing (ASPRS) specifications (2004) recommend that lidar checkpoints used for error assessments should be located on flat, uniform ground. A critical concern for this research is the accuracy of the remote measurements not on a flat control surface but on sloped surfaces. Indeed, it has been suggested that the error incurred in lidar readings increases with the angle of the target slope (Hodgeson and Bresnahan, 2004). Ultimately, the accuracy of the derived slope parameters may not be well represented by generic assessment practices. Applied research evidently requires a specific appraisal of the derived parameters in addition to quality measures of the raw data.

2. SITE

An 8 km stretch of the road and rail network between Newcastle and Carlisle has been chosen as the main focus for the research (Figure 1). The selected route contains extensive stretches of railway embankments, occasional cuttings and two significant highway earthworks. The railway sections suffer from persistent stability problems and have been the subject of several investigations by the network operator. The superficial deposits underlying the route include made ground, floodplain alluvium, river gravels and terrace and fan deposits over glacial sands and gravels and lodgement till. Beneath the drift material lies the solid geology of the Upper Limestone Group. The earthworks contain vegetation types considered representative of corridor environments nationwide, ranging from established trees, through shrubs to grasses and bare embankments. Concentrated within the floodplain of the South Tyne, there are little regional topographic differences to account for. The route rises 5 m over the 7 km from east to west, punctuated by a plateau at Haltwhistle that rises and falls by a further 6 m.

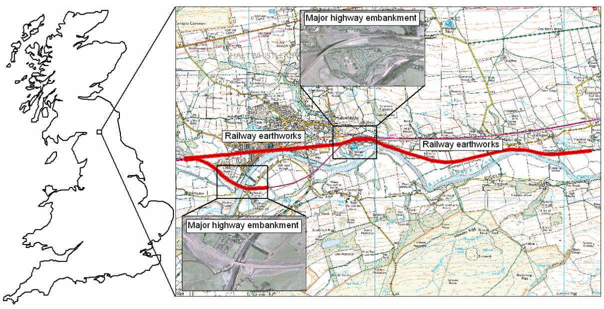


Figure 1. The transport corridor (highlighted in red) between Newcastle and Carlisle includes both railway and highway earthworks.

3. DATASET ASSESSMENT

An Optech ALTM 2050 scanning system was fitted to a Litton LN-200 Inertial Measurement Unit (IMU) and used to collect a helicopter-based lidar survey of the research area. First and last pulse returns and associated intensity information was recorded at a rate of 50 kHz within a swath width of approximately 220 m. The flying height varied between 300 and 400 m, producing a point resolution of up to 15 points per m^2; although multiple passes involving six individual flightlines were used to produce an overall point density in excess of 100 points per m^2. The overlapping flightlines enable the consistency of different surveys to be assessed. Digital images were simultaneously acquired with the use of an Applanix DSS322 digital camera system. The 22 Mpixel resolution resulted in ground coverage of approximately 193 m x 256 m and a pixel resolution of 0.05 m^2, given a 350 m flying height. The timing, position and orientation information at the time of each image capture were recorded with a separate IMU and combined with the camera calibration files to generate orthorectified images of the study area.

In order to assess the performance of the survey eight specially constructed check point targets were installed at four evenly distributed sites along the research corridor. The targets consisted of a circular wooden board of 1 m diameter mounted on adjustable studding (Figure 2). The outer 0.5 m was coloured black with an inner white circle in accordance with the design specification suggested by Csanyi *et al.* (2005). This generated clearly identifiable, rotation invariant surfaces of known size, shape and reflectance. The target was located on a tripod of metal studding which enabled a fixed elevation to be set and the tilt angle to be levelled. At each location one target was located on either side of the corridor to ensure three-dimensional error checks could be made (Csanyi *et al.*, 2005). The concentration of targets on the transport corridor rather than generically throughout the wider research area reflects the applied concern with errors specific to the earthworks. Prior to the survey flight a network of ground-based global positioning system (GPS) base stations was established and the position of the targets measured with differential GPS. In addition to the elevated targets, 30 conventional photogrammetric check points were also evenly distributed throughout the corridor route and fixed with differential GPS. These consisted of circular white targets of 1 m diameter and were kept separate from the control points used for the orthorectification; resulting in a representative coverage of locations against which the lidar and photogrammetric performance could be checked.

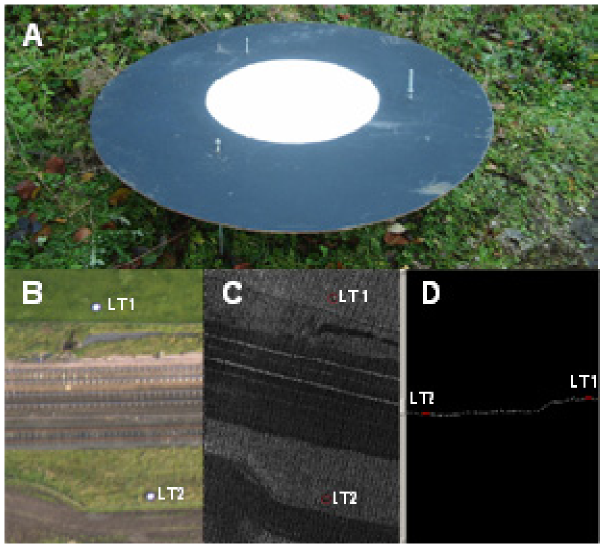


Figure 2. Check point analysis with the use of stilt-mounted circular targets (A), located on either side of the transport corridor they were clearly located in both orthorectified imagery (B) and Lidar points coloured by intensity (C), particularly when viewed in cross section (D).

The lidar survey data were processed in Terrascan, part of the Terrasolid suite of modules able to read in, transform, match and classify the 'raw' point cloud information. The data was checked for gross errors between flightlines and filtered for anomalously high or low points with respect to surrounding values. Terraphoto, another Terrascan module, was used to rectify the images onto the processed lidar elevations. The strong contrast provided by the black and white targets proved generally more effective as control points than the plain white photogrammetric targets, although both types were identifiable in the orthoimages and a lidar point cloud coloured by return intensity. Furthermore the raised surface of the elevated targets improved the accuracy of the location and therefore the position of each reference point.

The point location for each of the targets was extracted from both the lidar intensity map and the orthoimages and compared against the positions as determined by differential GPS. The root mean square error (RMSE) was calculated for both datasets, although it should be noted that no height (Z) values were calculated for the orthoimages because they were rectified directly on to the processed lidar model rather than relying on parallax differences in stereoimagery to extract the elevations (Table 1). The only significant differences noted between the performances of the two target types were the better horizontal and height accuracy of the raised targets in comparison to the photogrammetric targets that were level with the ground surface. The overall elevation accuracies obtained were marginally worse than the instrument specifications that claim a vertical accuracy of 0.085 m at a flying height of 1200 m. It might have been expected that the height information recorded would have been significantly improved by the reduced flying height of the survey, although a low cloud base and sporadic, light rain throughout the collection may have degraded the instrument performance. The continuous coverage provided by the imagery enabled the centre-point of each check point to be more accurately located, reflected in the reduced photogrammetry RMSE when all targets were considered.

Table 1. Check point assessment of different target designs for lidar and photogrammetric datasets.

		RMSE (m)		
		X	Y	Z
LiDAR RMSE	Elevated targets only	0.049	0.090	0.074
	Photogrammetric targets only	0.088	0.078	0.110
	Total weighted mean	0.138	0.126	0.092
Photogrammetry RMSE	Elevated targets only	0.040	0.091	
	Photogrammetric targets only	0.075	0.097	
	Total weighted mean	0.069	0.097	

The limitations on the precision of lidar point data were partially compensated for with the use of several overlapping flights, increasing the density of measurements. However, the combination of repeat passes may introduce new sources of error and therefore the dataset was reassessed for six individual flightlines of the same corridor section (Table 2). In general the height measurements were more accurate than the positional information and the improvement associated with the raised targets was again apparent. Considerable variability between the flightlines suggests that care should be taken when assessing multi-pass datasets to analyse the errors influenced by the flying conditions and direction specific to each pass. Whilst it is evident that raising targets above the surrounding area improves the ability to locate the target the positional accuracy remains limited with respect to the density of points that can be achieved.

Table 2. Check point assessment of different target designs for individual lidar flightlines.

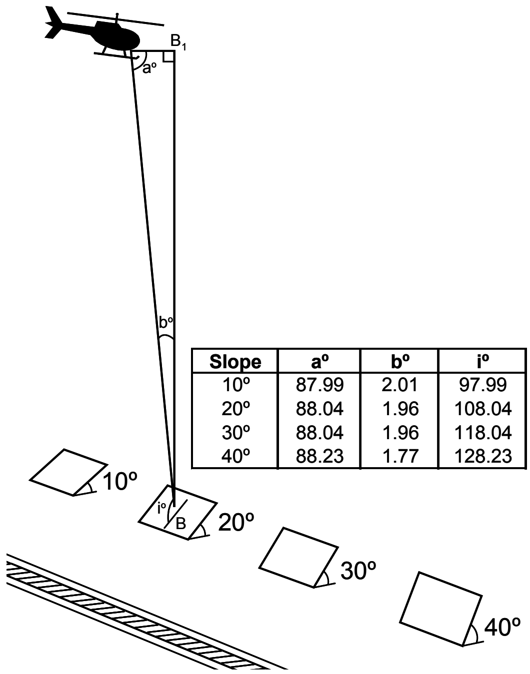
		RMSE (m)		
		X	Y	Z
LiDAR flightline 1	Elevated targets only	0.144	0.126	0.094
	Photogrammertic targets only	0.061	0.087	0.100
	Total weighted mean	0.077	0.094	0.099
LiDAR flightline 2	Elevated targets only	0.227	0.057	0.078
	Photogrammertic targets only	0.121	0.147	0.107
	Total weighted mean	0.142	0.130	0.101
LiDAR flightline 3	Elevated targets only	0.128	0.061	0.056
	Photogrammertic targets only	0.128	0.133	0.088
	Total weighted mean	0.128	0.119	0.082
LiDAR flightline 4	Elevated targets only	0.173	0.080	0.038
	Photogrammertic targets only	0.031	0.209	0.127
	Total weighted mean	0.058	0.184	0.110
LiDAR flightline 5	Elevated targets only	0.091	0.063	0.076
	Photogrammertic targets only	0.086	0.119	0.129
	Total weighted mean	0.087	0.108	0.119
LiDAR flightline 6	Elevated targets only	0.213	0.064	0.105
	Photogrammertic targets only	0.106	0.154	0.110
	Total weighted mean	0.127	0.137	0.109

4. SLOPE MEASUREMENTS: APPLICATION EVALUATION

4.1 Slope scale evaluation

The dataset assessment demonstrates the uncertainty present within standard error checks. The spatial variability evident within and between different flightlines also questions the suitability of relying exclusively on ideal horizontal surfaces for validating the application of slope modelling in the transport corridor environment. Indeed, it is the positional errors rather than the direct elevation errors that are of most concern with regards to slope assessments (Maling, 1989). An initial attempt has been made to quantify the errors specifically associated with variations in slope with use of control surfaces of fixed gradient. Four 1 m^2 target boards were installed on top of a railway cutting within 20 m of the tracks to ensure the angle of incidence from the sensors was as close to the nadir position as possible. The boards were set at 10º, 20º, 30º and 40º; these angles were considered representative of earthwork slope gradients. The trajectory information was used to refine the precise orientation to the boards at the time of capture (Figure 3). The 1 m^2 size of the boards enabled the effects of slope on point density to be determined and represented the smallest scale at which slope processes are likely to be monitored with a network.

The number of returns from each board was directly correlated to slope, with a minimum of 14 point measurements for each flightline from the board inclined at 10º reducing to 10 returns from the 40º board. The errors associated with each slope gradient were analysed with a MatLab script that fitted a three-dimensional plane through the data that minimised the sum of square errors within the laser returns (Figure 4). The gradient of this plane was compared to the known slope of the board, measured in the field. Given the variability noted above between different collections of the same targets, the gradients were calculated separately for individual flightlines in addition to the mean effect for the dataset as a whole (Figure 5). The mean errors show that there appears to be little difference in the overall accuracy of measurements on gradients of 20º or above, although a noticeable improvement was recorded in shallower slopes. The information received from the 10º board, closest to the ideal angle of incidence of 90º, also demonstrated significantly higher consistency between different passes of data collection, with all of the gradients within a 1.5º overestimate of the slope angle; this is also approaching the 1º error tolerance for the field set up of the boards. The consistent over-prediction of mean slope angles contrasts with an investigation of slope effects on interpolated low angled slopes that recorded an under-prediction in terrain below 8º (Hodgson *et al.*, 2005). The errors appear to be randomly distributed between under and overestimations in the models of the steeper gradients although patterns were noted within individual passes. For example, the errors associated with flightline 3 were generally larger than the other passes and appear directly correlated to slope steepness. By contrast flightline 1 was better able to measure slope within the set range, irrespective of an increasing angle of incidence. The data collected from flightline 1 outperformed the measurements made with the combined dataset of all flightlines for all fixed gradients. Therefore it may be preferable to determine the suitability of specific passes to the required application over the maximisation of point density with combined datasets.



Slope	aº	bº	iº
10º	87.99	2.01	97.99
20º	88.04	1.96	108.04
30º	88.04	1.96	118.04
40º	88.23	1.77	128.23

Figure 3. Control slope experiment to assess the effect of slope on lidar errors. The angle of incidence (i) reflects the off-nadir position (B) from the sensor.

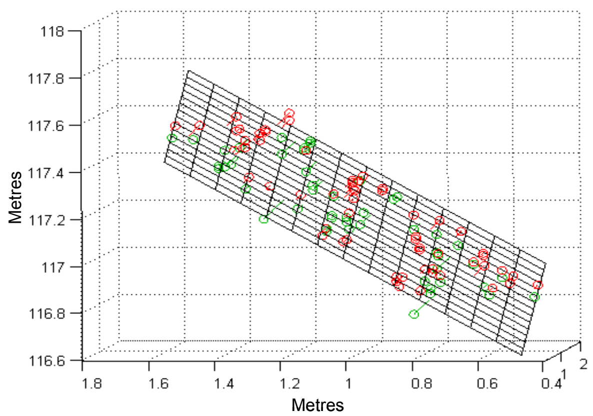


Figure 4. Slope error assessment. The red and green points and difference lines represent points above and below the plane of best fit respectively.

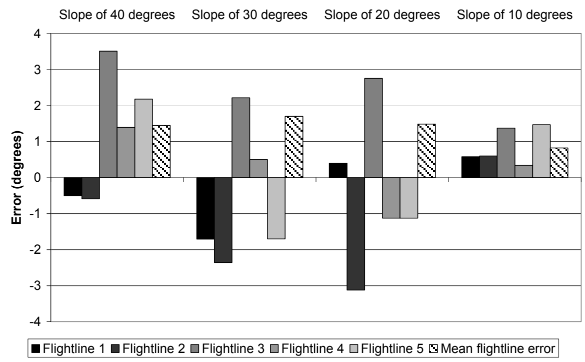


Figure 5. Slope errors determined for gradients representative of those found in transport corridor earthworks.

4.2 Network scale evaluation

The measurement of slopes with lidar data, which may themselves be directly correlated to error, is further complicated at the network scale because the sides of earthworks often contain uneven microtopography and are obscured by vegetation. In order to investigate the slope properties beneath vegetation cover lidar data can be filtered to extract only the returns assumed to be from the ground surface. The practice of virtual deforestation has become common practice for many slope and terrain applications (Haugerud and Harding, 2001). Despite providing a useful measure of slope, considerable uncertainty remains in the performance of the algorithms under different types of landcover (Sithole and Vosselman, 2004). The errors induced by elevation measurements, vegetation removal and the calculation of slope require careful consideration before the final gradients can be used for further analysis.

A modern highway embankment was selected to investigate the effect of the vegetation considered typical of transport corridors on slope measurements. Constructed in 1997, the earthwork has three distinct sections of vegetative cover ranging from short grass, through isolated saplings and shrubs to mature trees (Figure 6). The effect of vegetation in obscuring ‘ground’ hits and the resultant information loss is evident in the cross sections, which recorded progressively fewer returns from below increasingly dense cover. Previous investigations into the use of lidar to model slopes have suggested that measurement consistency is more important than overall accuracy (Hodgson *et al.*, 2005). Therefore, the impact of the changes in vegetation on the derived slopes was investigated for flightlines 1 and 3; determined to be the best and worst measures of slope respectively within the dataset. Given the assumption that the slope did not change during the data collection, the differences between the surfaces represent the measurement variability and thus the error in slope calculations (Figure 7). The height differences between the surveys appear to be relatively consistent, irrespective of vegetation cover. A base difference of 0.05 - 0.15 m meant that the slope patterns from both flightlines revealed significant similarity, reducing in gradient from 30º in the west to 25º in the east. Isolated areas of change beyond the general separation were associated with particularly dense vegetation, which also increased the incidence of geometric irregularities. The differences in the slope measurements were typically within ±4º over the 150 m stretch of embankment, although patches of greater slope error were associated with localised surface roughness. The high spatial resolution of the lidar was influenced by the hummocky surface in the grass covered area but fewer ground hits from areas with shrubs and trees led to smoother and more consistent surfaces.

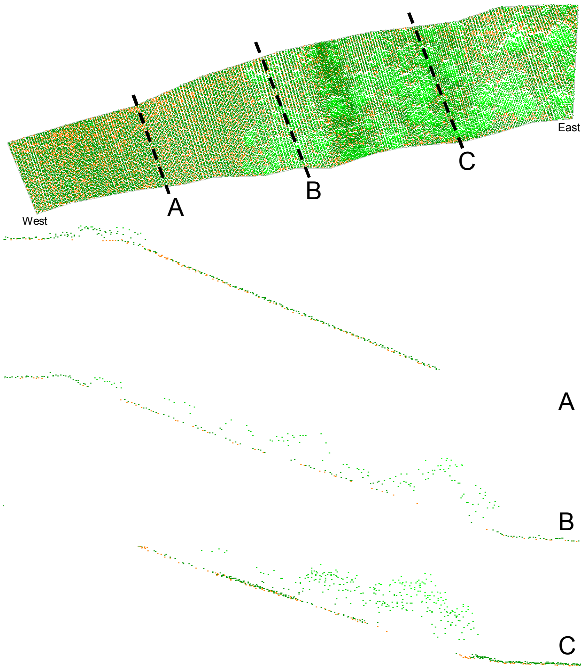


Figure 6. Lidar survey and cross sections of a highway embankment classified by height, colour and intensity into ground (brown), low (dark green), medium (green) and high (light green) vegetation.

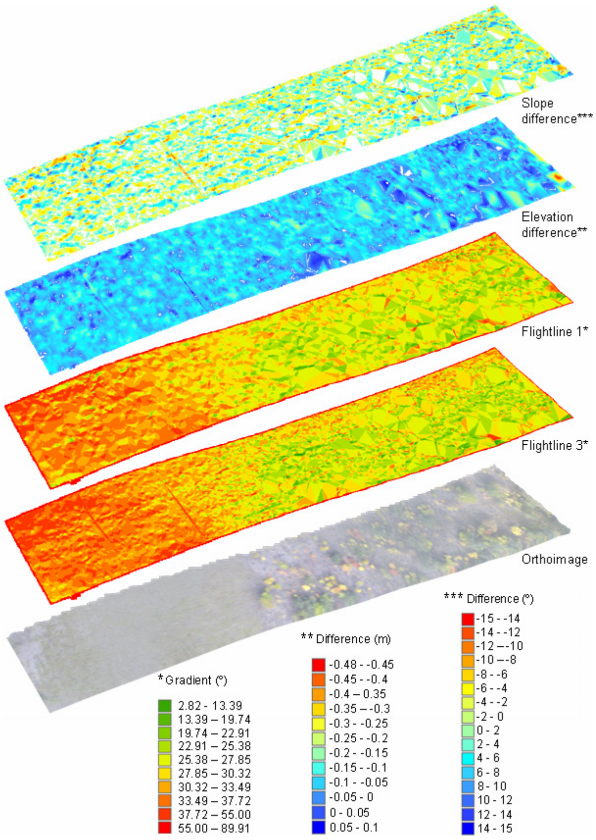


Figure 7. Analysis into the consistency in both elevation and slope models generated from separate lidar flightlines.

5. DISCUSSION

In the UK, a rich variety of remotely sensed data is now often routinely captured for commercial transport corridor applications such as mapping and asset inventory. In many cases there now exists a mismatch between the ability of modern sensors to collect earth observation data of increasingly high resolution and spatial coverage and the limited processing and utilisation practices used to analyse such information. The results of this investigation demonstrate the importance of evaluating the performance of the required derivatives from a dataset, in addition to analysing the quality of the dataset as a whole. For example, error checks performed on elevation measurements are often used to assess the performance of slope models produced by earth imaging technologies. However, the use of checkpoints indicates that despite accuracies that would be considered acceptable for many network mapping applications, the positional accuracy of lidar data may vary significantly according to the specific flightline used. Furthermore, the measurement of specifically designed targets on flat, even surfaces provides a poor indicator of measurement quality on the critical areas of concern: the slopes themselves.

Attempts have been made in this preliminary research to devise more appropriate indicators of the ability to derive the required parameters, in this case topographic gradients, from processed earth imaging datasets. The use of control slopes, measured in the field, demonstrated only a weak correlation between gradient and accuracy. The finding is likely to reflect the proximity of the targets to the ideal, nadir position for monitoring purposes. Therefore, the concerns over slope error within slope models may be minimised for the assessment of narrow transport corridors; although the implications remain important for applications such as floodplain modelling in which the full swath is used. The data have also revealed that the measurements from individual flightlines may be more or less well-suited to slope monitoring. Although Hodgson *et al*. (2005) found that slope measurements were increasingly under-predicted where gradients approached 8º, the varied response of individual flightlines identified in this study suggest caution must be exercised when suggesting generic slope patterns.

Slope gradient was found to have an effect on both the variability of height measurements and the number of returns. Parameter-specific error checks are therefore essential for applications such as transport corridor assessment where small changes in the gradient of artificial slopes may signify a higher propensity to fail. It is often thought preferable to maximise the point density of the collection. However, where sufficient resolution is achieved to capture microtopographic effects the consistency of the slope measurements is also reduced. The trade off between improving model detail and the consequent incorporation of greater levels of complexity and therefore an increasing potential for measurement inconsistency requires careful consideration, set against the objectives of each application. It is evident that the appropriate resolution and aspects of the data to be used should provide a primary focus for any new application of earth imaging.

The availability of high resolution earth imaging data is providing new opportunities to record conditions in a range of environments. This has resulted in increasingly sophisticated use of the data; elevations are no longer just required for surface visualisations but used as key inputs into quantitative analyses. This paper reports preliminary research to account for the challenges of applying high resolution remote sensing to the assessment of transport corridor earthworks. It is essential that the suitability of the data to the required application is assessed before satisfactory conclusions can be drawn. Further work is required on quantifying the effect of slope in areas beyond the nadir position, the nature and consistency of errors specific to the types of landcover found on earthwork slopes and the most appropriate scale at which to monitor the failure processes associated with earthworks.

6. FUTURE RESEARCH

It is evident that the extraction and application of information processed from remotely sensed data, requires specific and tailored assessment, particularly when multiple data sources are used. The research presented will enable slope measurements to be obtained, within established error margins, from earthworks within a transport corridor network. As noted above, slope stability is influenced by many factors such as slope characteristics, vegetation and climate. Each of these factors has a different effect on the likelihood of a slope to fail and can be measured with varying degrees of accuracy. Therefore, the problem of determining slope conditions involves uncertainty in both the ability to record the different parameters involved and the influence of each parameter on weakening or strengthening the slope. The ultimate aim of this work is to perform sophisticated risk analysis on earthwork slope stability through the integration of multiple remote sensing datasets and the extraction of error assessed parameters. Uncertainty in the measurement and effect of each of the parameters such as gradient on slope failure will be accounted for with the use of Bayesian interval probabilities within an evidential reasoning framework. This will enable the spatially and temporally diverse information commonly available on network conditions to be effectively utilised to provide quantified and intelligent asset management.

7. CONCLUSION

In conclusion this research has shown encouraging results for the application of high resolution earth imaging for the assessment of transport corridor slope stability. Whilst slope measurements are relatively accurate for slopes up to 40º in areas close to the nadir position, variability both within and between surveys must be accounted for. Conventional indicators such as a low RMSE measurement of a dataset may not be a satisfactory indicator of its ability to determine processed parameters such as slope. There is often a fundamental difference between the errors associated with each measurement in the dataset and the ability to obtain the required parameters for the application. A change of emphasis is required, away from the conventional assessment of artificial targets in flat, ideal areas to application specific indicators of performance.

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