INTELLIGENT INTEGRATION OF MULTI-SENSOR DATA FOR RISK ASSESSMENT IN TRANSPORT CORRIDOR ENVIRONMENTS

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ABSTRACT:

Roads and railways are founded on earthwork structures such as embankments, which can be susceptible to slope instability and failure, with serious economic and safety implications. Existing approaches to earthwork condition appraisal are labour-intensive and hazardous. While the increasing availability of high resolution geospatial data offers improved opportunities for remote and efficient slope stability assessment, there remains a gap between the availability of such data, and the subsequent extraction of intelligent information. In this research, high resolution lidar data and multispectral aerial imagery are supporting the extraction of the key stability controls of slope gradient, aspect, soil moisture and vegetation type. The influence of these parameters has been established through numerical modelling under existing and future climate scenarios, enabling stability to be quantified and mapped in a spatially continuous manner. The research has been applied to a test site located at Haltwhistle in northern England. Results highlight the challenges associated with establishing a suitable spatial resolution for parameter extraction and risk assessment in a GIS environment, with degradation in resolution from 20 to 0.5 points / m^2 required in order to overcome micro-topographic effects. A topographic wetness index (TWI), derived from the lidar DTM, was used to characterise soil moisture across the test site. Initial concerns over whether the restricted lidar coverage would be sufficient to capture broader-scale flow routing were allayed following investigations using a larger-scale DTM, which was found to produce results which were in good agreement with the lidar-derived TWI.

1. INTRODUCTION

Transport networks such as roads and railways are complex entities, extending over a range of scales and presenting a diversity of management challenges. Profitability, reliability and safety are crucial, and indistinguishable to the optimum operation of these networks (Mercer, 2002). Earthwork structures such as embankments are integral components, supporting road bridges, and maintaining the vertical alignment of rail routes. In England, embankments alone account for around 30 percent of all transport infrastructure, amounting to 5,000 km of rail routes and 3,500 km of trunk road (Perry et al., 2003). However, embankments are subject to the same external processes as natural slopes, generating potential for instability, which in extreme cases may result in slope failure. UK highway embankments are generally constructed to modern specifications and are therefore expected to remain stable under existing environmental conditions. However, in the context of uncertainty over climate change, their long-term sustainability is less certain. Furthermore, increased volumes of heavier and faster traffic are placing additional strains on existing infrastructure. UK railways are at more immediate risk. Much of the network dates from the mid-to-late 19th century, incorporating ageing earthworks constructed from poorly consolidated materials, prior to the introduction of modern engineering practices (Perry et al., 2003). Over recent years, an apparent trend in the increase of extreme rainfall events has increased concerns over the stability of railway earthworks, with numerous incidences of minor landslides and train derailments.

The assessment of risk is therefore a core activity for management bodies, and requires rigorous and continuous condition appraisal. However, this is an expensive and demanding task. Conventional approaches involve labour-intensive site inspections by trained engineers. Although geospatial information, in the form of aerial photography, has been used in the condition appraisal process for some decades, its main role has been as a source of supplementary information, supporting, but not directing, the decision making process. Engineering scale risk assessment demands high resolution input data, and the recent increase in the availability of data from techniques including airborne laser scanning and multispectral digital aerial imagery offers unprecedented opportunities for the direct incorporation of geospatial information in engineering analysis and management. However, the limited commercial exploitation of these techniques reflects the gulf which exists between their capacity to supply high resolution data, and the subsequent intelligent utilisation of this, particularly in relation to information extraction and the creation of value-added products. Bridging this gap represents a critical challenge, not just in the context of slope stability assessment, but more broadly across the geospatial information community, driven in part by the increasing prevalence of these data in the public domain.

The aim of the research presented here is to develop an efficient network-scale approach for remote assessment of risk in transport corridor environments. Crucially, this involves assessing potential for slope failure, rather than detecting existing symptoms of instability – a weakness of current approaches. This is achieved through the integration of a range of remote assessment techniques, including lidar, terrestrial laser scanning, and multispectral aerial imagery. Key slope stability parameters are then extracted from these datasets in

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order to assess their interaction and influence on slope behaviour, with the quantification of risk directed through numerical modelling of slope behaviour. This paper will present the outcomes of the parameter extraction process, examining aspects of spatial resolution, assessing the quality of the derived parameters, and discussing associated aspects. The initial outcomes of the modelling phase will also be presented and discussed.

2. METHODOLOGY

2.1 Test Site and Datasets

The research presented here was implemented at an eight kilometre-long test site located at Haltwhistle in northern England. This site is composed of the A69 trunk road, incorporating the Haltwhistle by-pass and including a number of major highway embankments. The test site also includes the Newcastle-Carlisle railway line which has a history of instability, with numerous minor landslides occurring over recent years. The site is largely confined within the floodplain of the River South Tyne, with some stretches of rail embankment located within fifteen metres of the river. Vegetation conditions within the test site are representative of those found on the UK road and rail network, and across northern England in particular. Grass, small shrubs and trees dominate, but bare earth slopes, and stretches of dense deciduous woodland are also relatively commonplace, particularly on the railway.

High resolution discrete pulse lidar data was acquired for the site on an approximately annual basis, in October 2006, July 2007 and April 2008. The data were collected from a helicopter platform, and provide high spatial resolution coverage, with a nominal point spacing of 20 points / m^2. Small format digital aerial imagery, including both colour and near-infrared photography, was acquired contemporaneously to the lidar data, at a resolution of 5 cm. The main purpose of this was to assist in interpretation of the lidar data. In order to investigate the influence of vegetation on slope stability, multispectral aerial imagery was collected in September 2007 using a compact airborne spectrographic imaging (CASI) sensor, mounted on a fixed wing aircraft. The sensor records data in 32 bands over the visible and near-infrared regions of the spectrum. This provides sufficient detail to enable advanced spectral analysis of the vegetation canopy. CASI imagery was acquired from a flying height of 1100 m, resulting in a pixel resolution of 0.6 m.

The quality of the lidar datasets was assessed by distributing a number of purpose-built targets throughout the study area during data acquisition. To further increase redundancy, a number of photogrammetric targets were also placed in the survey area. The check points, which were surveyed using rapid-static GPS prior to the flights, allowed the absolute positional accuracy of the lidar data to be evaluated. A detailed overview of these error assessment procedures is presented in Lim et al. (2007). The positional accuracy of both the October 2006 and July 2007 datasets was found to be within 10 cm in both plan and elevation. Due to recurring delays on the part of the lidar provider, the accuracy of the April 2008 dataset is yet to be assessed. A number of suitable check point features were surveyed in the test area by rapid-static GPS, in order to assess the positional accuracy of the CASI imagery, which had been georeferenced prior to delivery. This returned an $RMSE_{xy}$ value of 1.10 m. Although this may appear relatively poor given the pixel size of 0.6 m, this value is within the operator's specified tolerance of 1.50 m and was therefore deemed acceptable.

2.2 Extraction of Slope Stability Parameters

Remotely sensed datasets are heavily utilised for morphological analysis of terrain, with geographical information systems (GIS) facilitating straightforward determination of parameters such as slope gradient and aspect from digital terrain models (DTMs). This off-the-shelf functionality has become a fundamental aspect of landslide hazard studies (Dai and Lee, 2001). However, most of this research has focussed on natural landslides, and has largely involved the use of coarse- to medium-resolution satellite remote sensing datasets. Transport corridor slopes share similarities with natural slopes in terms of many of the destabilising processes. However, they are unique in the sense that these processes may act over relatively short and confined spatial extents, but can result in costly and devastating slope failure. This demands rigorous engineering-scale analysis, which is not yet readily achievable through satellite remote sensing. High resolution airborne data however can fulfil this requirement and, moreover, is well-suited to the acquisition of data across extended corridor networks.

In this research, the high resolution airborne lidar and multispectral aerial imagery datasets were employed to assess slope stability. Slope stability is governed by the complex interaction of a range of factors. Slope gradient, slope aspect, soil moisture and vegetation effects exert primary controls on stability (Dai and Lee, 2001; Ridley et al., 2004; van Westen et al., 2008), and can be obtained through analysis of geospatial datasets. In this research, the topographic influences of slope gradient and aspect were assessed through analysis of the lidar DTMs. This involved post-processing of the lidar point cloud in order to refine and optimise the data prior to DTM production. Following quality assessment, *Terrasolid's TerraScan* software was used to perform a ground classification. Although this was effective in removing non-ground points, in regions of particularly dense vegetation, large gaps were evident in the point cloud, leaving very few ground points from which to form the DTM. The filtered ground points were then further refined in order to preserve structures such as bridges and tunnels, and prevent the introduction of artefacts. This was a tedious process involving significant manual effort. Following this, the ground points for the corridor test site were imported to *ESRI's ArcGIS* software, where TIN and grid DTMs were generated for comparison. Slope gradient and aspect grids were then generated and assessed, as detailed in Section 3.1.

The second phase involved the assessment of soil moisture influences. Soil moisture exerts a particularly strong influence on slope stability, but is acknowledged as one of the most difficult components to quantify (Gritzner et al., 2001). However, the topographic wetness index (TWI) has been widely applied for characterising the spatial variability of hydrological influences, and can be derived directly through DTM analysis. The TWI can be defined as $\ln(a/\tan\beta)$ where a is the local upslope contributing area draining through a specific point, and β is the local slope (Sørensen et al., 2006). In order to develop an operational risk assessment approach, the TWI was used here for characterisation of soil moisture. The TWI was generated directly from the lidar DTM, using the Tarboton method for calculating TWI (Tarboton, 1997). This enables downslope routing in an infinite number of directions, rather than being restricted to the eight cardinal diagonals.

The CASI imagery was used to derive four land cover classifications for use in assessing vegetation influences. A supervised classification was performed to identify regions of bare earth; grass and shrubs; deciduous trees; and manmade ground. These classes encompassed the main vegetation (and non-vegetation) types found in the test site, whilst also corresponding directly to the numerical modelling scenarios, as detailed in the following section.

2.3 Quantitative Risk Assessment

The parameter information extracted from the geospatial datasets is of little value unless applied with some knowledge of slope behaviour and failure process. In this research this was achieved through finite element numerical modelling. This applies a coupled model which is able to account for both physical and hydrological aspects of embankment behaviour, mapping the finite grid elements output from the *SHETRAN* (hydrological) model as inputs to the *FLAC TP* (geotechnical) modelling grid. The software is configured to simulate slope behaviour under a range of scenarios, with outputs at daily intervals over an extended time series. The Newcastle-Carlisle railway line was used as a basis for the modelling. As discussed in Section 1, slope instability is a particular problem on this route.

Following analysis of the Haltwhistle test site, representative embankment dimensions were determined and a five slope gradients, ranging between upper and lower extremes, were also specified. Several site visits and vegetation surveys enabled identification of typical vegetation species along the rail corridor. These were then aggregated into three main classes: bare earth; grasses and small shrubs / trees; and semi-mature and mature deciduous trees. These were input to the modelling, where suitable leaf-area index (LAI) and other relevant parameters were selected. A recent geotechnical monitoring report (Owen Williams Railways, 2005) for a vulnerable section of track within the study area provided a valuable source of information on the soil and geological properties of this part of the site, and allowed these aspects to be parameterised with a high degree of confidence in the modelling. Meteorological influences, including rainfall and potential evaporation, were established using the RainSim software (Burton et al., 2008) and the EARWIG weather generator (Kilsby et al., 2007). These software packages, developed at Newcastle University, enable the generation of weather variables at daily time intervals across the UK on the basis of 5 km grid cells, under both existing and predicted future climate regimes. This allowed simulation of embankment behaviour under current and future climates (a 2080 scenario was used here), enabling assessment of longer-term sustainability. Table 1 details the modelling scenarios simulated in the research, which produced a total of 30 distinct combinations (5 x 3 x 2).

Risk is assessed through factor of safety (FoS), which is a direct output of the modelling software. As the FoS approaches a value of unity, the slope becomes increasingly unstable, and is deemed to have failed when the FoS equals one. FoS is a widely used and well understood measure of stability in engineering, and is therefore particularly relevant in this research, where the ultimate goal is to provide an operational risk assessment strategy. With FoS outputs corresponding to defined input scenarios, multi-variate regression analysis can then be carried out to determine the influence of individual parameters. This will allow the assignment of individual parameter weightings, enabling GIS-based analysis of the parameters which have been extracted from the geospatial datasets, and allowing risk to be directly mapped in a spatially continuous manner across the transport corridor.

Parameter	Value
Slope gradient	very shallow (11°)
	shallow (22°)
	standard (30°)
	steep (36°)
	very steep (49°)
Vegetation Type	bare earth
	grass and shrubs
	deciduous trees
Climate	current
	future (2080)

Table 1. Numerical modelling scenarios

3. RESULTS

3.1 Assessment of Extracted Parameters

Slope and Aspect: The first challenge involved selecting a suitable spatial resolution at which to carry out GIS-based risk analysis. In this respect, it was necessary to strike a balance between preserving the high resolution of the input data, and ensuring that the dominant morphological trends were adequately captured. A series of tests were carried out to evaluate the optimum grid resolution, with 1 m, 0.5 m and 0.25 m slope grids created from the input DTM points in *ArcGIS*. In the case of the 0.25 m grid, the overall slope trends of the embankments (typically 25-30 m in width) were obscured by the effects of fine-scale micro-topography, while with the 1 m grid, the edges and crests of the embankments became less well defined. In contrast, at a resolution of 0.5 m, the dominant slope gradients could be characterised, while retaining some variation across the slope, thus supporting engineering-scale risk assessment. This resolution (0.5 m) also conforms to that of the finite element grid used in the numerical modelling, therefore enhancing the transferability of the modelling results. A 0.5 m grid resolution was therefore utilised for both the slope gradient and aspect parameter extraction.

The next stage involved assessing the quality of the classified slope and aspect information. Due to a lack of contemporaneous field data, it was not possible to evaluate this directly. Instead, the 0.5 m raster values were compared to those of the TIN model derived from the full resolution input point data, which represented a more accurate surface. The raster and TIN datasets were generated independently, directly from the lidar points. The slope datasets were classified into 5° bands, ranging from 0° to 50° (i.e. ten classes in total), the latter being the absolute upper extreme of slope gradients occurring within the test site embankments. Ten random locations per class (fifty in total) were sampled in both the raster and TIN datasets. The exact values (as opposed to the classes that they fell within) of both slope gradient and aspect were recorded, and the difference between the raster and TIN values was computed. The results are shown in Figure 1, with both gradient and aspect assessed in relation to the slope gradient classes. Slopes between 20° and 30° appear to be associated with the lowest differences, with a mean absolute discrepancy of 0.7°. This compares to a mean difference of 3.6° for the range 40° to 50°. It is not surprising that the greatest differences are associated with slopes above 40°. These slopes are more likely to correspond to weak areas in the triangulation – for example near-vertical features around the edge of bridges or tunnels. Due to the discontinuous nature of the slopes around such areas, it is likely that the TIN and raster generation procedures may have arrived at results which are slightly less consistent than in more gently sloping areas.

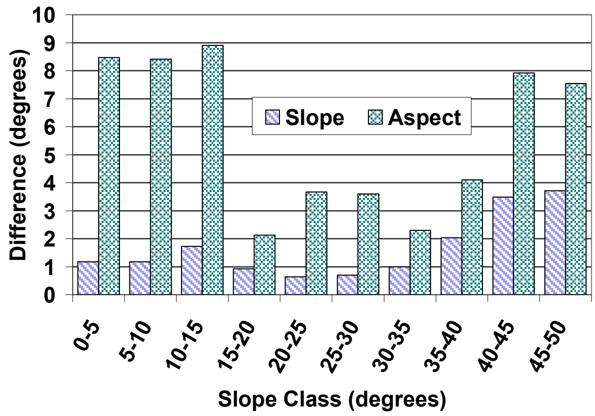

Figure 1. Discrepancies between TIN- and grid-based categorisation of slope (gradient) and aspect, with respect to slope class.

Figure 1 also highlights the relationship between slope aspect and gradient. This reveals that the closest agreement between raster and TIN-based extraction of aspect is again in medium slopes, in this case between 15° and 40°. The extreme upper and lower slope gradients exhibit the greatest discrepancies. This is particularly marked at the lower end of the spectrum, with mean aspect discrepancies of between 8° and 9° for slope gradients under 15°. This may be due to the fact that raster elevation measurements (upon which aspect is based) have been interpolated, and therefore will contain some degree of error. Any interpolation errors are likely to have a greater influence on aspect at low slope angles than they will have for steeper slopes.

Topographic Wetness Index: The next parameter considered was the TWI. Determination of optimal spatial resolution was more challenging, as the TWI has been found to be particularly sensitive to fine-scale topographic variations, resulting in local artefacts. Furthermore, lidar coverage of the test site extended only 100 m either side of the road and rail corridors. The test site is located within the floodplain of the River South Tyne, and there is considerable run-off from upland agricultural terrain which rises to both the north and south. The influence of this broader scale topography may therefore be important in contributing to localised saturation within the test site, and it was hypothesised that the lidar data may provide insufficient coverage to fully account for upslope drainage effects. In order to investigate this, a TWI was created for the test site and around 750 m of surrounding terrain either side of the corridor. Ordnance Survey's MasterMap Land-Form PROFILE 10 m DTM product was utilised for this, representing the highest resolution DTM available with suitable coverage. A 2.5 m TWI was then generated from the lidar data points. Figure 2 presents a basic visual comparison between the resultant TWIs. Saturation effects associated with the road and rail earthwork topography are largely unrepresented in the relatively coarse 10 m TWI, although major drainage features, including the tributaries feeding the River South Tyne, are evident, appearing as white linear features (Figure 2). In the 2.5 m TWI, the road and rail earthwork structures present strong signatures, indicating their localised influence on runoff. Crucially however, the predictions of moisture distribution which are evident in the broader-scale 10 m TWI are retained in the 2.5 m TWI, including at the extreme edges of the data. This indicates that the lidar data therefore provides suitable coverage for adequate determination of the TWI. Investigations are continuing in order to determine whether the 2.5 m TWI provides optimum resolution, or whether a higher resolution dataset would offer improved assessment of terrain-related moisture effects.

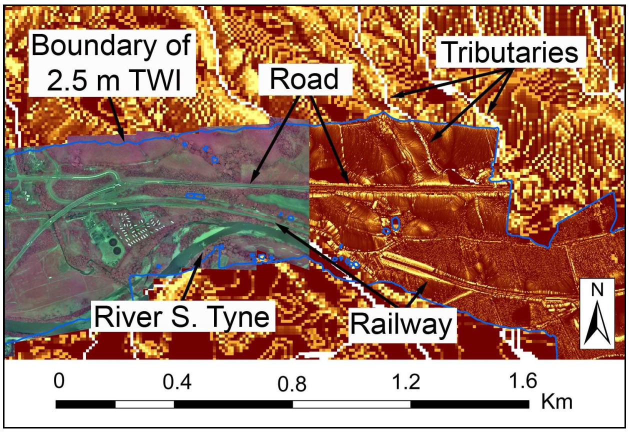

Figure 2. Comparison between broad-scale 10 m TWI and restricted 2.5 m TWI for central portion of test site.

Vegetation Classification: The CASI multispectral imagery was employed for extraction of vegetation parameters. The 0.6 m pixel size of this dataset conforms closely to the 0.5 m grid resolution of the slope and aspect datasets. A relatively straightforward approach was adopted by implementing a maximum likelihood supervised classification in *Leica's ERDAS IMAGINE* software. This was based on a total of 295 training sites, and allowed land cover within the transport corridor to be classified into one of four categories: bare ground; grass and shrubs; deciduous trees; and man-made surfaces. A fuzzy convolution filter was then applied to the results in order to remove speckle effects within the classification. Following this, an error assessment was carried out using 300 random samples, where the true ground class was defined through a combination of field knowledge and interpretation of the high resolution (5 cm) aerial imagery. This returned an overall accuracy of 88%. While this would indicate that this approach has been relatively successful, closer inspection of the classification results revealed a few minor issues. Firstly bare ground areas were sometimes mis-classified as vegetation, especially where these were adjacent to clusters of vegetation, or where vegetation was partially overhanging. However, such areas are likely to be influenced by the root systems of the adjacent vegetation, and therefore are likely to be more stable than isolated regions of bare ground. Secondly, the ballast material (angular stones) which forms the rail track-bed and which often spills over onto the upper slopes of the embankments, falls into the man-made surface class. Although this is to be expected, this does introduce complications in terms of how such regions should be treated in the risk assessment. However, it is probable that these areas can in fact be considered as being at relatively low risk, as the ballast is designed to provide stability and added drainage.

3.2 Numerical Modelling Results

Finite element modelling of embankment behaviour was carried out using the coupled *SHETRAN-FLAC* software, in accordance with the input scenarios detailed in Table 1. The results revealed that for the modelled railway embankment, all failures were of a deep-seated nature, as illustrated in Figure 3 (standard slope case under bare ground conditions). The most important factor influencing slope stability was found to be slope gradient. In contrast, vegetation was found to have a relatively minor effect with only a slight improvement in FoS moving from bare earth through grasses and small shrubs to semi-mature and mature deciduous trees. The influence of climate on embankment stability appears to be more complex, with the results indicating that while future climate conditions may lead to greater stability for shallow slopes, there is little difference between current and future climate for steep and very steep slopes. Further simulations are being carried out to investigate the spatial variability of the results along the Newcastle-Carlisle rail route, with modelling carried out on the basis of current and future climate scenarios corresponding to Newcastle in the extreme east and Carlisle in the extreme west of the network.

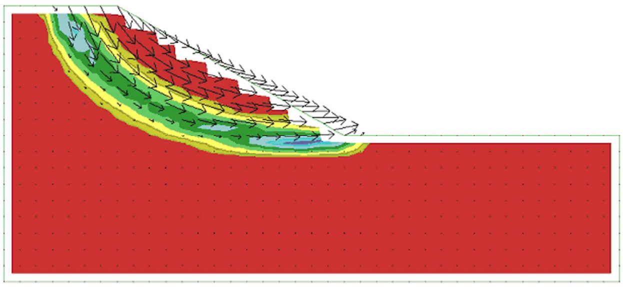

Figure 3. Deep-seated failure simulation in standard slope under bare earth conditions. Arrows indicate the velocity field (maximum = 2.77e-5 m/s).

4. DISCUSSION

The results highlight a number of aspects relating to the extraction of slope stability parameters from the geospatial datasets. Firstly, although the original lidar data was acquired at a nominal 20 points / m^2, the presence of gaps due to dense vegetation, and the practicalities associated with performing efficient GIS analysis over large extents, led to the data being degraded and interpolated to a 0.5 m regular grid. This then formed the basis for DTM-based slope and aspect analysis. Furthermore, this reduction in resolution was also found to be necessary in order to ensure that the dominant slope signatures could be extracted, rather than the effects of micro-topography, a consideration also noted by van Westen et al. (2008). This raises questions over the optimal resolution of data which should be employed for engineering-scale risk analysis in this type of environment. While there are advantages to acquiring data at 20 points / m^2 and higher, a resolution of 10 points / m^2 may be sufficient and more cost-effective. As mentioned above, there were particular problems with building reliable DTMs in areas of dense vegetation. However, developments in waveform digitising lidar and associated processing algorithms offer significant potential for improved DTM generation in vegetated terrain (e.g. Lin and Mills, in review). This technology is likely to become increasingly relevant for this type of analysis over the coming years.

The integration of datasets from multiple sources presents particular challenges in relation to the treatment of positional inaccuracies, differences in spatial resolution and the effects of multi-temporal discrepancies. The quantification and propagation of error is particularly important and is being handled here through rigorous assessment of the source datasets and the derived parameters. This work is continuing and further assessment will be carried out in order to directly quantify soil moisture through localised field sampling and relate this to the TWI distribution. Further assessment of slope, aspect and vegetation type will also be carried out.

This paper reports on research to-date. Remaining work will focus on establishing the linkages between the modelling results and the extracted slope stability parameters, and in delivering quantitative risk information across the corridor test site. The results of the risk assessment will be evaluated by differencing the three lidar DTMs (October 2006, July 2007 and April 2008) and examining slope changes. Although no major cases of slope failure are known to have occurred over this period, at least one landslip-in-progress in known to exist. Changes will then be compared to the results of the risk assessment to examine whether such areas have been flagged as being at high risk of failure. In addition, Network Rail, the railway operating body, have made available their database of risk gradings for the Newcastle-Carlisle line, and this will allow the results of this research to be directly compared to the existing, known status generated through conventional inspection approaches.

A separate facet of this research is the characterisation of soil moisture through novel analysis of vegetative indicators, using the CASI data introduced in Section 2.1. It is anticipated that in time this may provide an improved means of assessing soil moisture, which can be incorporated directly into the operational risk assessment strategy. In addition, factors such as geology and past failure history are also important in assessing the potential for failure. Future work will investigate the feasibility of incorporating these parameters through GIS-based analysis of digital geology datasets and the inclusion of earthwork inspection databases, such as that referred to above. This will require the assimilation of additional expert knowledge in order to account for the linkages between these parameters (particularly geology) and failure likelihood.

Future research will also examine the transferability of this approach to other sections of road and rail networks in different environments across the UK. A number of issues are likely to arise in relation to this. Firstly, the risk assessment strategy developed here hinges on the accuracy of the modelled predictions, which drive the spatial risk mapping. Numerical modelling is heavily dependant on the quality and accuracy of the input parameters, and factors such as soil composition and permeability are highly variable in a spatial context. Therefore, in order to develop a strategy which is robust for network-scale implementation across the UK, it may be necessary to carry out further representative modelling for a range of typical geology/soil scenarios. In addition similar research will be required in order to adequately assess slope stability in road networks. However, the research reported here presents the blueprint for achieving an operational remote risk assessment strategy.

5. CONCLUSION

This paper has presented a remote, integrated approach to assessing the risk of slope instability in road and rail corridor environments. This is based on the extraction of key slope stability parameters from lidar DTMs and multispectral aerial imagery, with quantitative risk assessment driven through numerical modelling of slope behaviour. The research has highlighted the difficulties associated with producing reliable DTMs from lidar data in areas of densely vegetated terrain, with difficulties arising despite a spatial resolution in excess of 20 points / m^2. Furthermore, in order to overcome the influences of micro-topography and extract the dominant slope gradient and aspect trends, the lidar DTM was further degraded to a resolution of 0.5 m. This raises questions over the optimum spatial resolution for this type of engineering-scale analysis, reinforcing the principle of data being 'fit-for-purpose' and cost-effective. This is particularly important in this research where the developed strategy must be suitable for operational network-scale risk assessment. This research demonstrates how multiple geospatial datasets can be exploited to extract complementary information and how this information can be utilised in an intelligent manner to address a major challenge in civil engineering infrastructure management. This reinforces the value of multi-sensor data. Further benefits could have been derived had the data been acquired from a single multi-sensor platform which would eliminate temporal (and other) disparities between datasets and offer the benefit of tightly coupled sensor configurations.

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