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The use of remote sensing techniques for monitoring and characterization of slope instability

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Abstract

Understanding changes in slope geometry and knowledge of underlying engineering properties of the rock mass are essential for the safe design of man-made slopes and to reduce the significant risks associated with slope failure. Recent advances in the geomatics industry have provided the capability to obtain accurate, fully geo-referenced three-dimensional datasets that can be subsequently interrogated to provide engineering-based solutions for monitoring of deformation processes, rock mass characterization and additional insight into any underlying failure mechanisms. Importantly, data can also be used to spatially locate and map geological features and provide displacement or deformation rate information relating to movement of critical sections or regions of a slope.

This paper explores the benefits that can be obtained by incorporating different remote sensing techniques and conventional measurement devices to provide a comprehensive database required for development of an effective slope monitoring and risk management program. The integration of different techniques, such as high accuracy discrete point measurement at critical locations, which can be used to complement larger scale less dense three-dimensional survey will be explored. Case studies using a combination of aerial and terrestrial laser scanning, unmanned aerial vehicle and hand-held scanning devices will demonstrate their ability to provide spatial data for informing decision making processes and ensuring compliance with Regulations.

Keywords: Slope monitoring; UAV; laser scanning; slope instability

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1. Introduction

In recent years, there has been considerable advancements in the geospatial industry, with focus placed on capturing the real world in an unprecedented amount of detail. This increased focus on capturing large datasets has exposed engineers in the mining and minerals industry to data that would have been previously unimaginable. Different remote sensing technologies are now available, each having specific benefits for engineering geology-based applications: such as rock mass characterization, spatial analyses and monitoring of deformation processes. Nevertheless, despite the potential advantages of each remote sensing technique, there are associated limitations that should be considered depending on the nature of the problem one is dealing with. This could lead to the necessity to integrate different techniques to obtain complete and detailed data to be used for different purposes.

This paper explores the benefits of integrating the most commonly available remote sensing techniques for performing engineering-geological studies, with specific focus on application for the mining industry.

1.1. Light Detection and Ranging (LiDAR)

LiDAR technique, which originated in the 1960s, can be used to obtain detailed and complete geometrical information rapidly and accurately by generating spatially accurate geo-referenced 3D point clouds. Modern laser

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scanners measure distance using an Electronic Distance Measurement unit and electronically capture angular measurement to compute a position, much like the technology used in total stations, but considerably faster (new instruments can record more than 1,000,000 points/s [1]) and with improved accuracy (usually about 5-10 mm [2,3]). An important characteristic of some laser scanner models is also the ability to discern the vegetation from the surface of interest using the *first arrival* and *last arrival* technique.

Different types of LiDAR survey are possible. When the instrument is a land-based scanner it is commonly called Terrestrial LiDAR (TL). In addition to TL, technological advancements have provided the option of utilising an instrument on a moving platform by using Inertial Measurement Units (IMU). This includes both Airborne (AL) and Mobile (ML) LiDAR systems. AL surveys are undertaken parallel to the ground, commonly at an altitude between 1000 m and 3000 m (lower altitude is possible when using helicopters or Unmanned Aerial Vehicle). The instrument then produces a grid file of elevations spaced at a set interval from a starting coordinate, where the resultant dataset is a 3D survey of the environment. ML, instead, commonly refers to mobile systems deployed on a ground vehicle. This is an evolving technique that has recently seen major development. An example is the ZEB REVO [4], that is a hand-held ML system that works independently of GPS and is designed to be carried by an operator who is free to capture data simply by walking around underground mines or open pits [4]. Instruments like this are characterized by good acquisition speed (more than 40,000 points per second), short range (30 meters underground, 15 meters outside), but tend to have lower accuracy compared with traditional systems. However, due to its simplicity and rapidity of use, this system offers unique application for the mining industry.

1.2. Structure from Motion

The photogrammetric process, which leads to the realization of a 3D model starting from 2D images, allows acquisition of 3D coordinates of every point located in the overlapping zone of two photos of the same area taken from two different points of view. Measurement accuracy of the techniques is governed by a wide range of different factors including accuracy of Ground Control Points (GCP), calibration of the camera, and the focal length of the lens [5]. Although the error within the surveys can vary greatly, it is noted that with calibrated Digital Single Lens Reflex (DSLR) cameras a precision of 1:10000 to 1:20000 is largely achievable (5-10mm at 100 m using a 35mm lens) [5]. Technological developments are still rapidly improving in respect of the detail, efficiency and accuracy of photogrammetric processes. In recent years, for example, a low-cost photogrammetric method has been increasingly used to solve engineering-geological problems. This method, called Structure from Motion (SfM), uses the same basic principle of stereoscopic photogrammetry. However, it differs in that SfM doesn’t require the 3D location and position of the camera(s), or the 3D location of a series of control points to be known a priori for obtaining a 3D model in a relative coordinate system [6]. In SfM, the camera position and orientation is solved using a highly redundant, iterative bundle adjustment procedure, using a set of multiple overlapping photographs to identify common points to be used for image correspondence [7]. This method has simplified the photogrammetric surveys and has allowed Aerial Photogrammetry (AP) to be successfully undertaken from UAV systems. In recent years, there have been considerable developments within UAV technology and resulting wide range of applications in which it has been applied. In many cases, the UAV has been used as a photogrammetric measurement platform to provide spatial data of an environment, for both small scale and large scale applications [8].

2. Data integration

As previously indicated, the quantity and quality of geometric data achievable by using remote sensing techniques is undoubtedly great, but it is important to be aware of the possible disadvantages and limitations of each technique and take these into account before approaching/planning any survey. AL data, for example, is taken from above and usually at a point spacing of 0.5-1 m in mining applications. This allows wide aerial coverage of an area and can be used for obtaining important topographic information of a large site, such as an open pit. However, detailed information about the rock mass (e.g. data about single discontinuities) is lacking, due to the spacing and orientation of the data capture. In addition, if there are areas of overhanging rock mass the information beneath could be left unrecorded, because the scanner requires direct reflectance of the laser from the surface of interest. On the contrary, TL can produce a comprehensive dense point cloud of a slope, where the spacing between the individual points can often be less than a millimetre apart. However, one of the limitations of using TL is that due to its ground-based application problems can arise due to longer working times and "blinding", where areas of the point cloud can become occluded by objects in front of the recorded slope. The problem of blinding is also particularly prominent with rock traps, when the toe of the slope can sometimes be left unrecorded when the rock trap occludes the toe of the slope.

Photogrammetry can be much cheaper than LiDAR technology and can be used to cover large areas in short working times. As with LiDAR, the measurement methodology is line-of-sight and therefore Terrestrial Photogrammetry (TP) can suffer from occlusion from objects in the foreground, such as rock traps. However, this can be largely overcome by obtaining images from different setup locations, achievable by using larger lenses when further away. However, areas of vegetation can cause problems where any information underneath or behind can be left unrecorded causing problems in certain applications (particularly in legacy pits or slopes). In addition, there may also be safety implications with set-up locations adjacent to haul roads or near the crest of slopes. UAV-based AP can overcome these set-up problems, but the inability to filter vegetation without leaving holes or gaps in the data/model may still occur.

Another disadvantage of photogrammetry is that it is a passive system, therefore good illumination, weather and site conditions are needed during the survey. For example, the presence of shadows caused by irregular geometry of a rock face or direct sunlight may cause problems. Shadows can result in the area being unrecorded, which can be a significant problem in high, steep faces and when photogrammetry is undertaken from ground-level from a fixed position or poor set-up locations [9]. The combined use of different techniques can overcome such problems, and sometimes is the only way to obtain useful and complete information required for specific engineering-geological studies.

3. Case studies

This section illustrates different case studies, taken from research projects within the south-west of England, where different remote mapping techniques have been integrated for different analyses in a mining context; such as, compliance of rock trap geometry with Regulations, monitoring of slope regression and material deposition, and spatial analyses for identification of critical areas of potential slope instability.

3.1. Monitoring of rock trap geometry

Example use of integration of data from TL and hand-held ML (ZEB1 [4]) is shown in Fig. 1. Fig. 1(a) shows an example point cloud of a section of slope obtained from 5 different TL scans set-up locations. The different scans were locally aligned using the ICP algorithm on 22 separate constraints with a mean absolute error of 1 mm. The local registration was then referenced to OSGB36 grid using fixed targets that were surveyed using Differential Global Navigation Satellite System (DGNSS). In view of the complex slope geometry blinding has occurred resulting in gaps or holes within the point cloud. A cross-section taken through the slope, shown in Fig. 1(a1), highlights the lack of detail necessary for delineation of the rock traps at the toe of the bench. In order to overcome this problem, a hand-held ML (ZEB REVO) was used to provide additional data. The principal disadvantage of this instrument is the short acquisition range (15 meters outside), but in this case it was used to provide fast acquisition of missing data by walking around the edge of the rock trap. The ZEB REVO system includes an inbuilt IMU into the laser scanning unit. However, when the data is processed via the online server the data supplied includes the registered point cloud models and the trajectory of the IMU. The trajectory of the IMU is colour coded to indicate the accuracy of the registration undertaken (blue good – red bad). In this survey the IMU data indicated that a registration has been achieved with negligible errors. Once constrained the ML data was registered to the TL using cloud to cloud alignment techniques and the ICP algorithm, obtaining an alignment error lower than 10mm. The result of the integration of the two point clouds is illustrated in Fig. 1(b) and 1(b1). The cross-section shown in Fig. 1(b1) clearly shows how TL and ML data can be integrated and successfully used for auditing rock trap designs (for compliance with Regulations) and rock face slope angle of benches, given the necessary resolution and detail of the final point cloud. The hand-held ML was able to in-fill the missing data and provided additional data for the mine operator.

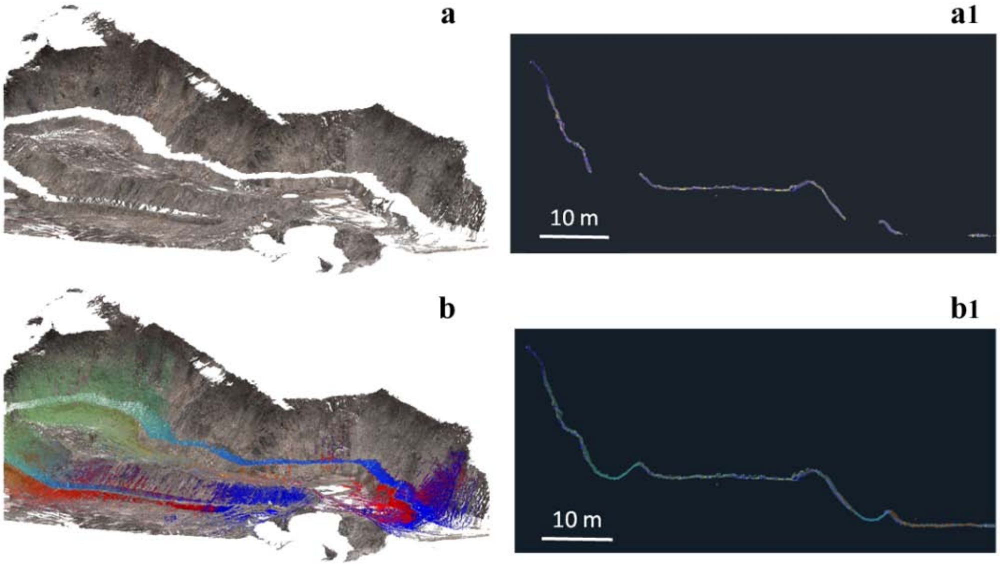

Fig. 1. (a) Example point cloud data generated from 5 TL set-up locations of a part of a slope; (a1) Cross-section taken through point cloud shown in (a); (b) In-fill of point cloud data using hand-held ZEB1; (b1) Cross-section taken through point cloud shown in (b).

Combining data from different technologies can also be used to overcome data limitations. For example, a LiDAR survey could be used to in-fill the missing data from a UAV survey due to the presence of vegetation. Detailed initial planning would need to be undertaken to focus and optimize combined use of TL/AL surveys, but the benefits would offset the overall survey costs. Likewise, the complementary use of TL or UAV technologies can be used for integrating data from AL in areas where higher resolution is required for subsequent analysis. This requires an awareness of necessary data resolution for problem-solving at different scales and for optimization of use of the different remote sensing techniques/technologies.

3.2. *Monitoring of slope regression and material deposition in an open pit*

Acquisition of large amounts of geometrical information in a short time is undoubtedly a major advantage of the use of remote sensing techniques in dynamic working environments. As previously stated, AL has the ability to filter out vegetation, therefore producing an accurate representation of ground topography. Example use of multi-temporal analysis for calculation of differences in volume between different AL flight campaigns (2011 and 2015) is shown in Fig. 2 for a section of an open pit. Active regions of instability (loss of volume) and deposition (increase in volume) can be readily depicted in three dimensions, shown in Fig 2(a) using the open source software CloudCompare [10], and changes in cross-section, shown in Fig. 2(b), highlight the change in slope profile.

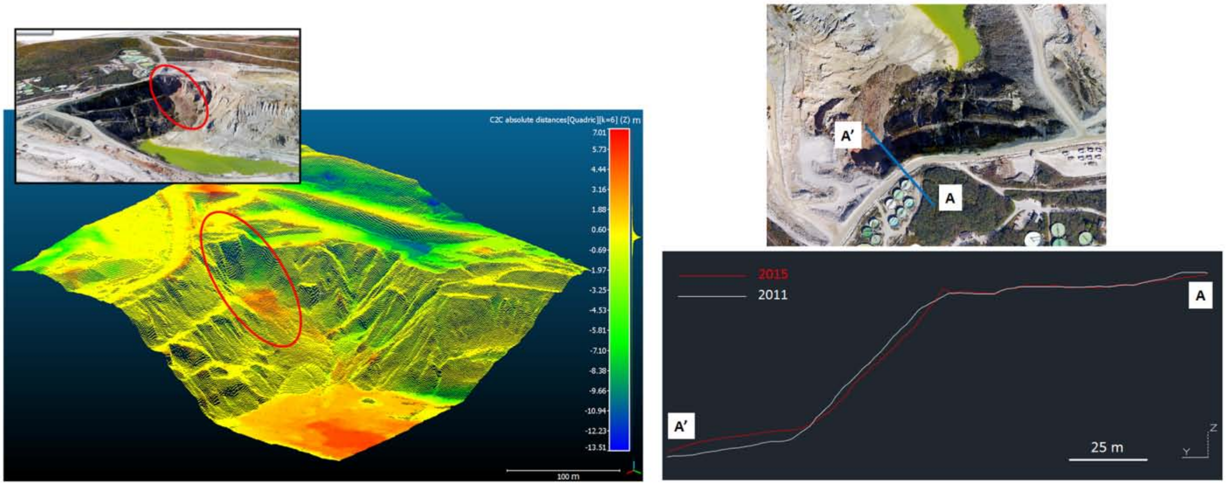

Fig. 2. (a) CloudCompare analysis. Figure shows cloud-to-cloud distance values in metres between two different DTM (2011-2015); (b) 2D cross sections on the red circled area of (a). White line refers to the 2011 DTM, red line refers to the 2015 DTM.;

For this kind of regional or relatively large scale comparative analysis the AL data has a sufficient level of resolution for obtaining good results. However, there are specific applications, where more detail (increased point cloud density) is necessary. An example of this is shown in the next case study.

3.3. *Spatial analyses in an open pit*

Spatial data concerning the geometry of the slope, using AL and hand-held ML data, can also be combined with geological data in order to identify areas of possible instability at different working scales. The next example combines slope geometry attributes with spatial distribution of alteration grade within an open pit. For design purposes an initial analysis was required to highlight slope benches with high alteration and with slope angles greater than 45 degrees. The slope angle analysis was undertaken in a Geographic Information System (GIS) environment. Fig. 3(a) shows the result of such an analysis using a high resolution Digital Terrain Model (DTM) obtained from 2015 AL and integrated with ML information in order to have sufficient resolution at a single bench scale. Red pixels, shown on Fig. 3(a) identify areas where the slope angle is greater than 45 degrees.

The final step was to combine the geological map, which indicates the spatial location of high grade alteration material, with the slope angle map. Fig. 3(b) identifies areas or slopes characterized by both high grade alteration material and a slope face angle greater than 45 degrees. This information was then used for more detailed limit equilibrium analyses. Further analysis was also undertaken for slope regions associated with low alteration grade material, as slope instability is more likely to be discontinuity controlled in these areas. An initial kinematic stability analysis for planar sliding, wedge sliding, flexural, and direct toppling was performed and the limit safety angle calculated for possible slope direction, in relation to the 4 discontinuity sets identified within the quarry (J1 81/082;

J2 83/321; J3 15/261; J4 83/003) from previous TL point cloud analysis and interrogation.

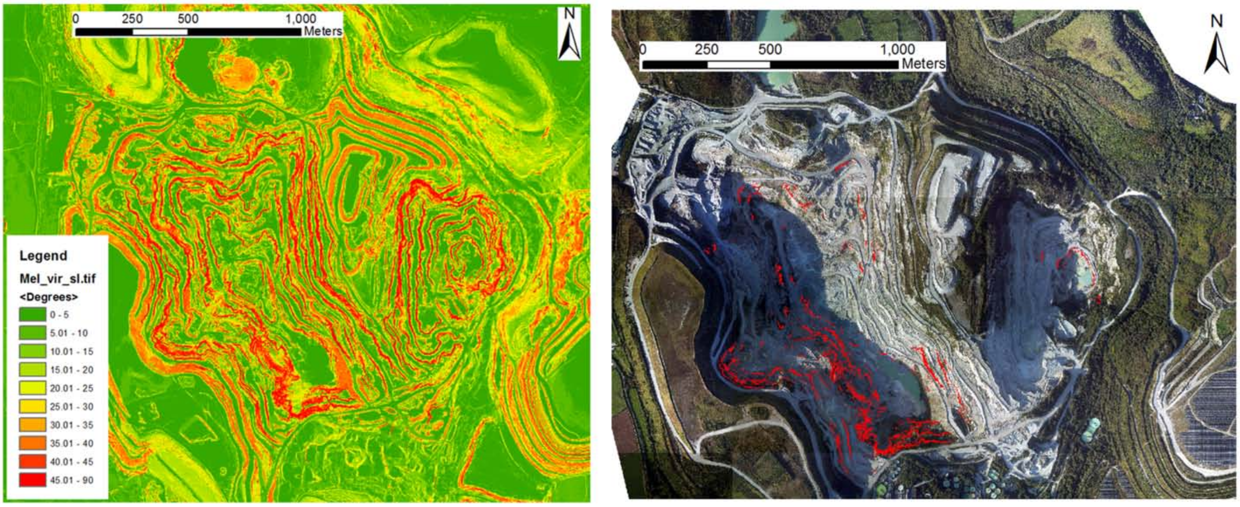

Fig. 3: (a) Slope angle analysis in an open pit; (b) Identification of areas characterized by both high grade alteration material and a slope face angle higher than 45 (red pixels).

A GIS-based spatial analysis was then performed. The first step was to calculate the slope and the direction of every cell using the “Slope” and "Aspect" GIS functions. This information was then combined with the geological mapping data. These attributes (alteration grade, aspect, slope, limit angle) were then combined in the GIS environment. Fig. 4 shows where the alteration grade material, slope angle and direction of the rock face and system of discontinuities are all present, which combine to promote the potential for discontinuity-controlled instability in the form of toppling to most likely occur

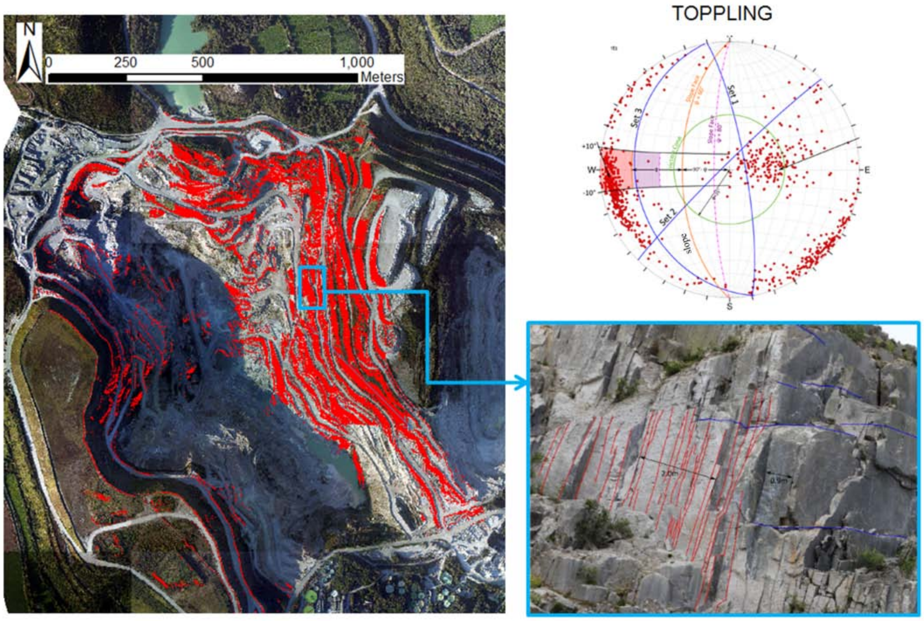

Fig. 4: Results of spatial analysis for identification of possible instability due to toppling.

As indicated by Brideau et al. [11], the results of the kinematic analysis are strongly influenced by the topography of the study area. The combination of data from AL with additional hand-held ML data provided the necessary detail required for the subsequent analysis and interpretation.

4. Results and discussion

The results presented in Fig. 2 clearly highlight areas where material has been excavated or removed (yellow/green points) and deposited (orange/red points) during the time difference between the AL flight campaigns. The data could also be used to measure the accumulation of material at the bottom of the open pit (important for planning purposes related to removal of the volume of material). The area highlighted with a red ellipse in Fig. 2(a) shows how CloudCompare analysis can be used to visualize the extent of erosion (loss of material) on the upper part of the slope and deposition of material in the lower part of the slope. This can also be highlighted in a CAD environment by comparison of 2D sections lines from periodic surveys of the area (Fig. 2(b)). Observing the two cross sections depicted in Fig. 2(b), the amount of erosion and deposition that occurred over the 4 year period can be defined. In this case, minor sloughing of the slope face occurred and the cross-sections were subsequently used to undertake detailed limit equilibrium analysis to assess long-term instability of the slope taking into consideration temporal/seasonal changes in ground water levels.

The results shown in Fig. 3 suggest that sections of the pit surface have a combination of "slope angle/high alteration grade material" that could potentially lead to instability through rotational failure, depending on groundwater conditions. This information highlighted regions that require further investigation to ensure their long-term stability. Fig. 4 presented the results of the analysis performed using the same remote data, complemented by additional data at a bench-scale resolution, for identifying possible discontinuity-controlled instability. The analysis highlighted that planar and wedge sliding was unlikely to occur in the pit, while there are some parts of the pit that are influenced by potential flexural and direct toppling. Fig. 4 summarizes the result of the toppling GIS analysis, where red pixels represent areas where failure may occur in the low alteration grade material and where the slope angle exceeds the calculated limit angle for a given slope direction. The results strongly agree with field observations, highlighting the benefits of using an integrated approach, capable of providing point data at different working scales.

Table 1 shows the potential use of remote sensing technologies with respect to common engineering-geological applications, and the recommended resolution of the data for subsequent evaluation of the data.

Table 1: Data resolution required for 3D data analysis tasks and the associated technologies suitable for data collection (modified from [12]).

	Resolution (pts/m^2)	TL	TP	Photogrammetry from rotor UAV	Photogrammetry from fixed-wing UAV	AL
Map regional faults and land formations	5				✓	✓
Map fractures >5m(tree cover.)	20	First/Last arrival				✓
Map fractures >5 m	20	✓	✓	✓	✓	✓
Map fractures >1m	100	✓	✓	✓	✓	
Map fractures >0.5m	500	✓	✓	✓	✓	
Map fractures >0.1m	1000	✓	✓	✓		
Map slope change >1m^3(tree cover.)	20					✓
Map slope change >1m^3	20	✓	✓	✓	✓	✓
Map slope change >0.25m^3	100	✓	✓	✓	✓	
Map slope change >0.1m^3	500	✓	✓	✓		

From Table 1, it is clear that in certain contexts it may be necessary to combine or integrate different techniques, especially when it is necessary to perform studies at different working scales (regional, whole slope or detailed bench analysis). The selection of appropriate remote sensing methodologies is therefore dependent on a number of factors including the nature of the application, data resolution required, purpose and type(s) of the analysis to be undertaken, type of failure mechanism likely to occur, size/extent of the selected area to be evaluated, expertise of personnel, access/set-up constraints and, importantly, the budget available. Careful planning of the survey and associated logistics is therefore required in order to understand potential problems and limitations of selected equipment/technologies. The case studies presented in this investigation highlight the benefits of combining datasets from different methodologies. For example, the newly available ML hand-held technology was successfully used to complement data from more traditional TL and TP point clouds when working at different scales. The level of detail and accuracy obtained from integration of different remote sensing techniques must meet the standard required for different topographic application(s) and there is a need to ensure that the data meets the requirements necessary to ensure that the mining operation complies with any statutory Regulations.

5. Conclusions

The case studies presented show the benefits of combining datasets from different remote sensing technologies to complement or in-fill missing data resulting from inherent limitations in one or either technology. An integrated approach has been able to provide valuable, spatially accurate data for subsequent analysis and associated interpretation. Analysis of point cloud data within a GIS environment can provide valuable spatial awareness of potential instability, highlighting areas that require further investigation. Use and novel application of the newly available hand-held ZEB REVO highlights the need to ensure that users remain aware of, and take advantage of, new developments in remote sensing technology. Analyses of both spatial and temporal changes from remote sensing data provide valuable information for planning, monitoring of potential instability and risk management in the mining and minerals industry.

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