Applications of photogrammetry to rock slope hazard assessment for linear transportation corridors

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ABSTRACT
Rock slopes may pose hazards to adjacent transportation corridors. To manage the issue, rock hazard rating systems have been developed for railway and highway organizations to rate slope hazards and prioritize mitigation works. A review of several rating systems resulted in the identification of parameters used in rock slope hazard assessment schemes, which could be evaluated from photogrammetry. A case study demonstrating this approach is presented.

RÉSUMÉ
Les pentes rocheuses peuvent présenter des risques pour les corridors de transport voisins. Pour gérer ce problème, les systèmes d'évaluation de risque ont été développés pour les organisations ferroviaires et routiers pour évaluer les dangers posés par les pentes et de prioriser les travaux de mitigation. Un examen de plusieurs systèmes d'évaluation a abouti à l'identification des paramètres utilisés dans les systèmes d'évaluation de risque pour les pentes rocheuses, qui pourraient être évalués avec la photogrammétrie. Une étude de cas démontrant cette approche est présenté.

1 INTRODUCTION

Rock slopes and their potential instabilities have been characterized as being hazardous for transportation corridors throughout North America (Abbott et al. 1998b). These transportation corridors are often built through or adjacent to rock slopes making them susceptible to falling rock and creating a situation where avoidance of these falling or fallen materials is impossible. Rock hazard rating systems, in place in railway and highway sectors, were created and implemented generally for the use of prioritization of mitigative works for rock slopes along transportation corridors (Pierson 1991, Abbott et al. 1998a).

The implementation of a rock hazard rating programme involves the training of key personnel (Pierson 1991); this training, though specific to each rock hazard rating system (RHRS) is designed to minimize inconsistencies in the approach of rating a rock slope. Even with training it is still possible for technical personnel to introduce bias to their rating.

The potential explored in this paper is the introduction of photogrammetry data for the development of models to aid in extracting objective data, introducing data not currently obtainable through typical RHRSs and exploring the viability of these data being used to complement RHRSs.

2 ROCK HAZARD RATING SYSTEMS

Rock hazard rating systems are in use in multiple states and provinces throughout North America. The systems that are currently in use and explored in this paper include the:

- Oregon Department of Transportation Rock Hazard Rating System (Pierson 1991);
- Colorado Department of Transportation Rock Hazard Rating System (Stover 1992, Russell et al. 2008);
- Canadian National Railway Rock Hazard Rating Assessment (Abbott et al. 1998a);
- Ohio Department of Transportation Landslide Hazard Rating Matrix (Liang 2007); and
- Ontario Ministry of Transportation Rockfall Hazard Rating System (RHRON) (Franklin et al. 2012).

All of these systems are for highway rock slope ratings except for the Canadian National Railway Rock Hazard Rating Assessment (CNRHRA).

2.1 Development of Systems

The development of these rock hazard rating systems began with the Oregon Department of Transportation (ODOT) and the Federal Highway Administration in the United States of America (Pierson 1991). This first RHRS came with the recommendation that their system be used as a starting point for state highway departments to develop their own systems appropriate to their local geological conditions.

This RHRS uses a 6-step approach to state-wide slope inspections which begins with a slope survey (Pierson 1991). This is followed by a preliminary rating that classes slopes as either imposing a high, moderate, or low hazard on the roadway at its toe. This is based on the historical rockfall activity and the estimated potential for rock on roadway; where the latter factor encompasses consideration of the size of material, the quantity of material/event, the amount available and the ditch catchment effectiveness.

The third step in the ODOT RHRS is the detailed rating, which involved the scoring of 10 geological, geometrical and traffic-related criteria (Pierson 1991).

From this detailed rating, preliminary design and cost estimates are made for remediative works to aid in the next step, which is the identification of projects to be developed that review period/year. The final step of the ODOT RHRS is the annual review and update of slopes and their associated ratings.

As suggested by the ODOT, their RHRS was used as a foundation for the development of RHRSs in the USA and also in Canada for both highway- and railway-adjacent slopes; this includes the Colorado Rock Hazard Rating System (Stover 1992, Russell et al. 2008), the British Columbia Rock Hazard Rating System (Trow Consulting Engineers Ltd. 2004), the Virginia Rock Slope Management Project (Hoppe and Whitehouse 2006), Ontario RHRON (Franklin et al. 2012), to name a few.

2.2 Critical Factors from Rock Hazard Rating Systems

The parameters used in the RHRS systems were identified and grouped by sector. These sectors included:

- Location,
- Slope geometry,
- Characterization of instability,
- Characterization of rock face,
- Rock strength and durability,
- Erosion, movement and preliminary rating,
- Risk considerations,
- Remediation estimates; and
- Remediation and/or cost benefit estimates.

A total of 47 unique factors were identified during this review, some of which were utilized in several RHRSs. Specific remedial construction works parameters have been excluded from this analysis due to fact that the nature of their evaluation encompasses specific construction cost estimates relating to machinery, signage and labour required; all of which are outside of the scope of this study. To identify factors that are the most critical to rock slope hazard assessment, a tally of the frequency of use of the various parameters was conducted. From this analysis (including the preliminary and detailed stages of two of the rating systems) the most critical parameters were identified as those that repeated at least 3 times out of a possible 7 systems/stages.

The value of three was chosen to be high enough to be considered critical; being that a parameter is repeated in nearly half of the RHRSs (ie. parameters deemed important by most experts who created the RHRSs). This selection also eliminated parameters that were less common (e.g. available paved width for avoidance), parameters that were most geographically specific (e.g. roadway width), parameters considered to be subjective in the field (e.g. slake durability index and rate of movement), as well as eliminating many parameters not visible in 3D data (e.g. ditch overspill index and remediation estimates). This resulted in identification of a total of 20 factors as shown in Table 1. Note that three factors (slope angle, failure type and annual average daily traffic {AADT}) that have a rating of less than 3 have also been included due to the authors' opinion of their inclusion adding significant value to either hazard or risk assessment.

3 ROCK SLOPE ASSEESSMENT USING 3D MODELS

The purpose of determining the most critical factors for rock slope hazard assessment for this project was to identify the parameters that can be evaluated using a 3D model.

3D models can be generated using a variety of tools; where the most commonly used in rock slope characterization includes: digital photogrammetry (Sturzenegger and Stead 2009), close- and long-range LiDAR (light detection and ranging) (Lato and Vöge 2012), airborne LiDAR (Sturzenegger et al. 2007), airborne photogrammetry (Birch 2006), and mobile-terrestrial LiDAR (Lato et al. 2009).

Advantages that have been recognized by Sturzenegger and Stead (2009) through using 3D systems and models include the ability to:

- Sample in low- or high-level areas not typically accessible for manual outcrop mapping,
- Sample larger areas for window mapping, leading to more statistically relevant data sets,
- Reduce risk to geotechnical personnel by conducting mapping from a remote location,
- Building a permanent and archival record of rock slope surface, and
- Collect orientation data of discontinuities where traditional methods would be interrupted by magnetic geological conditions.

All of these advantages make it clear that 3D models should be explored for their viability in complementing rock hazard rating systems.

3.1 Identifiable RHRS Parameters from 3D Models

The benefit of using a 3D model in the context of RHRSs can only be realized by the ability to extract information that is valuable for rock slope hazard assessment.

Information that can be gathered from 3D models developed from photogrammetry or LiDAR data include: discontinuity traces and orientation, discontinuity set characterization, potential unstable blocks/zones, geometry of slope (slope height and slope angle in particular), change detection and monitoring of fallen blocks, and movement and surface displacements (Abellán et al. 2006, Jaboyedoff et al. 2007, Sturzenegger and Stead 2009, Jaboyedoff et al. 2012).These pieces of information can be collected from 3D models generated from LiDAR or photogrammetric data; however the advantage of photogrammetry data is the inclusion of colour data in the models.

This colour information can be viewed as an image texture draped over a digital terrain model (DTM) (Figure 1) or individually on DTM points as singular pixels. Since the colour data is embedded in the pixels (and their locations) in the model it is slightly different than the

Table 1. Summary of critical slope hazard assessment factors and their relative importance to rock hazard assessment based on a review of several rock hazard rating systems.

	Hazard Rating Systems							
	Oregon (1990)		Colorado (1997)	British Columbia (1998)	Ohio (2007)	Ontario (2012)		Research
Parameter	Prelim RHRS	Detailed RHRS	RHRS	CN RHRA	Landslide Hazard Rating Matrix	Prelim RHRON	Detailed RHRON	Relative Importance to Slope Rating
Transportation Sector	Highway		Highway	Railway	Highway	Highway		
Location								
Start point of segment	0	0	1	1	0	0	1	3
End point of segment	0	0	1	1	0	0	1	3
Slope Geometry								
Clear Zone/Ditch Width	0	0	1	1	0	1	0	3
Slope Angle	0	0	1	0	0	1	0	2
Slope Height	0	1	1	1	0	1	0	4
Characterization of Instability								
Failure Type	0	1	0	0	0	1	0	2
Magnitude/Volume	0	1	1	1	0	1	0	4
Frequency/History of rockfalls	1	1	1	0	1	1	1	6
Reach	1	0	0	1	0	1	0	3
Characterization of Rock Face								
Face irregularity	0	1	1	0	0	0	1	3
Joint/structural geometry	0	1	1	1	0	0	1	4
Block Size	0	1	0	1	0	0	1	3
Rock Strength and Durability								
Rock friction/Phi p (Roughness)	0	1	1	0	0	0	1	3
Erosion, Movement and Preliminary Rating								
Water Table	0	1	1	0	0	0	1	3
Risk Considerations								
Ditch/Mitigation Effectiveness	0	1	1	1	0	0	1	4
Average Vehicle Risk	0	1	1	0	1	0	0	3
Annual Average Daily Traffic (AADT)	0	0	0	0	1	0	1	2
Posted Speed Limit	0	0	1	1	1	0	1	4
Sight distance	0	1	1	0	0	0	1	3
Remediation and/or Cost Benefit Estimates	0	1	0	0	1	0	1	3

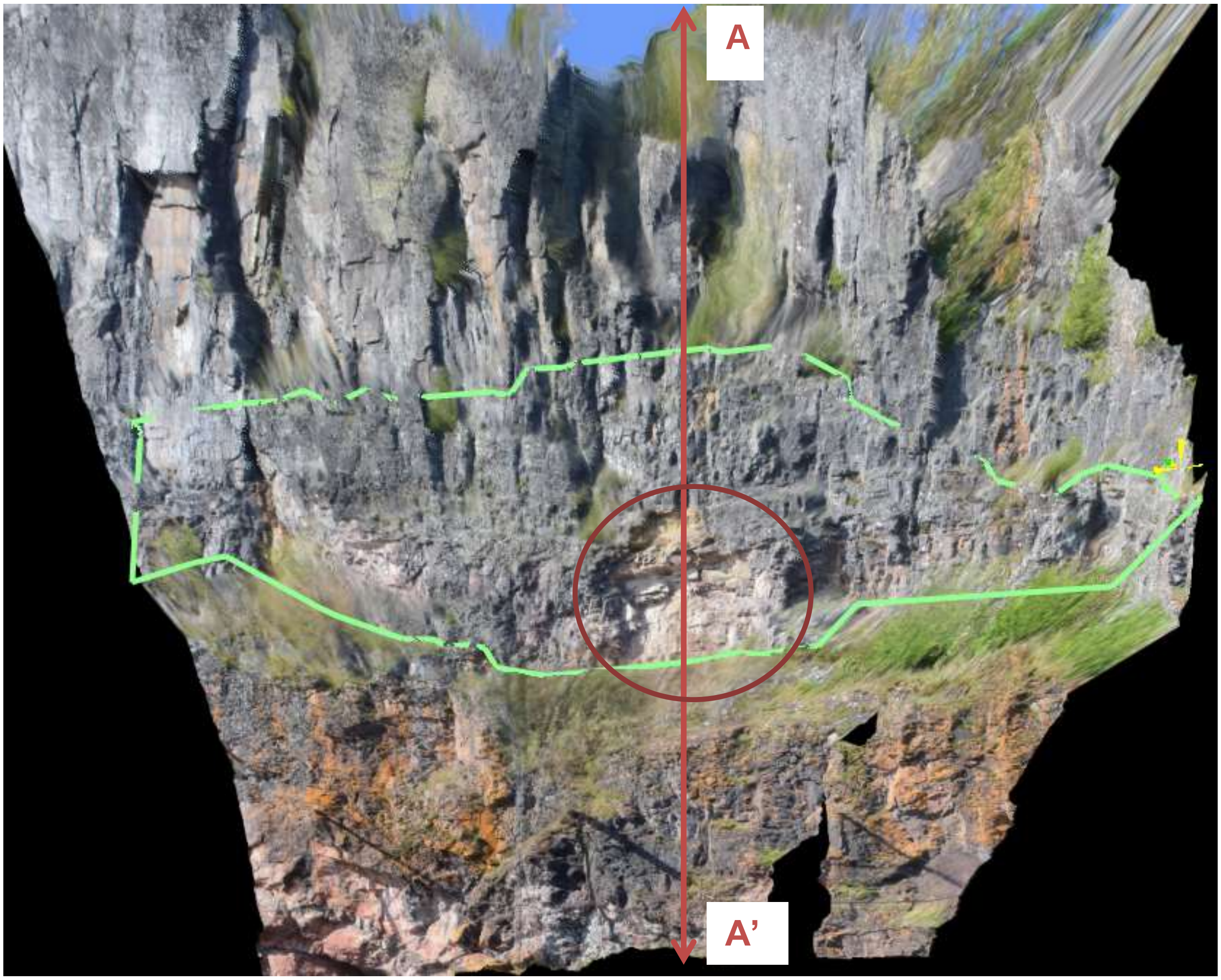

Figure 1. The Case History site viewed as a DTM with the image texture draped on top and with the study zone outlined. Cross section A-A' is the section where a profile was extracted from a 3D model and corrected for areas that were occluded. Cross section A-A' was also estimated using a laser range finder for visible points of interest. The circle in the centre of the image encloses a fresh zone where a rockfall occurred in the summer of 2012.

method of draping an image over a LiDAR model and relying on point/pixel-matching accuracy to drape an image over a DTM. Furthermore, subject to optimal lighting conditions, good quality photogrammetry data can also be collected in a fraction of the time – thereby limiting the exposure of collection personnel to the potential slope hazard.

An issue with the use of photogrammetric data, identified by Wickens and Barton (1971) in the early uses of photogrammetric techniques, is the interference of shadowed areas with the development of the model by reducing the density of data in those locations Changing lighting conditions due to weather changes or cloud cover can also pose difficulties in matching pixels due to the change in colour of the surface from image to image (ADAMTechnology 2010). Before photographing a rock slope the optimal time of day should be selected to minimize the shadows covering the slope.

Similarly consideration should be given to the orientation of the slope with respect to the path of the sun. There may be sections of the slope which are never lit by the sun. For example, on a south facing slope, in the northern hemisphere, joints dipping to the west may daylight from the slope but will be in shadow for most of the day. Consideration should also be given to shadowing due to overhanging features on a slope. Therefore capturing images while the sun is low in the sky, or on dull days where there is limited light contrast, could minimize this complication.

Occlusion is also created by lack of visibility of the objects of interest (Sturzenegger and Stead 2009). Data collection for a rock slope can be limited by equipment, vegetation, topography, property access and/or safety. Since photogrammetry is a line-of-sight technology, if an object is not visible then it is not captured or included in the generation of a 3D model; which could be due to solely look angle, but also vegetation (Figure 2a & b). For this reason it would be beneficial to capitalize on the use of aerial data or data collection from multiple vantage points, if available or accessible.

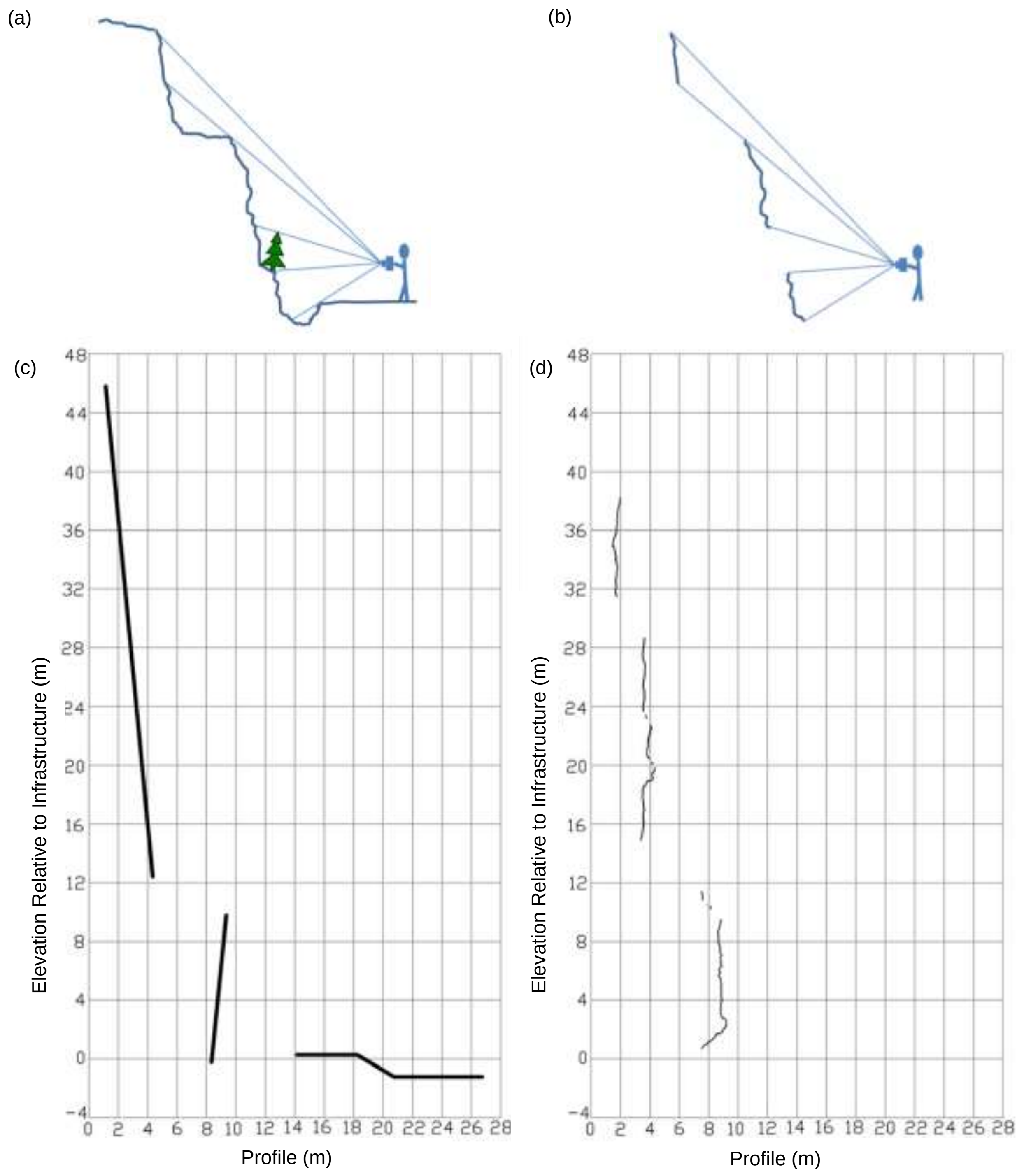

Figure 2. Cross section and occlusion schematic diagrams, where: (a) is a schematic diagram showing a sample rock slope profile being photographed for photogrammetric analysis, (b) is a schematic depicting reasons for occlusion due to look angle or vegetation, (c) is the profile created from unique measurements taken using a handheld laser range finder, and (d) is the profile taken from cross section A-A' on the 3D photogrammetry model seen in Figure 1.

Another consideration with discontinuity analysis in 3D models is defining the appropriate parameters for grouping co-planar adjacent triangles that represent a single rock joint (Lato et al. 2009). The key parameter utilized defines the maximum angle between normal vectors of adjacent triangles used to define a plane; this is termed the "angle offset" in this software package. In defining the limit the user must consider the joint surface undulation to ensure that natural variability is captured.

Furthermore, the DTM mesh density will also limit the features captured (Lato et al. 2009); where a denser DTM will capture more detail on rock joint.

4 CASE STUDY OF ASSESSMENT OF A ROCKFALL SITE ADJACENT TO LINEAR INFRASTRUCTURE

To explore the effectiveness of using photogrammetry within rock hazard rating systems, a data collection and analysis programme was undertaken on a rock slope adjacent to a railway in Northern Ontario.

4.1 Site Description

The site that was chosen for consideration is a rock slope that is just north of the town of Red Rock, ON. This site is considered to be of particular interest due to a rockfall that occurred during the summer of 2012; the summer of the data collection field investigation. This site ranges from approximately 40 to 45 m in height, and is a total length of nearly 30 m. At cross section A-A', seen in

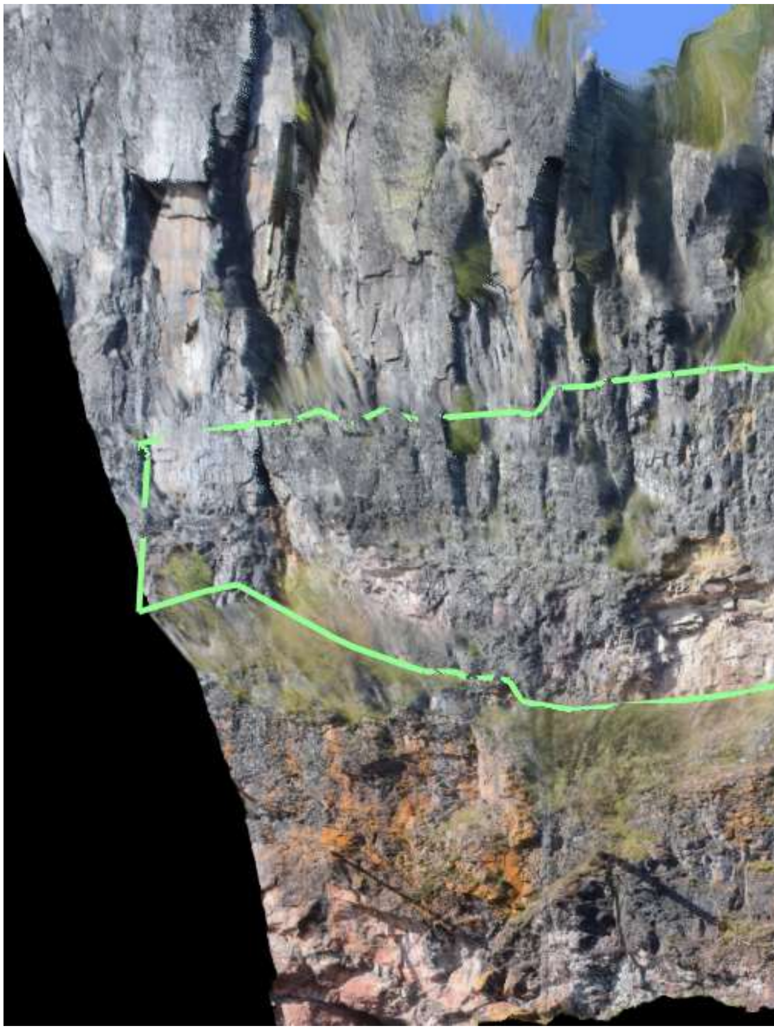

Figure 1, the ditch width at the base of the slope is 5.8 m. Several additional points were measured at this location on the rock slope using a laser range finder and were used to develop an approximate cross section (Figure 2c). Data acquisition was limited by the site being located adjacent to a lake – the maximum horizontal distance away from the toe of the slope that was accessible on land is 24 metres.

The geology of this site is similar to the Kama Hill bluffs, which are located approximately 18 km away from the case history site.

These bluffs have been extensively studied through a highway expansion project (Wood et al. 2009) and are mesas which contain diabase sills from the Upper Keweenawan Supergroup (Mesoproterozoic ~1100Ma). These diabase sills, though now eroded, intruded into the metasedimentary rocks of the Sibley Group (Lower Keweenawan Supergroup ~1339Ma). The structure in the diabase sills is dominated by vertical joint sets that created the nearly vertical face that is evident in the upper two portions of the cross section extracted from a photogrammetry model (Figure 2d). The lower lying Sibley rocks are made up of predominately mudstones, shaley dolostones, and dolomitic limestones; all with interbedded sandstone that tend to be bright red to purple in colour. The Kama Hill bluff is also known to have natural benches that are typical in this site as well, where these benches separate the diabase and the sedimentary rocks as well as varying portions of intrusive flows.

At the contact of the diabase and the sedimentary formation the blocks are smaller than within the diabase sill, but larger than within the sedimentary rocks. This smaller blocky area was the source of the recent rockfall mentioned and is the particular study area of this paper; shown outlined in

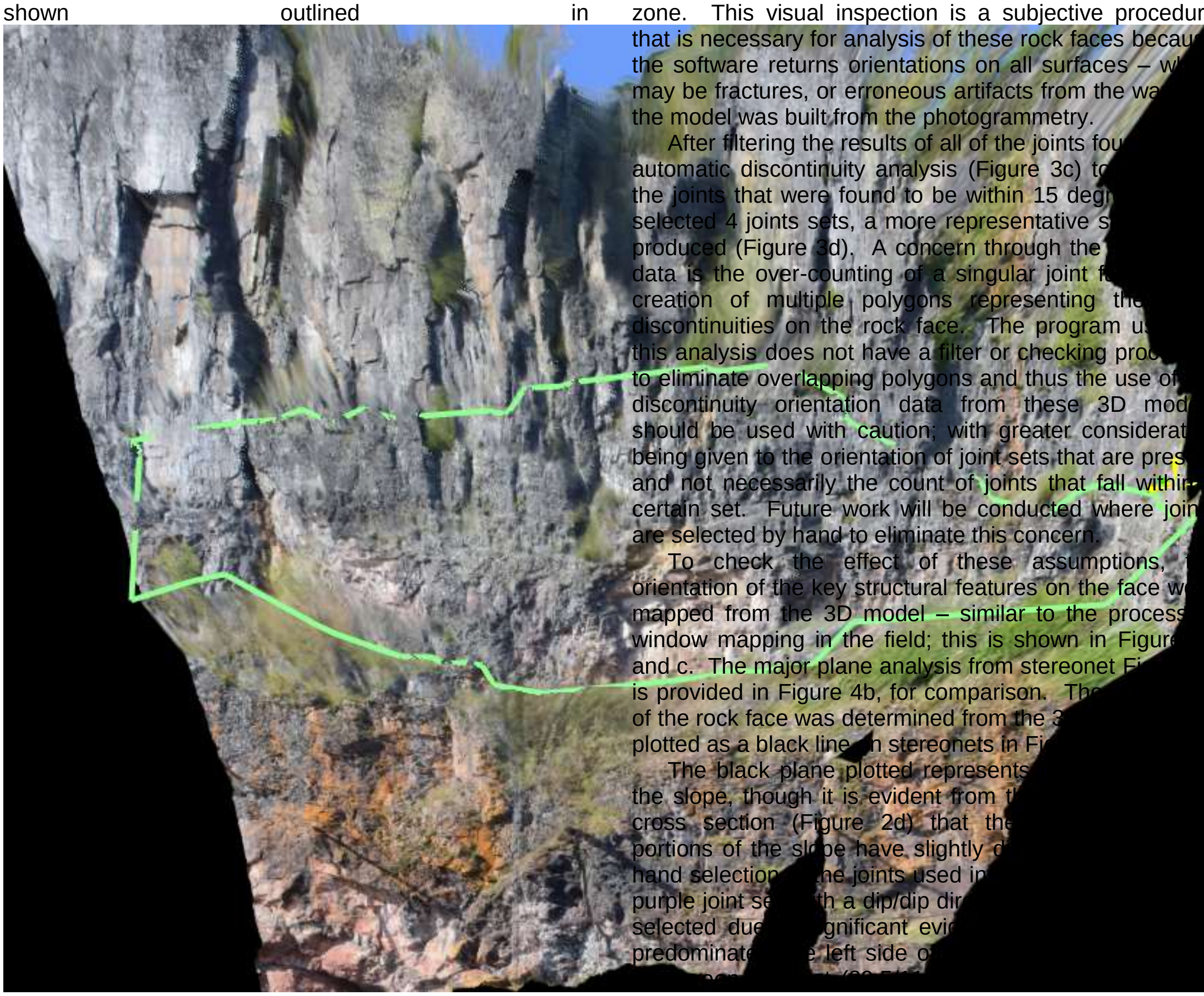

Figure 1.

4.2 Analysis of Case Study Rockfall Zone

This case study site was selected to determine if photogrammetry could be used to assess the structure and geometry of the rockfall zone. Utilizing a semi-automatic discontinuity characterization, within the AdamTech software, rock faces were identified and their orientations plotted on a stereonet, as shown in Figure 3. The analysis was conducted using the model that was merged in a front-facing view, making some features that are sub-perpendicular to the rock face difficult to visualize due to irregular meshing patterns in those orientations; this was a function of working in a 2.5D software environment.

A parametric analysis was conducted to determine the best search parameters to be used in the automatic discontinuity identification. In the software, this includes the varying of the angle offset, the point offset and the minimum face size. Through a visual inspection of the model, several joint faces were selected as being representative of the rock structure in the outlined rockfall zone. This visual inspection is a subjective procedure that is necessary for analysis of these rock faces becau[illegible] the software returns orientations on all surfaces – w[illegible]h may be fractures, or erroneous artifacts from the wa[illegible]t the model was built from the photogrammetry.

After filtering the results of all of the joints fou[illegible]e automatic discontinuity analysis (Figure 3c) to [illegible]y the joints that were found to be within 15 degr[illegible]e selected 4 joints sets, a more representative s[illegible]s produced (Figure 3d). A concern through the [illegible]s data is the over-counting of a singular joint f[illegible]e creation of multiple polygons representing th[illegible]e discontinuities on the rock face. The program us[illegible]r this analysis does not have a filter or checking proc[illegible]e to eliminate overlapping polygons and thus the use of [illegible]e discontinuity orientation data from these 3D mod[illegible]s should be used with caution; with greater considerat[illegible]n being given to the orientation of joint sets that are pres[illegible]t and not necessarily the count of joints that fall withi[illegible]a certain set. Future work will be conducted where join[illegible]s are selected by hand to eliminate this concern.

To check the effect of these assumptions, [illegible]e orientation of the key structural features on the face w[illegible]e mapped from the 3D model – similar to the process [illegible]f window mapping in the field; this is shown in Figure[illegible]a and c. The major plane analysis from stereonet Fi[illegible]c is provided in Figure 4b, for comparison. Th[illegible]n of the rock face was determined from the 3[illegible]s plotted as a black line [illegible]n stereonets in Fi[illegible]

The black plane plotted represents [illegible]f the slope, though it is evident from t[illegible]c cross section (Figure 2d) that the [illegible]r portions of the slope have slightly d[illegible]e hand selection [illegible]he joints used in[illegible]e purple joint se[illegible]th a dip/dip dir[illegible]s selected due [illegible]gnificant evi[illegible]h predominate[illegible]e left side o[illegible]. [illegible]e consideration of its presence in the shadowed zones of the rock face. Though it was not possible to characterize many of these faces, or determine if they have the same

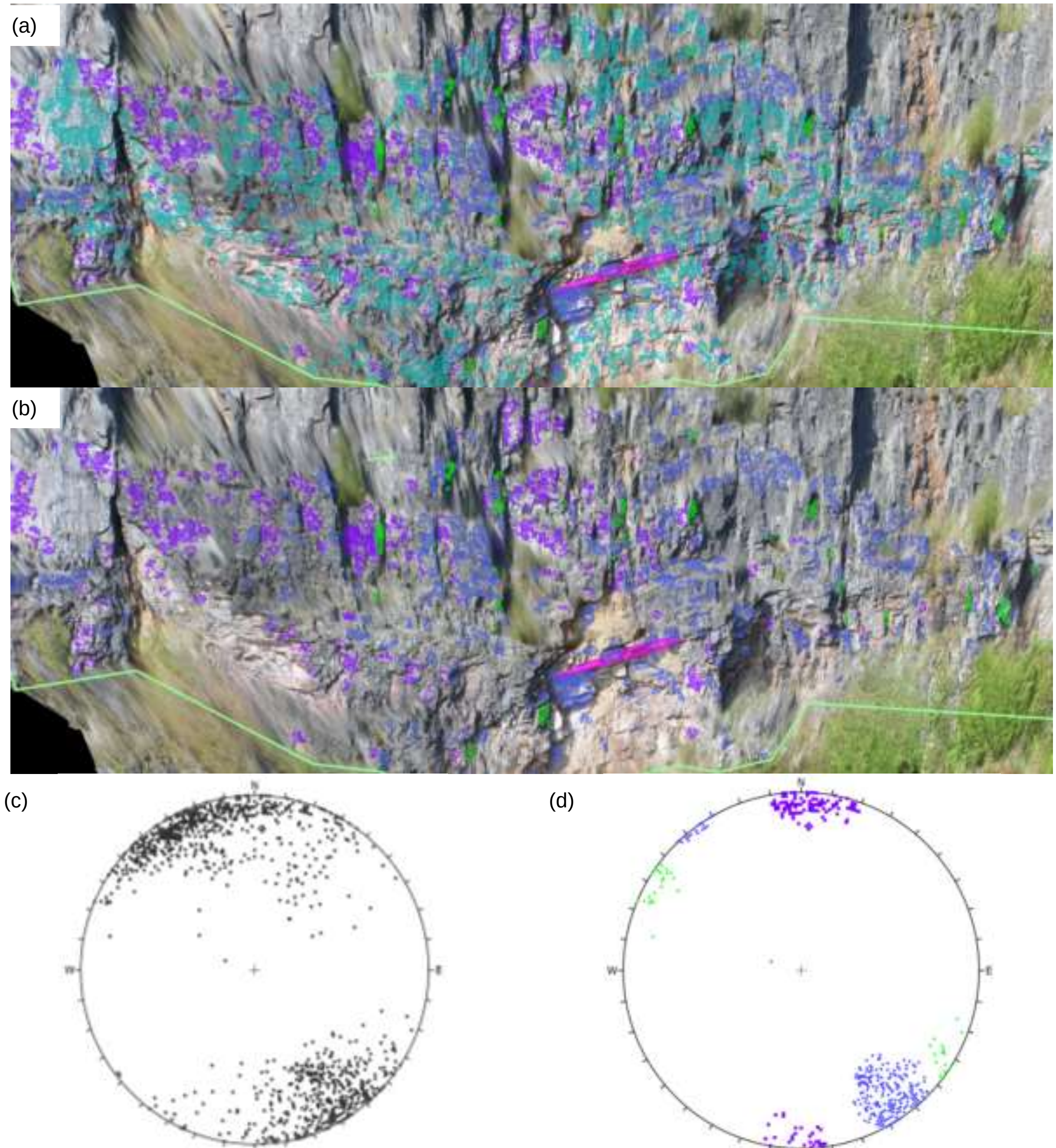

Figure 3. Images representing the discontinuity characterization analysis from the rockfall zone of the site of interest, where: (a) shows all of the polygons detected, (b) shows only the 4 user-defined joint sets, (c) is the symbolic stereonet plot of all of the joints, and, (d) is the symbolic stereonet plot of the user-defined joint sets from 3b.

orientation due to shadowy conditions, a few features were identified but are likely underrepresented. The pink joint set (19/107.4) was selected directly on the rockfall zone where the only feature was clearly visible due to shadowing under these joints and the evidence of smaller features on the right side of the slope not being identifiable by the software.

The blue joint set (77.8/323.7) was selected directly from the rockfall zone as well and is considered by the authors to be a considerable contributor to the rockfall itself; however automatic discontinuity characterization on that surface was limited due to the minimum face size parameter included in the search function. With the use of this structural information and the associated stereonet created, stability analysis techniques could easily be applied and are planned for future analysis.

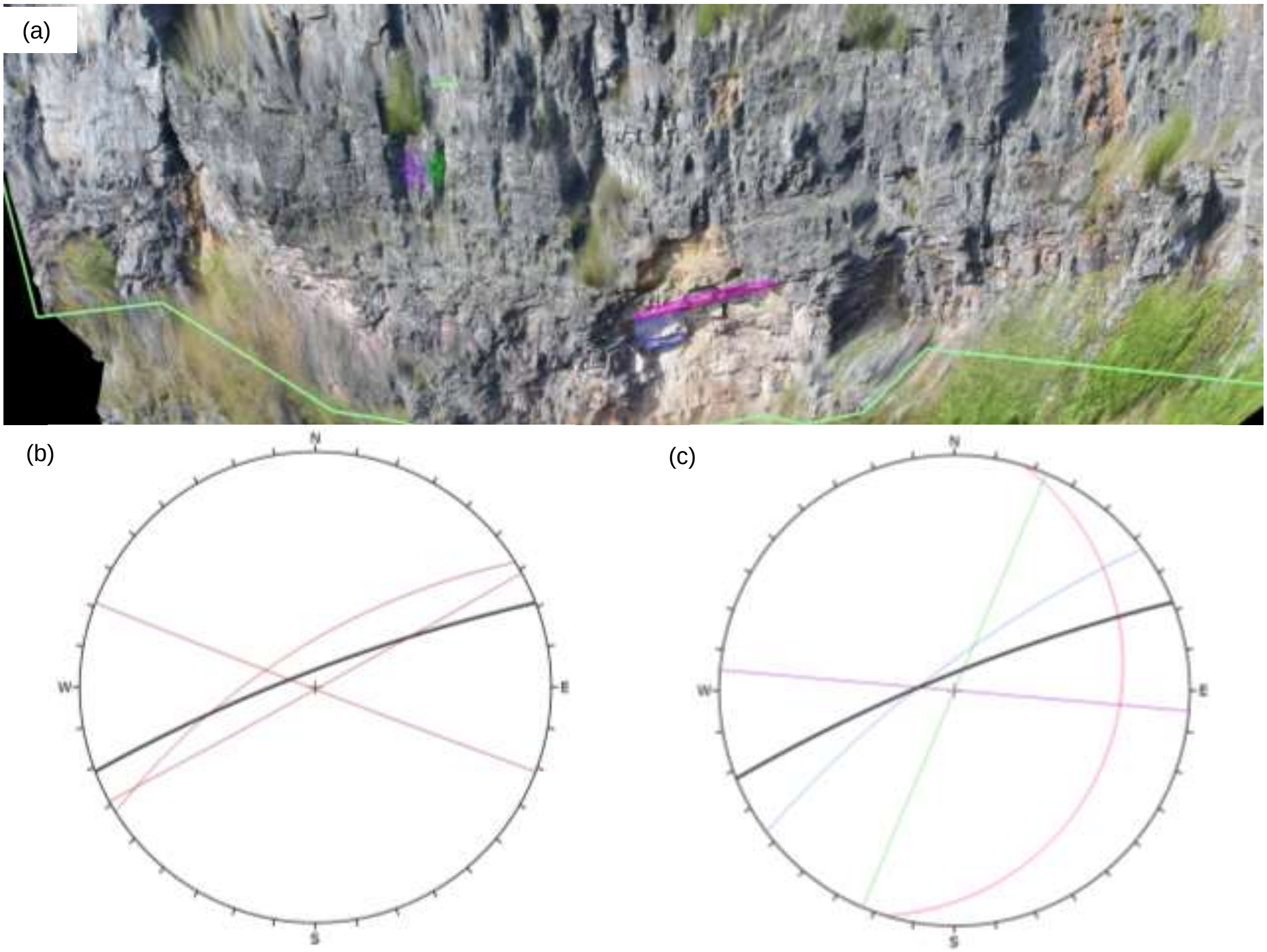

Figure 4. Images comparing the automated mapping and simulated field window mapping. (a) shows the joints that were selected by hand from the rock face as representative of the structure of the rockfall zone area, (b) shows the orientations of the major planes selected from the full data set (Figure 3c above), and (c) shows the orientation of the major planes from 4a. The black line on the stereonets corresponds to the orientation of the rock face.

4.3 Parameters Determinable for RHRSs

Through the analysis and consideration of the 3D model generated for the case history site, a variety of parameters could be considered for rock slope hazard assessment, as described in **Error! Reference source not found.**. The parameters that could be determined and given a rating, depending on the RHRS used, includes the start and end point of a segment, which is crucial for segmenting a large, continuous rock slope into sections that differ in geological makeup or zones with different potential failure modes. The slope angle and slope height can be determined from photogrammetry data. It is also possible to cut a more detailed cross section from the rock slope surface, as seen in Figure 2d, which can be used in 2D rockfall trajectory analysis.

Furthermore, face irregularity - and the consideration of potential launching features - could be easily rated by using the 3D model which can be rotated on the computer screen for ease of assessing the slope face unevenness from various viewing angles. Joint/structural geometry can be extracted from photogrammetry models as shown in this study as well as in previous studies (Sturzenegger and Stead 2009, Pate and Haneberg 2011).

4.4 Potential for future evaluation

This leaves several parameters that still have the potential for evaluation from photogrammetric models but have yet to be explored in this study. Firstly, block size could be determined, and is part of the future work of this study; it is quantifiable from the use of 3D photogrammetric data as input information for developing discrete fracture networks. Additionally, the magnitude or volume of unstable material could be determined by finding unstable zones through stereonet rockfall analysis and using knowledge of estimated block sizes to calculate potential unstable volumes.

History of rockfalls, part of a study in progress, can also be determined through the comparison of models generated of the same slope at different points in time; where rock is known to have been moved or removed. Reach, or potential reach of rockfalls, could also be determined through calculating parameters for use in rockfall trajectory analysis such as seed volume and block size and mass.

5 CONCLUSIONS

The exploration of the use of photogrammetric data to potentially complement rock hazard rating systems has promising results but still requires engineering judgement throughout the process; as well as an understanding of the biases and over counting of joints that are encountered in semi-automatic analysis. The selection of search parameters requires estimation of joint shapes on the rock slope. The selection of discontinuities used to define joint sets necessitates an understanding of rock slope outcrop mapping and the transition of that knowledge for usage in a model environment.

Several parameters have been proven to be describable through the analysis of a photogrammetric model, including: start and end point of a segment, slope angle, slope height, face irregularity, and joint/structural geometry. The potential for analysis of sequential photogrammetric models taken at different points in time permits the consideration of change of rock slope condition (eg. rockfall volumes). Furthermore it is possible to evaluate block size, volume of unstable material, history of rockfalls, and potential reach of rockfall material through the use of the photogrammetric data.

The implementation of rock hazard rating systems has enabled provinces and states to rate the hazards transportation corridors adjacent to slopes are subject to and use these ratings to prioritize any remediation works on these slopes. The use of photogrammetric data for determination of critical RHRS parameters can be advantageous for multiple reasons, including gaining access to data higher on the rock slopes, minimizing exposure of personnel to rock slope hazards, as well as gaining data for analysis of larger windows. With all of this under consideration it is clear that 3D models, in general, and photogrammetric models in particular can benefit a rock slope hazard assessment and the development of rock slope condition history.

6 FUTURE WORK AND RECOMMENDATIONS

Future work on this project will include the integration of discontinuity characterization data for use as inputs into discrete fracture networks (DFNs) to determine probable block sizes. These data will be obtained from 2.5D digital terrain models through various collection methodologies; the first of which will be a semi-automatic characterization methodology. These data are obtained through the creation of polygons that are identified by the software program after search parameters are defined; including the maximum point offset, the maximum angle offset and the minimum face size. Further methods for collecting discontinuity data will include a virtual straight line scan line mapping procedure, a virtual circular scan line mapping procedure and a virtual window mapping method.

Through the characterization of polygons, in the various collection methods, joint sets are identified and can be isolated for further analysis in a DFN model. The parameters characterized from the photogrammetry model will include: orientation data, fracture intensity data, and face size data at a minimum.

Additional ongoing and future work includes the comparison between digital terrain models (DTMs) from LiDAR data and photogrammetric data. Analysis and further comparisons will be conducted and released in a future publication.

Furthermore, an ongoing study is considering the affect that the view orientation of DTMs during merging has on the meshing algorithm of the final DTM; and thus how discontinuity characterization and therefore different joint sets are affected from the irregular triangles created in the 2.5D model. This study will examine the merging of the DTMs from different vantage points to optimize the data collected on the discontinuities of the rock face as a whole, and the joint sets in particular.

Recommendations for improving the use of photogrammetric data include the use of an unmanned aerial vehicle to collect aerial data from a higher vantage point and with a high quality camera. This would help significantly cut down on occlusion and could help improve on the resulting cross-sectional data.

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