PHOTOGRAMMETRY OF FRACTURE LINES AND AVALANCHE TERRAIN: POTENTIAL APPLICATIONS TO RESEARCH AND HAZARD MITIGATION PROJECTS

Dave Gauthier[1]*, Michael Conlan[2] and Bruce Jamieson[2]

[1]Dept. of Geological Engineering, Queen's University, Kingston, ON, Canada
[2]Dept. of Civil Engineering, University of Calgary, Calgary, AB, Canada

ABSTRACT: Recent advances in both digital photography and computer processing power has led to the ability to generate detailed, richly coloured three-dimensional models of complex surfaces using only a consumer-grade camera and commercial software. This technique, called 'structure from motion' photogrammetry, has been applied to hazardous rock slopes, landslides, flood-prone river channels, and other geohazard problems. In these cases the results often meet or exceed the level of 3D detail and accuracy provided by a traditional LiDAR survey. Where LiDAR is expensive and requires specialized equipment for observations of snow, the photogrammetric approach is relatively cheap and can easily model snow covered surfaces – or the snow itself. In this paper we describe the method and discuss applications of this technology for mapping and modeling crown fractures, downed avalanches, and avalanche terrain. First, we present the results of modeling the crown surface of a fresh deep slab avalanche and demonstrate some of the fractographical and snow-structure features that were observable and quantifiable, many of which allow direct insight into the fracture propagation direction and the snowpack layering. We then present preliminary results of test models we created for the full path of a downed avalanche and discuss the potential applications to avalanche investigations. Lastly, we include some snow-free terrain models and explore how these might be used for runout analysis, hazard mapping, terrain classification, etc.

KEYWORDS: fracture lines, terrain mapping, hazard mitigation, investigations

1. INTRODUCTION

Recent advances in both digital photography and computer processing power has led to the ability to generate detailed, richly coloured three-dimensional (3d) models of complex surfaces using only a consumer-grade camera and commercial software. 'Structure from motion' (SfM) photogrammetry has been applied to hazardous glacial and rock slopes, landslides, flood-prone river channels, and other geohazard problems (e.g Haneberg, 2008; Sturznegger and Stead, 2009; Ganzalez-Diaz et al., 2013; Whitehead et al., 2013; Magreth et al, 2011; Gauthier et al., 2014; Javernick et al., 2014; Wolter et al., 2014). The results often meet or exceed the level of 3d detail and accuracy provided by a traditional LiDAR survey (e.g. Figure 1). Where LiDAR is expensive and requires specialized equipment for observations of snow, the photogrammetric approach is relatively cheap and with careful fieldwork can

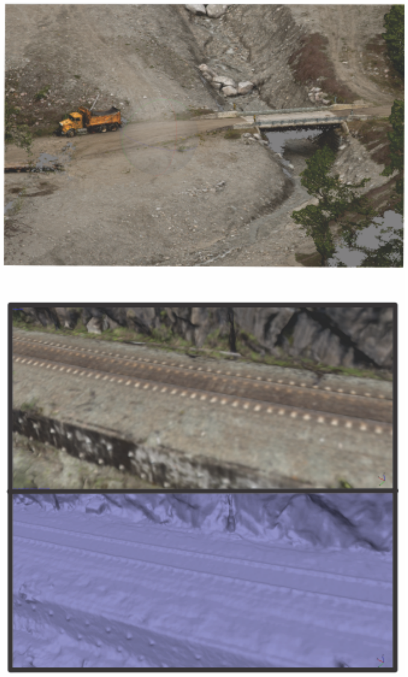

Fig. 1: Example of very high resolution 3d photogrammetry models. The photos for these models were taken manually, from a moving helicopter.

---

* *Corresponding author address:*
Dave Gauthier, Dept. of Geological Engineering, Queen's University, Kingston, ON Canada;
tel: 613-893-4920;
email: dave@davegauthier.ca

easily model snow covered surfaces – or the snow itself.

In this paper we introduce the SfM technique to the snow science community, and present several case studies to demonstrate some of the potential applications to research and hazard mitigation projects. We report on a detailed fracture line study at a deep slab avalanche, the documentation of a downed avalanche, and the mapping of vegetation damage associated with a past avalanche – all using detailed 3d terrain models generated directly from photographs. We also discuss some considerations for collection of appropriate photos for photogrammetric modeling.

2. METHODS - PHOTOGRAMMETRY

2.1 Photography

In its most basic form, photogrammetric modelling only requires two overlapping photos, taken from different locations, in which case the 3d geometry can be solved for the area of overlap. This is essentially the traditional method used to generate topographic maps from stereo-pair air photos, where the parallax of near and far field features in the photos can be used to calculate their relative distances from the camera positions, and hence solve their 3d location. Since the SfM method is intended to simultaneously handle tens or hundreds of photos, the overlap between them must be at least 2/3 in order to link all the parts of a scene together. This means that every part of the scene that is to be modeled in 3d must appear in at least three photos (more is better). Good photography is critical: large format, well-lit, and sharp digital photos are best. At minimum a high-end consumer grade point and shoot digital camera should be used, although very coarse 3d models can be generated from photos collected with a smartphone if necessary. For high-precision, very detailed models, a full-frame digital SLR camera should be used, since this format provides the maximum ground pixel size available, and therefore the best resolution. Unlike traditional methods, calibrated or metric cameras and lenses are not required, and for relative-only modelling neither are GPS coordinates, scale bars, or other forms of ground control. The key requirement is sharp photographs having extensive overlap. Oblique photos of terrain or other objects are acceptable – or preferable, especially in steep terrain or when taking photos from a helicopter.

2.2 Structure-from-motion photogrammetry

We processed all of the images for this study and generated 3D models using the commercial software ‘Photoscan Pro’ version 1.0.4 by Agisoft (www.agisoft.ru).The software uses the SfM algorithms to resolve the relative locations and camera orientations of each image using automatically detected matching points across multiple images taken from different locations. A ‘multi-view stereo’ triangulation routine then generates a depth map for each image, which contain the 3d coordinates of individual pixels. Dense point clouds (as per LiDAR) and polygonal meshed surfaces can be generated from the depth maps. Andrew et al. (2012) describe photogrammetry data collection, processing, and applications to rock slopes, in detail, while Westoby et al (2012) discuss the SfM method for geoscience applications. Note that each step of this process is in true 3d space, rather than the 2.5d of typical DEM or other GIS and mapping formats.

For reference, the processing of a few tens of ~10 megapixel photos is possible using a high-end laptop or decent quality desktop computer, although the processing time may be a few hours to generate a point cloud having approximately 1 million points. For higher resolutions or more photos, a gaming or graphics-optimized computer is required at minimum, with better results possible with better video cards and more RAM (e.g. >32 MB). Point clouds of up to 100 million points are possible with this configuration. Even visualizing the models in 3d can be taxing, in the absence of high-end graphics capabilities.

The raw 3d model is relative-only, meaning that while it may be highly accurate in representing 3d shapes of objects, it is not oriented properly, nor scaled to the correct size, nor georeferenced. The scale issue can be resolved by manually entering the size of a recognizable object in the model; however, ideally the camera or some ground feature GPS coordinates are available, in which case the software will automatically attempt to georeference the model (i.e. convert the 3d point coordinates to lat/long/elevation), which automatically solves the orientation and scaling issues. Of course, the accuracy of the solution depends on the accuracy of the coordinates and spatial layout of the cameras and/or features. For reference, with >100 high quality photos the raw model may be within 2% of true scale and coordinates when camera peripheral GPS is available, based on our experience.

Fig. 2: Photo of the crown area of the deep slab avalanche modeled in this study. Some of the fractographical feature are evident on the crown surface. (ASARC photo)

3. CASE STUDIES

3.1 *Fracture line studies*

Figure 2 shows the crown of a size 3 (destructive) avalanche, which occurred in the Selkirk Mountains of British Columbia, Canada, in 2014. The slab was between 1 m and 3.5 m thick. The crown had many recognizable fractographical features (these are relief features, having up to a few centimetres relief, on the crown surface). They form as a result of the tension fracture that occurs there during avalanche release (see Gauthier, 2012). The characteristic pattern of these features can indicate both the direction of fracture propagation and its origin, so may be useful as part of fracture line studies. Photogrammetric modelling may solve one of the main issues in studying these features: the difficulty in capturing and quantifying their geometry and relief. To that end, we made a series of overlapping photographs of the crown surface of this avalanche for photogrammetric modelling. Figures 3 and 4 show the results.

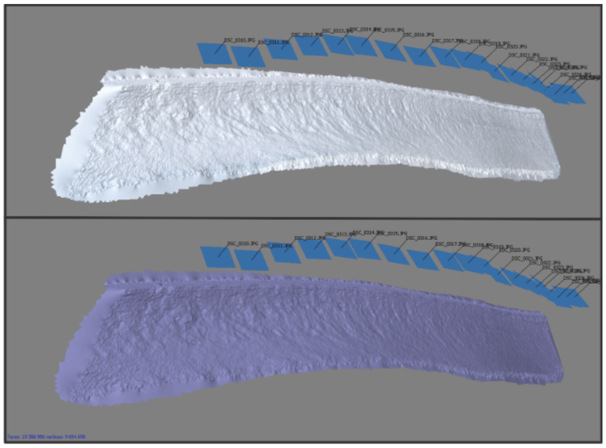

Fig. 3: Rendering of the shaded (top) and surface-only (bottom) 3d model of the crown surface of the deep slab avalanche shown in Figure 2, viewed from the front and side slightly. The bed surface is at the base of the model, and the snow surface is at the top.

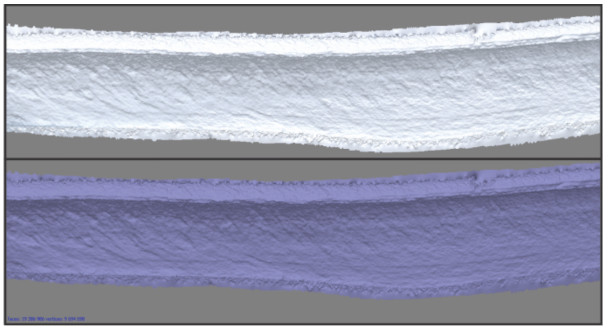

Fig. 4: Rendering of the 3d crown surface model, oriented to highlight the fractographical relief features, viewed from the front and slightly looking down. Note the curved 'steps' across the surface, and the horizontal features which coincide with prominent layers in the snowpack.

We found that the ridge/rib/hackle features oriented generally across the thickness of the crown and associated with fracture propagation were evident in the 3d model, as was the asymmetry in the 'plumose' or curved features, indicating propagation from right to left in Figures 3 and 4.

The model was able to effectively portray the downslope curvatures of the slab. The upper portion of the slab was displaced downslope because of higher creep rates in the less stiff snow layers.

The model also identified stiffer layers within the snowpack. One such layer was in the middle of the slab and the other was at the base (Figures 3-5). Both layers correspond to hardness differences in the snow profile. The middle layer was smaller-grained and had a slightly harder hand hardness than adjacent layers. The bottom layer was a knife-hard melt-freeze crust, directly above the failure layer.

To further illustrate these features and to test a potential analytical method, we applied an aspect-shading filter to the model using a GIS approach, which essentially applies similar colours to parts of the model facing in similar directions (Figure 5). Since the crown was curved there is a general variation in aspect across the model, but this method did provide a means to highlight the surface features on the crown, and quantify them to some degree.

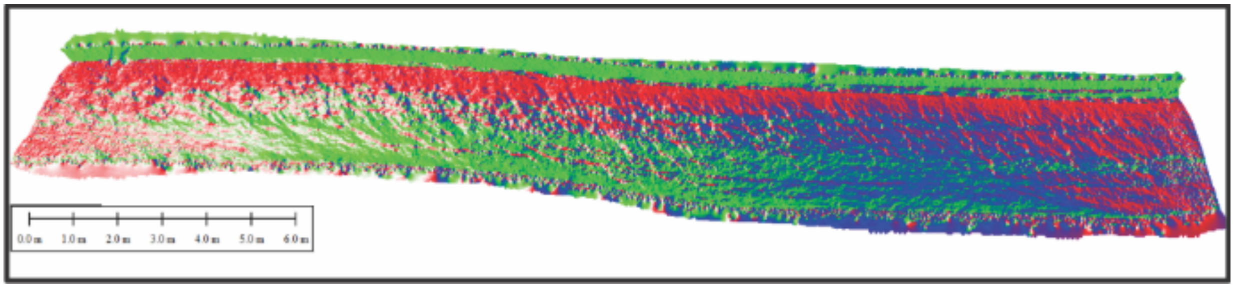

Fig. 5: Aspect-shaded surface model of the same crown surface as Figs. 3 and 4, viewed from the front, which highlights the fractographical (curved, across the crown) and snowpack layering features (linear features along the crown) recorded in the 3d model. This format allows for the quantification of these features.

3.2 *Avalanche investigations*

Figure 6 shows an oblique image, captured shortly after an avalanche had occurred near Blue River, BC, in 2006. We used approximately 20 photos of the avalanche and its path as a test of the ability to generate 3d models downed avalanches, and for cases where photos were not collected specifically for photogrammetric modelling. In this example we were able to model the entire path, from peak to maximum runout, although only the start zone had adequate overlap in the photos for detailed model generation. In the start zone, we were able to capture the 3d geometry of the crown surface, which means that the approximate release volume could be calculated. The terrain was modeled well enough to generally surpass any available mapping or traditional field approaches, even with these ad-hoc photos. With a dedicated field campaign and good quality photography we anticipate that results for snow covered terrain, including the release and deposition areas of downed avalanches, would approach the resolution and accuracy of the examples in Figure 1, in which case even damaged vegetation, ski-tracks, rescue excavations or detritus, etc. would be captured and preserved in the coloured 3d model.

3.3 *Mapping and hazard mitigation projects*

We also made a test model of the runout zone of a large avalanche path in the Coast Mountains, BC, to test the utility of photogrammetric modelling for path mapping and hazard assessment or mitigation projects. In this example the track and start zone were obscured by cloud (Figure 8), but the runout zone – including a large area of vegetation damage – was visible. We generated a 3d model of the terrain using photos captured from a smart phone, taken out of a moving helicopter. The resulting model was low-quality compared to the results in Figure 1, but we were able to get a general sense of the geometry of the runout zone, and make some basic linear measurements of the area of recent vegetation damage (caused by an air blast?), and the overall trim-line width of the runout. In addition, elevation and coordinate values for any point in the model are readily available with a few mouse clicks (Figure 8).

4. DISCUSSION

The typical approach to fracture line studies, avalanche investigations, and hazard mapping invariably involves photographs, to one degree or another, especially given the low-cost and portability of consumer-grade cameras, and the ubiquity of smart phone cameras. This means with minimal preparation and additional investment, nearly any subject of a photograph could be the subject of a detailed 3d model. The examples we presented here are just a few of the cases where a person may already be in position during snow studies or mapping fieldwork – on the snow, or in a helicopter – with a camera in hand, and could just as easily take a set of photos suitable for photogrammetric modelling. The additional cost to an operation would be limited to the cost of generating the model, which is certainly low compared to collecting LiDAR or purchasing dedicated satellite imagery, for example.

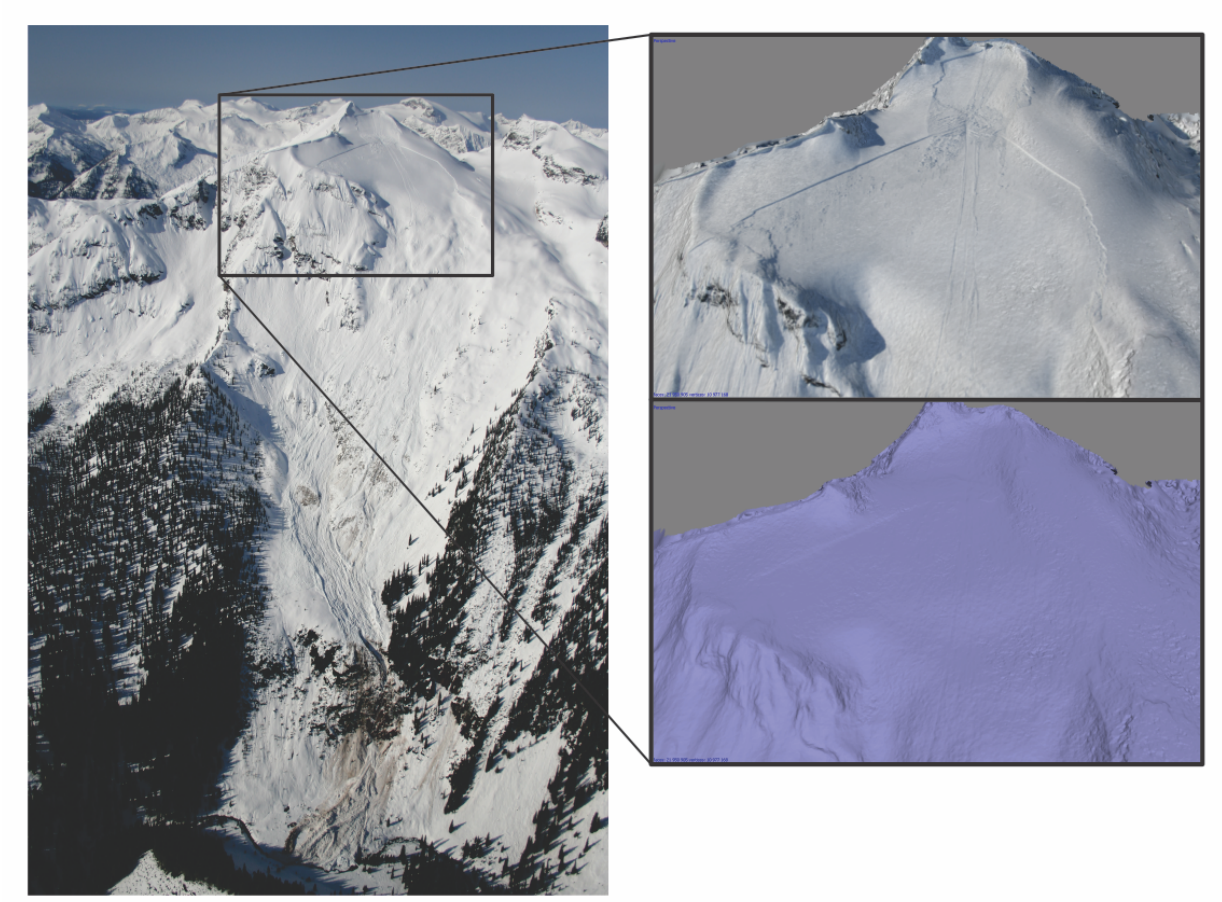

Fig. 6: Oblique photo, and surface models for a slab avalanche, highlighting the potential utility of the photogrammetric method for documenting and mapping downed avalanches. In this case we modeled the start-zone and release area in detail. Note the crown surface in the surface-only model. Having captured the geometry of the fracture line means that the volume of the release in this area could be calculated, and, for example, compared with the deposit volume in the runout zone. (Mike Wiegele Heliskiing photo).

Photogrammetric modelling may be particularly useful for investigating avalanche accidents, where important features may be obscured by snowfall, melting, etc., shortly after an event. The current approach would be to estimate elevations, avalanche dimensions, and the positions of relevant features using a GPS or altimeter, all of which would benefit greatly from the ability to map the exact relative positions of everything on or in an avalanche path in the time it takes to capture 100 or so photographs. The modelling could take place later, as long as the photos were captured early in the investigation.

The crown surface example we presented (Figures 3 and 4) highlighted both the ability of the photogrammetric approach to accurately model in three dimensions the fractographical features of the crown surface, but also to document and potentially quantify them. In our example we applied a set of GIS tools to this problem (Figure 5), but surely other approaches are possible. This opens the door to advancing the study of crown fractography, which has the potential to delineate fracture origin, propagation direction, and potentially the role of stiffer or softer layers in the slab during avalanche release (see Gauthier, 2012).

In other studies (of debris flow channels) we have been able to generate a very detailed model of the source, channel, and deposition areas using approximately 200 photos taken from a helicopter. A similar result would be possible for an avalanche path of any size. Where other studies have evaluated the use of DEM-type mapping products for extreme runout prediction, over the traditional 2d transect approach (e.g. Sinickas and Jamieson, 2014), the method we are demonstrating here would provide a level of detail at least one order of magnitude better than a typical DEM, and the ter-

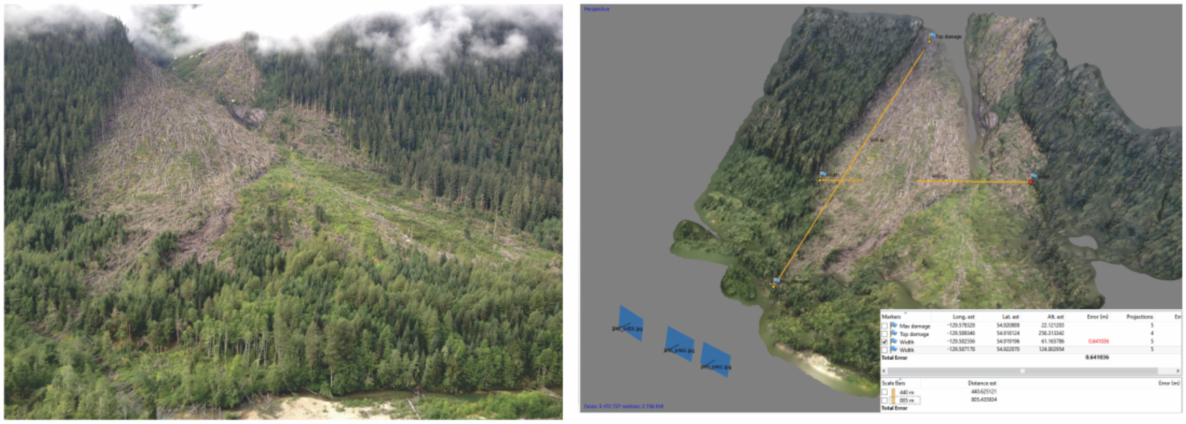

Fig. 8: Oblique photo and model of the runout of a large avalanche path, with significant vegetation damage. The model was generated from smartphone photos, and while coarse, it is suitable for measuring approximate dimensions, slope angles, etc.

rain model itself would be coloured, tree heights would be captured automatically, and historical vegetation damage may even be visible. In fact, the level of detail available would surely be more than even the most sophisticated dynamic runout modelling software could utilize, so for now the main application may be simply as a detailed mapping tool, to supplement traditional field observations.

In our other studies (of rock slopes), we have tested with some success the use of camera-equipped unmanned aerial vehicles (UAV) for collecting the photographs. There are scenarios where UAVs or drones are very useful for this work, although the aircraft typically suffer from very low payload capacity (small cameras only), short range, poor stability in high winds, low altitude limits, and difficult landing and take-off requirements. Furthermore, commercial UAV flights are currently banned in the US, and in Canada the UAV must remain within line of sight of the pilot at all times, even when the aircraft is capable of autonomous flight.

5. CONCLUSIONS

In this paper we demonstrated the potential applications of an emerging tool in natural hazard assessment. ‘Structure from motion’ photogrammetry allows for the creation of detailed 3d models of small (crown surfaces) or large (avalanche path) scale features, using only a set of overlapping photographs. The main limitations of the method can be solved using a GPS-equipped camera in many cases, or including some items of known size and orientation in the model area, for later calibration.

We tested the method for crown/fracture line studies, and showed that both the general shape and surface relief (fractographical) features of the crown can be modeled in 3d. We also showed that both avalanche terrain – snow covered or otherwise – and even the geometry of avalanche release areas can be modeled successfully, and discussed the applications to avalanche investigations or for mapping exercises in support of hazard mitigation projects, where the results can easily surpass what is available from Google Earth or even commercial DEM or orthophoto products, and may even surpass the fidelity of aerial LiDAR in some cases (e.g. Figure 1). Particularly for steep terrain (which is poorly captured in map products or with downward-looking sensors) and whenever time and efficiency are of the essence, photogrammetric modelling is an important tool for capturing avalanche and terrain features in three dimensions.

In this paper we discussed and tested three simple applications for avalanche studies. We did not describe the potential for quantitative change detection, where a 3d model from one time is compared to one from another, and any differences between the two are automatically mapped in 3d (see Gauthier et al, (2012, 2013, 2014) for examples of this on rock slopes and debris flows). This could be useful for accurate measurement of avalanche deposit volumes, snow supply monitoring, catchment maintenance, cornice growth, wind erosion and deposition, etc.

ACKNOWLEDGEMENTS

Thanks to Ruedi Beglinger for field support, and Mike Wiegele Heliskiing for field support and sharing of images.

MC and BJ thank the Natural Sciences and Engineering Research Council of Canada (NSERC), Parks Canada, HeliCat Canada, the Canadian Avalanche Association, Mike Wiegele Helicopter Skiing, Canada West Ski Areas Association, Backcountry Lodges of British Columbia Association, the Association of Canadian Mountain Guides, Teck Mining Company, the Canadian Ski Guide Association, Backcountry Access, the B.C. Ministry of Transportation and Infrastructure Avalanche and Weather Programs, the Canadian Avalanche Foundation, and TECTERRA for their support of ASARC.

DG thanks the Canadian Railway Ground Hazard Research Program, which includes CN Railway, Canadian Pacific, Transport Canada, NSERC, University of Alberta, and Queen's University, for support.

REFERENCES

Andrew, R., Arndt, B., and Turner, K. Instrumentation and monitoring technology. In: Turner, K. and Shuster, R. (eds), Rockfall characterization and control, Transportation Research Board, Washington, DC, pp 56-71, 2012.

González-Díez, A., G. Fernández-Maroto, M. W. Doughty, JR Díaz de Terán, V. Bruschi, J. Cardenal, J. L. Pérez, E. Mata, and J. Delgado. Development of a methodological approach for the accurate measurement of slope changes due to landslides, using digital photogrammetry. Landslides, 2013, pp. 1-14.

Gauthier, D., Hutchinson, J., Wood, D., Morris, A., 2014. Rockfall source detection and volume measurement from autonomous UAV- acquired photogrammetry: A case study from a transportation corridor in northwestern Ontario, Canada. Proceedings: 65th Highway Geology Symposium, Laramie, WY, 7-10 July 2014.

Gauthier, D., Lato, M., Hutchinson, J., and Edwards, T., 2013. An annual cycle of rock movements on a slope affecting the railway corridor in the White Canyon of the Thompson River, BC, from serial LiDAR scans. In: Proceedings, GeoMontreal – Canadian Geotechnical Conference, Montreal, QC, 29 September – 3 October 2013

Gauthier, D., 2012. Slab avalanche crown surface fractography: observations and applications. International Snow Science Workshop, Anchorage AK, Sept. 2012.

Gauthier, D., Lato, M., Hutchinson, J., and Edwards, T., 2012. Rockfall and talus accumulations from serial LiDAR scans: A railway case study from the White Canyon, Thompson River, BC. 65th Canadian Geotechnical Conference, Winnipeg, MB, Sept. 2012.

Haneberg, William C. Using close range terrestrial digital photogrammetry for 3-D rock slope modeling and discontinuity mapping in the United States. Bulletin of Engineering Geology and the Environment 67(4), 2008, pp.457-469.

Sinickas, A., and Jamieson, B., 2014. "Comparing methods for estimating beta points for use in statistical snow avalanche runout models", Cold Regions Science and Technology,104-105, pp. 23-32, 2014.

Sturzenegger, M., and D. Stead. Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts. Engineering Geology 106(3), 2009, pp. 163-182.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. 'Structure-from-Motion'photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology, 179, 2012, pp 300-314.

Whitehead, K., B. J. Moorman, and C. H. Hugenholtz. Brief Communication: Low-cost, on-demand aerial photogrammetry for glaciological measurement. Cryosphere 7(6), 2013.

Wolter, Andrea, Doug Stead, and John J. Clague. A morphologic characterisation of the 1963 Vajont Slide, Italy, using long-range terrestrial photogrammetry. Geomorphology, 206, 2013, pp 147-164.

Margreth, S., Faillettaz, J., Funk, M., Vagliasindi, M., Diotri, F., & Broccolato, M., 2011. Safety concept for hazards caused by ice avalanches from the Whymper hanging glacier in the Mont Blanc Massif. Cold Regions Science and Technology, 69(2), 194-201.