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Challenges from North to South
Des défis du Nord au Sud

On the precision, accuracy, and utility of oblique aerial photogrammetry (OAP) for rock slope monitoring and assessment

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ABSTRACT
In this paper we summarize our experience in testing and refining various applications of oblique aerial 'structure from motion' photogrammetry to rock slope monitoring and assessment. We tested this method at a number of Canadian railway rock slope sites using both autonomous-UAV and handheld-helicopter photography of steep, otherwise inaccessible rock slopes. We demonstrate that change-detection between detailed 3D slope models acquired at different times is possible, with lower detection limits in the range of 0.5 to 1m^3 given careful data collection and processing. We explore the precision and accuracy of this method, and demonstrate that both are comparable to other 3D remote sensing methods. While the advantages of this approach are rapid deployment at sites not amenable to other sensors, the limitations are in detection of small deformations, and uncertainties in the scale problem, which is ubiquitous in photogrammetric approaches.

RÉSUMÉ
Dans cet article, nous résumons notre expérience de test et d'amélioration des diverses applications de la photogrammétrie aérienne oblique «structure from motion» pour la surveillance et l'évaluation des pentes dans le roc. Nous avons testé cette méthode à un certain nombre de sites ferroviaires canadiens en utilisant à la fois un drone autonome et un hélicoptère portatif pour photographier les pentes rocheuses raides ou inaccessibles. Nous démontrons que les changements de détection des pentes, entre les modèles 3D détaillés acquis à des moments différents est possible, avec des limites de détection plus basses de l'ordre 0.5-1m3 et avec la collecte et le traitement des données minutieux. Nous explorons également des détails sur la précision et l'exactitude de cette méthode, et démontrons que les deux sont comparables à d'autres méthodes de télédétection 3D. Bien que l'avantage de cette approche soit un déploiement rapide sur les sites ne se prêtant pas à d'autres capteurs, les limitations résident dans la détection de petites déformations et les incertitudes dans le problème d'échelle, qui est omniprésent dans les approches de photogrammétrie.

1 INTRODUCTION

Recent advances in digital photogrammetric processing have made possible - and practical - many applications of photogrammetry to geotechnical and geological problems. For example, the 'structure from motion' (SfM) approach to photogrammetry utilizes the information contained in a large number of detailed, but otherwise not specialized, digital photos to automatically generate dense three-dimensional (3D) models of remote surfaces (See James and Robson, 2012; Westoby et al, 2012 for a detailed review of SfM and applications in geosciences). In contrast, previous approaches to digital photogrammetry relied heavily on calibrated cameras and lenses, and complex manual intervention in the scene and during pair-wise processing, often with inferior results in uncontrolled circumstances. This has meant that oblique photogrammetry has, until recently, been restricted to land-based photography (e.g. Sturznegger and Stead, 2009; Wolter et al., 2013), whereas the current study and others in this volume (e.g. Arenson et al, 2015; Kromer et al, 2015; Lato et al., 2015) have applied SfM photogrammetry to oblique aerial photographs.

In this paper we summarize our experience in applying the SfM method to the assessment and monitoring of steep rock slopes, using manually and autonomously collected oblique aerial photos. The main objective was to test the efficacy and potential applications of the oblique aerial photogrammetry (OAP) approach for 3D rock slope assessment and change-detection, at locations not amenable to other aerial and land-based remote sensing approaches such as aerial or terrestrial LiDAR (ALS, TLS) and photogrammetry.

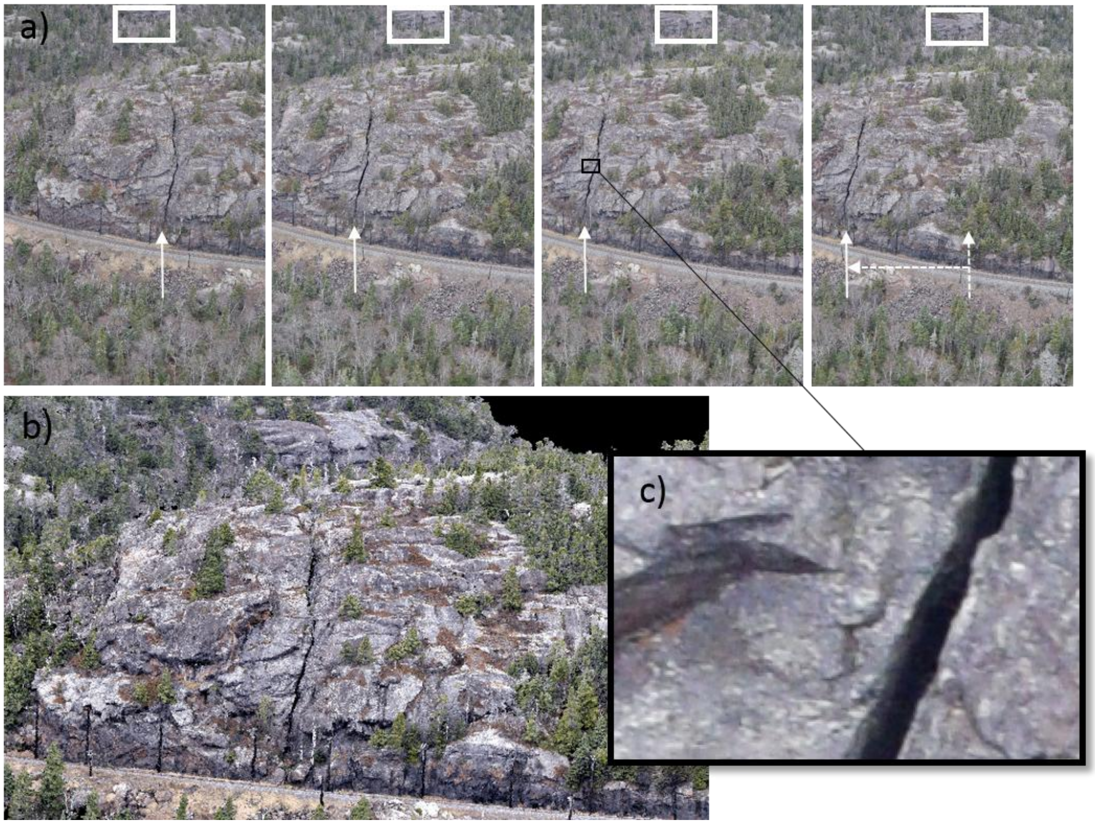

Figure 1. Example of (a) input photos for part of an OAP campaign; (b) resulting 3D point cloud for the area; (c) typical resolution of the input images required for a high level of detail in the models. CP Heron Bay Sub, Mile 81. Slope height approximately 30 m.

Many researchers and practitioners are exploring the applications of aerial photogrammetry using the SfM technique, in disciplines such as geology (e.g Vasuki et al, 2014; Fonstad et al., 2013), glaciology (e.g. Russell et al, 2014; Hugenholtz et al, 2013), hydrology (e.g. Javernick et al, 2014), and large-scale geohazards (e.g. Roberti et al, 2014), although we aren't aware of previous work using OAP for rock slope assessment.

From the geotechnical perspective, one reason to capture 3D models of steep rock slopes is for quantitative inspection and monitoring using 'change-detection', where serial models are compared quantitatively and in 3D (as opposed to 2.5d DEM-based approaches), and any differences between the two are mapped. Many of these model differences represent real change on the slope (e.g. rockfall), which occurred between the dates of the 3D data collection. Identifying rockfall in this way using LiDAR data has become relatively widespread, with limits of detection in the sub-cubic metre range (See Abellan et al 2014). Recently, however, very small in-situ block movements of a few mm have been detected using LiDAR data, and interpreted as evidence of progressive failure (Kromer et al, 2015). In this paper we evaluate the potential applications of the SfM method, using oblique aerial photos, for rock slope monitoring using change-detection, and test the potential of this method for use where other technologies are not appropriate.

2 METHODS AND DATA

James and Robson (2012) describe SfM photogrammetry, which is fundamentally the same as all photogrammetric approaches: it is an analytical method of solving the relative 3D locations of the cameras which captured a series of overlapping photos of a particular subject, and then solving the 3D coordinates of the matching pixels in each photograph, thereby mapping the surface of a remote object in 3D. For this study a typical approach would be to collect a few hundred photos, from which several hundred thousand image tie-points would be automatically identified, and from which a point-cloud output containing tens of millions of individual, unique points could be generated (Figure 1). We used the commercial SfM software 'Photoscan Pro' (Agisoft, 2015), and off-the-shelf camera equipment for this study. One general advantage of the SfM approach is the automatic lens-calibration and tie point selection, which means that other than the focal length and sensor size, no prior knowledge about the remote surface or the camera and lens are required at any point during model development.

We collected photos either using handheld, full-frame or cropped DSLR and mirrorless digital cameras in a moving helicopter, or automatically from a fixed-wing UAV. We generally found the helicopter approach to be more efficient for large areas, and generally lower cost than the UAV, although for smaller areas or locations not close to helicopter bases the UAV is surely a cost-effective and useful tool.

Change-detection was conducted using the free-ware package ‘Cloud Compare’, and its iterative closest-point (ICP) algorithm, and point-to-mesh distance routine (Cloud Compare, 2015). The main advantage of Cloud Compare (other than low cost) over many commercial software options is its ability to deploy the ICP and simultaneously adjust the scale of one model, so that the very fine alignment of two models of slightly differing scale (common in photogrammetry data) can be achieved without issue. The residuals of the fine alignment contain the real changes between two models (e.g. a rockfall), so a very close match at the fine alignment stage is critical. The general steps are: 3D point cloud > meshed surface > ICP alignment and scale adjustment > point-mesh shortest distance > map residuals (above detection limit).

The methods and insights we discuss in this study are based on oblique aerial photogrammetry (OAP) campaigns at numerous hazardous rock slope areas of different character along Canadian railway corridors in Quebec, Ontario, and B.C., using photos collected by an autonomous fixed-wing UAV (OAP-U), and manually from a moving helicopter (OAP-H). We collected OAP photos on multiple occasions for change-detection at three of these sites. In addition, we had access to data from several commercial deployments owned by industrial partners (see Arenson et al, 2015; Kromer et al, 2015; Lato et al, 2015). We used these data to investigate the practicable resolution, precision and accuracy of the OAP 3D data. We also tested a number of different approaches to the scaling problem inherent in photogrammetry, and evaluated the lower change-detection limits possible using OAP models.

3 RESULTS

3.1 Resolution, precision/accuracy, detection limits

The ultimate resolution of the 3D point cloud is limited by computing power, effective image overlap, and ground pixel size. The latter is in turn is controlled by camera sensor size and pixel count, effective lens focal length, and the distance between the camera and the remote surface (e.g. rock slope). For our studies, point-cloud resolution ranged from tens of points per square metre (OAP-U) to thousands of points per square metre (OAP-H). Higher resolutions are possible, but for large areas the data quickly become unwieldy, and the extra effort to generate such high resolution data yields diminishing returns. Given the range in achievable resolution, we suggest that the objectives of a practical deployment be considered independently, and a target resolution identified prior to fieldwork and processing.

We analyzed real-world precision by collecting two sets of photos of the same rock slope simultaneously, using two different cameras from slightly different vantage points, and comparing the results using the 3D change-detection method (e.g. Figure 2). In this case, with perfectly precise results we would expect to see no

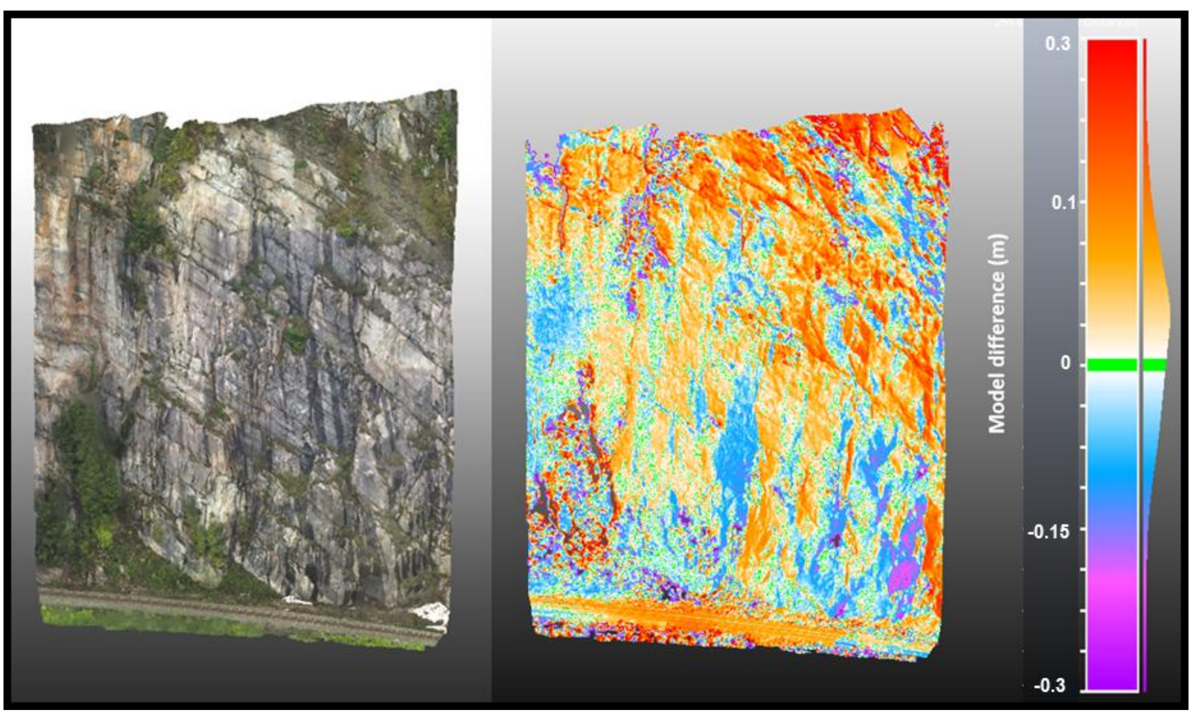

Figure 2. Comparison of slope models collected simultaneously using two different cameras to test precision. Image on right is the difference map for the area in the left image. The distribution of differences is indicated by the histogram along the colour scale, and shows that most (i.e. >95%) of the difference (i.e. precision) is +/- 0.15 m. CN Albreda Sub, Mile 55. Slope height approximately 80 m.

difference between the two datasets, and therefore any deviation is a measure of the imprecision between two. In this experiment we found that the model differences between meshed surfaces (generated by Photoscan, which deploys the Poisson Reconstruction; Kazhdan et al, 2006) were mostly in the range of +/- 0.15 to 0.2 m. This imprecision represents noise in the input point clouds and resulting model surfaces, ICP alignment error, and some small model differences between the vantage points of the cameras. The residuals are normally distributed, with a mean value very close to zero. The implication is that a change-detection signal smaller than +/- 0.15 m would be lost in the noise of the comparison between two models (Figure 2). Although some real change could have been detected within the noise, it would not be possible to differentiate the two, so +/- 0.15 m would be the practical change-detection limit.

For each change-detection analysis we plot the residuals in this way, and identify a unique limit of detection; in our studies this has ranged between approximately +/- 1 m (OAP-U) to +/- 0.15 m at best, with photos captured from a moving aircraft at a range of 250 m to 500 m from the subject slope. Note that the absolute value of the between-scan precision can be reduced with smaller ground-pixel size (i.e closer range), although in practice this would require very small study areas.

The precision values quoted above suggest that individual features on the order of decimetres in dimension could be detectable in the data. For discrete rock volumes, we expect that the practical change-detection limit of discrete blocks, spread over large areas, is probably on the order of 0.5 to 1 m^3, or near the hazard-threshold for some scenarios (e.g. rail operations). Smaller blocks may be detectable with more advanced processing, or additional effort. This is a focus of on-going research by the authors.

We assessed shape-accuracy (see below for scale accuracy) both qualitatively and quantitatively. Qualitatively, we find that features of known size and shape (e.g. retaining walls, rock bolts, vehicles, etc.) are recognizable down to about 0.15 - 0.2 m, beyond which the features may be identified, but their form is not captured (Figure 3). Quantitatively, we compared TLS, ALS, and photogrammetry data using the 3D best-fit approach outlined above. Although the LiDAR data are subject to precision limits on the order of a few centimetres in our studies, we would consider the LiDAR to be 'true' in this comparison. In most comparisons, we found that the distribution of residuals had an average close to zero, and a range of +/- 0.3 to 0.5 m. Note that the scales were matched as part of the alignment, so only shape differences (due to error, and real changes) contribute to this value.

3.2 Scaling and registration

One of the fundamental limitations with all photogrammetric analyses is that they are relative-only, until additional information on the scale, orientation, or georeference of the remote surface (and/or camera locations) are input (LiDAR data are natively scaled and leveled). Collectively these operations may be called

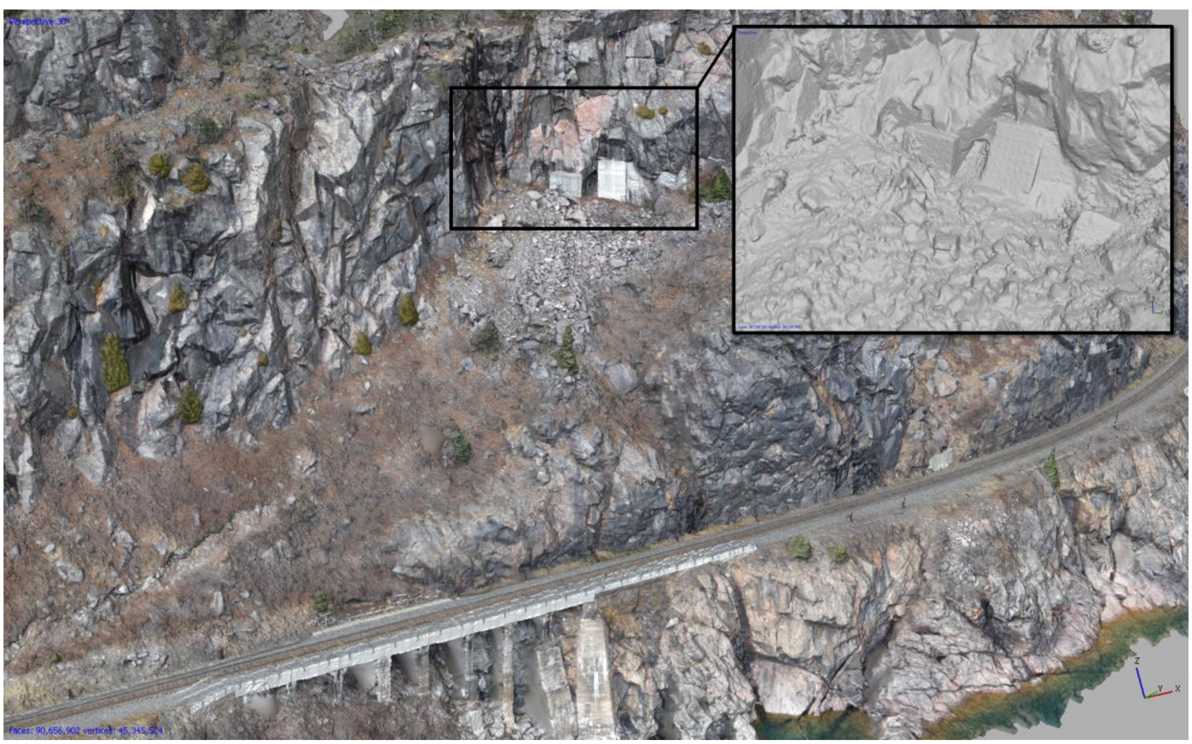

Figure 3. 3D model highlighting a practical level of detail achievable with OAP-H. Inset shows surface models of rock buttress, in which tie-back bolts are visible. CP Heron Bay Sub, Mile 72. Slope height approximately 100 m.

'registration' of the models. The level of registration required depends on the objectives of the problem: for simple unitless change-detection, no scale is required; for quantitative change-detection, the correct scale is important; for structural mapping the correct 3D orientation is critical; for a detailed slope assessment, both would be required. Georeferencing is required to connect the point clouds and models to other surveyed data or GIS products, with the additional benefit of solving the scale and orientation problems as well.

Note that the change-detection method does not explicitly require any ground control or georeferencing, as it relies on a point-by-point 3D alignment and matching of the 3D data; however, accurate volume estimation requires correct scale, which is often easiest achieved by registering the data in real-world georeference.

We tested several registration approaches in this study:

- Applying an approximate scale-bar, measured in the field and located manually in the 3D data for scaling only. This is simple and fast, but requires site access and no validation is possible;
- Collecting tens of ground-control points (GCP) in the field or in TLS/ALS data, located manually in the 3D data. This is labourious, and requires site access and/or supplementary 3D data. The results are georeferenced, except for TLS (scale and partial orientation);
- Making a 3D best-fit (ICP) alignment to TLS, ALS, or DEM. Precise georeferencing solution (except for TLS, as above), but requires access to additional 3D data
- Direct georeferencing through the use of in-camera geotagged photos, which is simple and fast, but still requires additional data for validation.

In our experience, geotagged photographs (in-camera, or with a peripheral device connected to the camera), while in no way required for a successful model, are very useful for registration. The software reads the coordinates automatically, and registers the resulting model in real world coordinates. Comparisons of uncorrected OAP data with properly georeferenced data (e.g. ALS) have shown that scale is normally within 5%, and often within 2-3%, of true; however, errors in the elevation and signal drift in the GPS typically lead to a vertical offset and slight rotation of the model coordinates, which is not possible to resolve without an additional validation data source, e.g. surveyed ground control or LiDAR.

Since one of the main advantages of the OAP method is that it doesn't explicitly require site access, and since one would often choose to deploy OAP where a slope of interest is otherwise inaccessible (e.g. no vantage point for TLS), some of the registration options would be either impractical or impossible (e.g. collecting ground control measurements on a high rock face).

That said, in many cases the real-world deployment of OAP will either follow or precede the collection of other data sources, e.g. aerial LiDAR. In those cases the 3D alignment routine makes for simple registration of all previous or subsequent OAP data. Either way, the registration problem is not trivial, and must be adequately treated before these data are suitable for application to geotechnical assessments or design.

3.3 Comparisons to other methods, limitations

The main benefits of OAP are its rapid deployment (particularly of OAP-H), interchangeability with other sorts of 3D data, high-fidelity and full-colour nature, and the ability to develop 3D models of slopes that are otherwise inaccessible. In general, OAP can be quick to deploy, very reliable, and precise and accurate enough for rock slope monitoring and assessment.

The registration problem presents an obvious disadvantage to this method. In our experience with both research and commercial deployments of OAP, the main reason to select this approach is because either 3D data are critical to solving a geotechnical problem but no other source is available or applicable, and/or because there is little or no lead time, and quick delivery of the 3D data is paramount. In both these cases, one accepts the limitations of OAP since its main upsides, remote access and rapid deployment and data delivery, are desirable.

3.4 Applications and deployment

With the general move toward risk-based, multi-hazard slope rating and assessment frameworks (See Pierson et al, 2012) has come an increased interest in incorporating remotely-sensed 3D data and analysis. Several reports in this volume (e.g. Arenson et al, 2015; Kromer et al., 2015; Lato et al, 2015) describe stand-alone applications of OAP to geotechnical problems; however, it seems that Ortiz et al (2015) are the first to report specifically on how OAP-H data, and change-detection analysis, could be included in the set of slope assessment and management parameters captured in a risk-based 'Geohazard Asset Management' system.

As with other 3D remote sensing approaches, a model which captures the 3D state of a slope (and threatened infrastructure) at a single point in time could provide the basis for detailed structural and geological mapping, site and construction plan development, remediation design, etc.; we have found that OAP can be used for these purposes, often where other approaches are unsuitable (e.g Figure 4). Furthermore, the detailed and full-colour nature of the data open up new possibilities. For example, Lato et al (2015) report on a case where rockfall hazard was very precisely characterized, without the need to estimate block size/volume or fall height distributions, because the OAP slope model allowed these parameters to be *measured* rather than estimated – all from the desktop. While this in no way nullifies the need for careful fieldwork and 'boots on the ground' investigations, it does to some extent allow the engineer or geoscientist to be more efficient in their approach to fieldwork, and in many cases provides

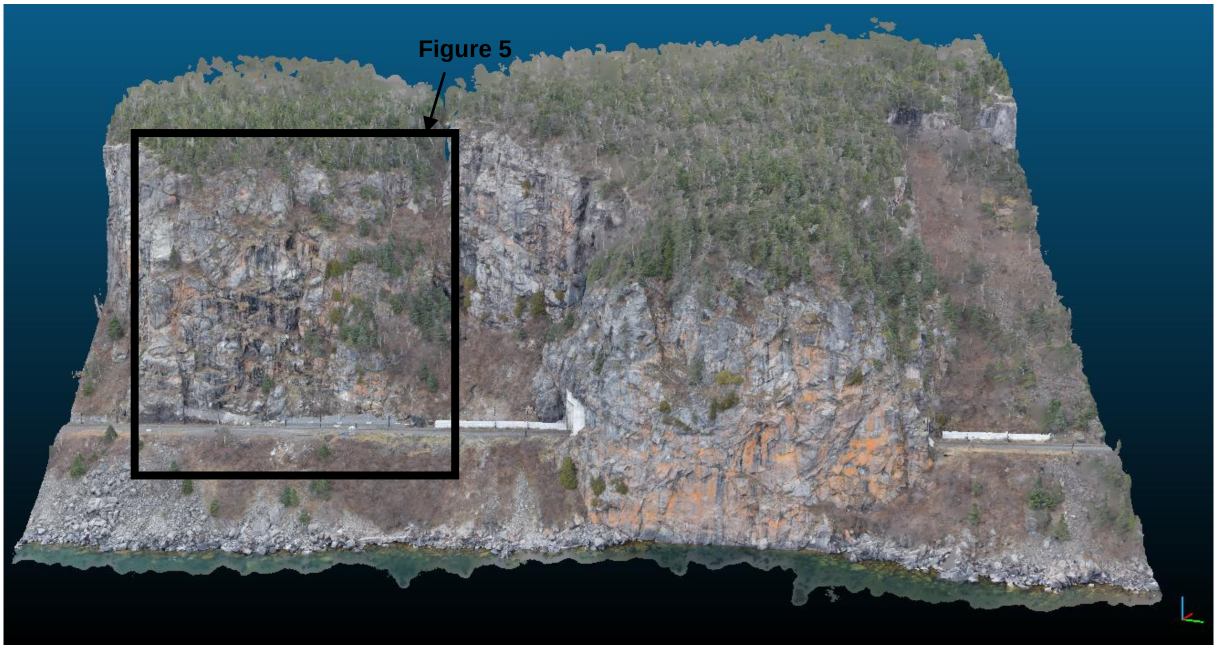

Figure 4. Section of slope studied using OAP-U and OAP-H in 2012, 2013, 2014, with area of Figure 5 indicated. CP Heron Bay Sub, Mile 71. Slope height approximately 100 m.

access to slopes that cannot be reached by traditional approaches, nor, for that matter, with other remote-sensing technology. And, perhaps most importantly, a first-time slope model can be used as a baseline dataset for future change-detection analysis.

While geological and geotechnical analysis is critical to hazard characterization, one of the key inputs to most risk-based slope assessment frameworks is some index or measure of the level of activity or frequency of the occurrence of a given hazard. These frequency inputs would traditionally be gathered through field inspections involving general subjective comparisons to earlier conditions and in some cases manual comparisons of previous oblique aerial or ground-based photographs, and of course through (often truncated, biased or unreliable) incident and maintenance records. As we have demonstrated, 3D change-detection using OAP, independently or in combination with other remote-sensing technologies, offers the potential to do this quantitatively, and to produce accurate change-maps of rock slopes, particularly for rockfall hazards. The areas of 'change' or difference between serial 3D models must be carefully reviewed (e.g. Figure 5), but in general discrete block rockfalls and other large-scale displacement events are recognizable, provided they exceed the limit of detection (usually decimetres) for a given survey. This approach to rock slope inspection means that manual, in situ comparison of current conditions can be avoided, as can the potential pitfalls of incomplete or biased occurrence records, thereby freeing the time and effort of the experienced engineer or geoscientist to focus on the more esoteric or nuanced parts of the slope assessment. The 3D change-maps may be archived as part of the inspection record, used to guide follow-up analyses or remediation, and may be converted (via count, volume, etc) into a quantitative frequency-magnitude parameter for the rating or assessment system. All of these may be especially valuable for slopes that are otherwise inaccessible, or are not visible (for the purposes of inspection) from a convenient location (e.g. high natural slopes above a linear infrastructure right-of-way).

The deployment of OAP can range from ad-hoc, broad opportunistic surveys (i.e. already in a helicopter with a camera) to targeted approaches to small areas. The range in time, effort, fidelity, detection-limit, and cost is wide, and largely depends on the target resolution, and the precision of the 3D data. We conducted some preliminary tests of the relationship between field and processing effort and the quality of the results, and our results suggest that:

- Photographs captured with a modern digital SLR camera are very much preferable to point-and-shoot or other small devices, although good quality OAP models can be produced from most decent cameras
- Full-frame super high-resolution images are not *required*, but all other things being equal the resulting model will be superior to one generated from smaller images; however, in many cases the full-frame photographs at full-resolution are difficult for file transfer and processing, and are subsampled during the point-cloud generation stage. Furthermore, there is certainly a fundamental diminishing returns function for point-cloud and model density, and for many geotechnical problems speed and efficiency may be more important than resolution.
- 3D models adequate for basic geometric and structural interpretation can be captured from a

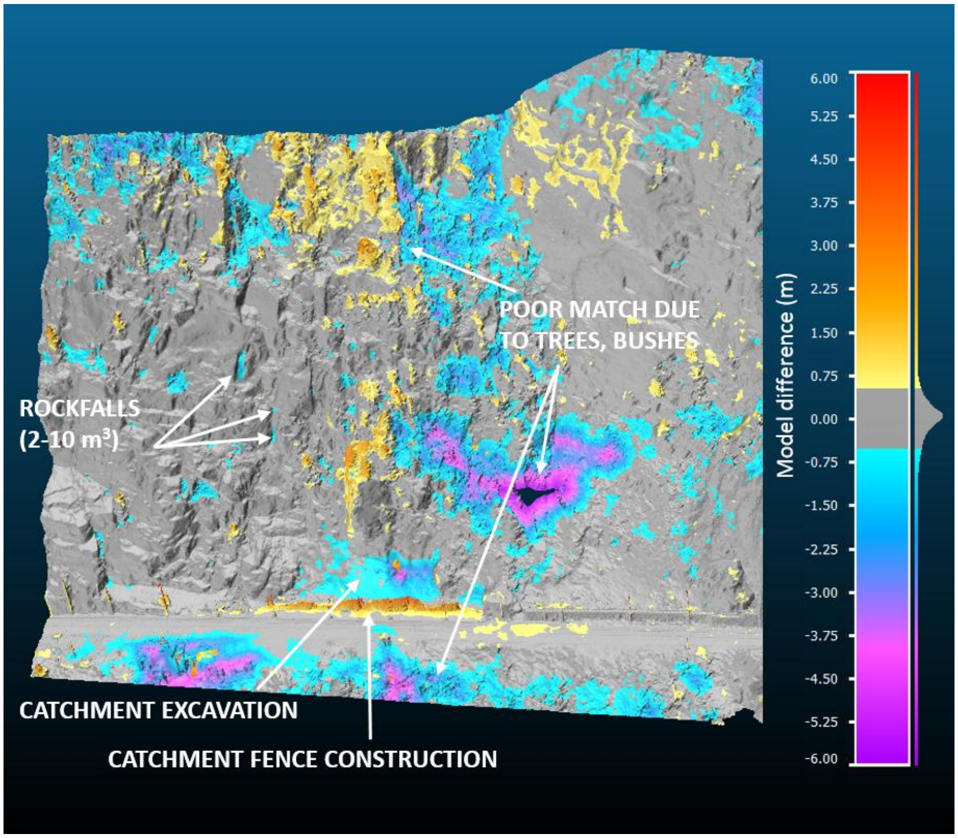

Figure 5. Difference map for section of slope indicated in Figure 4, comparing OAP-U from 2012 with OAP-H from 2014. Both GCP and geotagged photos were used for scale. Distribution of difference and limit of detection indicated in histogram and grey bar to right of colour scale. See Gauthier et al. (2014) for more detail on the rockfall, including volume calculations. CP Heron Bay Sub, Mile 71. Slope height approximately 100 m.

single flight pass from a wide vantage point, and at relatively high speed (e.g. a few km from the slope, flying at 50km/h). Full processing of such surveys would be less than 1 hour per km. For detailed investigation or change-detection much closer, slower flight paths are required. Hundreds of photos collected from multiple elevations, plus many hours of processing per km would be the norm. Even more detail could be gathered or much smaller areas, at a similar level of detail

4 CONCLUSIONS

Our experience with applying OAP to rock slope monitoring and assessment problems has shown that: precision of 10 cm to 20 cm is achievable; raw scale-accuracy in the range of 2% to 5% is typical, in some cases even in the absence of ground reference; and shape-accuracy at a similar level to, although noisier than, aerial or terrestrial LiDAR can be expected in general.

The main benefits of OAP are its rapid deployment (particularly of OAP-H) and data delivery compared to other aerial approaches; interchangeability with other sorts of 3D data; high-fidelity and full-colour nature; and the ability to develop 3D models of slopes that are otherwise inaccessible. In general, OAP can be quick to deploy, very reliable, and precise and accurate enough for rock slope monitoring and assessment. Particularly for regular inspection or emergency response, when an engineer or geoscientist is often already in a helicopter, with a camera in hand, the added value of OAP far outweighs the additional effort of collecting extra photos.

Further research is required to refine the preliminary results presented here, and to develop further expertise in the applications of the method to steep rock slopes. We expect rapid advancement in both the research and practical/commercial deployments of SfM, once its full potential is recognized by the broader geotechnical community.

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