Railway Ground Hazard Research Program Update: Rock Slope Hazard Assessment

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ABSTRACT
Rock slope stability assessment is enhanced by the collection and interpretation of remotely sensed data from both terrestrial and aerial sources. Analysis of the data at the network scale, using airborne data, permits us to identify large natural slopes which may be the source of rock failures onto the infrastructure below. Focusing in on these slopes, using higher resolution, sequential data sets, generates a wealth of information which can be used to assess stability, including: identification of rock slope failure events, back analysis of rockmass conditions including failure mode identification, consideration of deformation rate and style prior to failure, block shape, volume and failure surface analysis, and triggering events. Similar analyses are done to characterize the hazard created by active talus slopes. The outcomes of this work can be used as case histories to calibrate rockfall models which will in future be used to assess potential hazards as they arise, and to focus rock slope hazard management activities.

RÉSUMÉ
L'analyse de la stabilité des pentes est grandement améliorée par l'utilisation de données obtenues à distance à l'aide d'outils avec prise de vue terrestre et aérienne. L'analyse de données provenant d'une source aérienne fournit une résolution à large échelle permettant l'identification de larges pentes et traits naturels pouvant causer des effondrement sur des infrastructures. L'étude détaillée de pentes, en utilisant des ensembles de données séquentielles temporelles à haute résolution, permet d'analyser la stabilité des structures, de même qu'identifier des événements de rupture de pente rocheuse passé. Ainsi, le mode, le taux de déformation, le style avant la rupture, les conditions du massif rocheux, y compris la forme du bloc, la surface du volume et de la rupture, et les événements déclencheurs peuvent être étudiés en détails en utilisant de telles donnés. Des analyses similaires sont effectuées pour caractériser le danger créé par les talus actifs. Les résultats de cette étude peuvent être utilisé à des fins de calibrations pour des modèles de chutes de roches. Ces modèles peuvent à leur tour être utilisés afin d'estimer le potentiel de rupture à des fins de gestions de risques.

1 INTRODUCTION

The Canadian Railway Ground Hazard Research Program is entering the 14th year of collaborative research and development. Working together with the University of Alberta, CN Rail, Canadian Pacific, Transport Canada, and the Geological Survey of Canada, the team has identified and conducted research with a practical outcome on a number of different issues affecting the railways.

In this paper, we will provide an update on the extensive research work conducted on the identification of potential failure of rock slopes adjacent to the tracks, the anticipated failure mechanisms, and the ability to provide warning in advance of failure to permit mitigative efforts to be undertaken. Utilizing aerial (fixed wing aircraft, helicopter and Unmanned Aerial Vehicle - UAV) and terrestrial data from LiDAR and photography from multiple view points and at various scales, we have collected data for a number of years from active rock slopes. Following a framework developed to identify potential source zones from larger scale data, permits us to focus on sites requiring more frequent and more detailed data collection and analysis, utilizing more focused investigation methods.

The data sets included are from a number of sites along railway infrastructure in British Columbia.

2 USE OF REMOTE SENSING TECHNIQUES

The effective use of remote sensing techniques for rock slope stability assessment has been demonstrated by a number of authors (Sturzenegger and Stead, 2009; Telling et al, 2017; Francioni et al, 2018), and can include a variety of data acquisition methods and vantage points. In the case of the rock slopes discussed in this paper, multiple approaches have been taken, in order to evaluate the data collected by different techniques (Fig. 1) and to examine the effectiveness of merging different data sets.

Figure 1: Remote sensing techniques used for rock slope stability analysis in the RGHRP project.

When combining the data from the different vantage points and sources, one has to be careful that the required accuracy and precision of the resulting three dimensional object is sufficient for the investigation, and that it optimizes the use of the remotely sensed input data to reduce the amount of occluded zones within the geometrical model. This concept is discussed in more detail by Lato et al (2015a, 2015b). In this paper, we focus specifically on the use of LiDAR data and photographs.

Remotely sensed data can be used: at the network scale, over 10's to 100's of kilometers, generally collected using airborne methods; at the corridor scale, over 10's to 100's of meters, using airborne and/or terrestrial methods; or at the site scale, over 1 to 10's of meters using closer range terrestrial methods. The work flow for moving through the stages of the search phase, considering progressively denser point clouds is discussed by Gauthier et al, (2017), with the key steps shown in Figure 2.

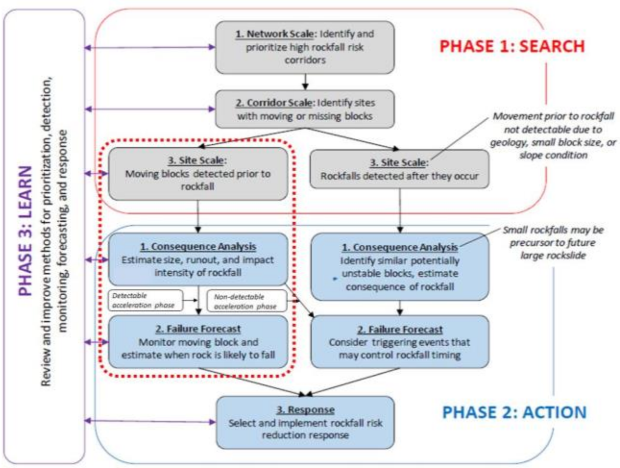

Figure 2: Workflow for rockfall failure forecasting and mitigation (from Gauthier, et al, 2017).

3 CORRIDOR SCALE ANALYSIS

One of the major challenges for infrastructure hazard assessment is the issue of large, natural rock slopes located at substantial distances above the railway infrastructure. Identifying potential source zones that may have an impact on the track below is challenging – there are many 1000's of kilometers of track with this potential. Remote sensing, conducted initially at the network scale, provides the basis for an assessment of these hazards. The identification of a reasonable risk decision approach to manage these hazards is difficult, due to the low frequency and high consequence of these types of failures, and is subject to continuing data collection and definition of appropriate procedures and work flows.

Lower density data (<10 points / m^2) over a large area can be used to identify rock slopes with a higher probability of generating rockfalls (Fig. 3). Utilizing aerial LiDAR data, Carter et al (2018) discriminate between vegetation and bare exposed rock, and rock outcrops and talus slopes (Fig. 4) to identify slopes to be further assessed.

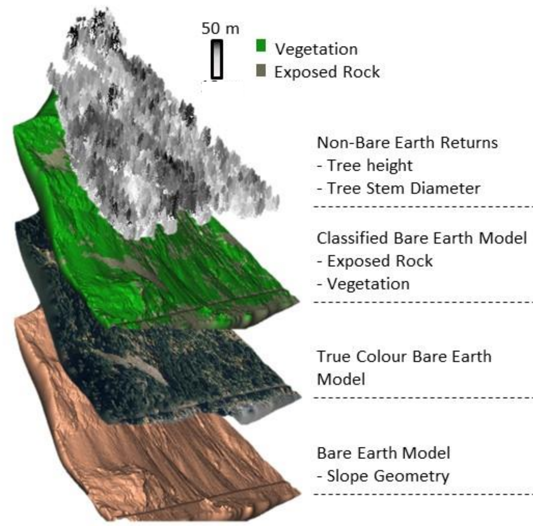

Figure 3: Corridor scale slope analysis to identify potential high rockfall activity sites, from aerial LiDAR and photography (from Carter et al, 2018).

Work is ongoing to consider the interpretation of vegetation patterns, including the tree height and diameter (Figure 3), so as to define where rockfalls have been active and have damaged vegetation, or where vegetation provides an effective natural barricade to attenuate rockfalls, as discussed by Dupire et al (2016), thereby reducing the risk to the underlying infrastructure. The outcome of the work is to identify sites which pose higher hazards and should be assessed in more detail at the site scale.

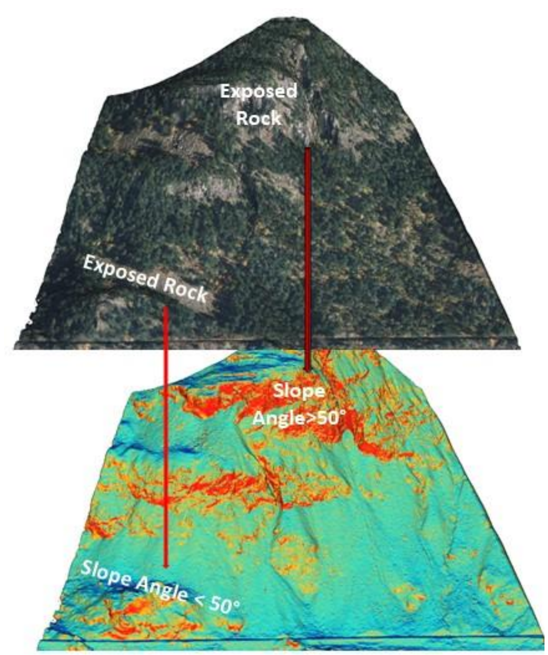

Figure 4: Classification of vegetation, talus and rock slope angle from the data types shown in Figure 3 (from Carter et al, 2018).

4 SITE SCALE ANALYSIS – ROCKFALL EVENTS

The objective of the analysis of slope condition at the network scale is to focus attention on higher probability sites at the local, site scale. At the site scale, the stability of the slope can be evaluated from comparison between higher resolution data, generally collected more frequently. At the frequency of terrestrial LiDAR scans shown in Figure 5, the patterns and magnitude of pre-failure deformation can be determined by comparing sequential data sets. In this case, back analysis after a 2600 m^3 failure in the White Canyon, BC, showed that small volume rockfalls ranging from 0.01 to 18 m^3 occurred from around the perimeter of the eventual fall, indicated that the material showed signs of deformation for as many as 200 days before failure, and demonstrated that the upper part of the main block displayed accelerating deformation greater than 8 cm, just prior to failure (Kromer et al, 2015).

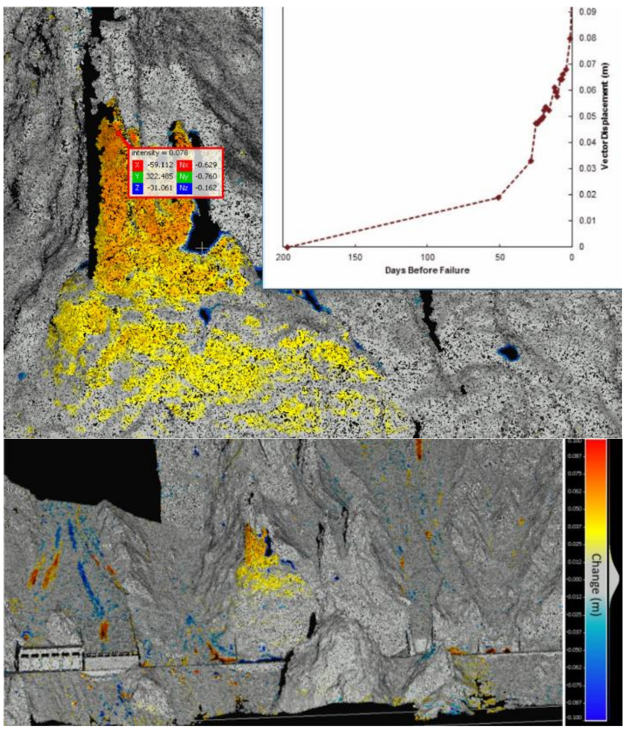

Figure 5: Detection of change from a series of LiDAR scans of the rock slope, including material loss (blue colour scale) and material gain (red colour scale). In the lower image, the rock is deforming towards the canyon, in the months prior to slope failure (from Kromer, 2017).

Most of the rock slope failures identified from analysis of data collected over the six year period of this study are smaller volume events, less than 10 m^3. One such event, shown in Figure 6, failed by sliding on the plane identified during the post-failure scan. Ongoing research is evaluating the relationship between the directional roughness of such joints, with the failure plane dip, and the magnitude of deformation recorded before failure (Graham et al, 2018). The conceptual model of the expected deformation style, shown in Figure 7, whether by translation or rotation, is being developed to understand the relationship between failure mode and warning thresholds (Rowe et al, 2017a).

Figure 6: Analysis of a fallen block, showing from left to right: Surface of block prior to failure, back fracture following failure, visualization of the detached shape from behind and analysis of the roughness of the sliding surface. (after Graham et al, 2018).

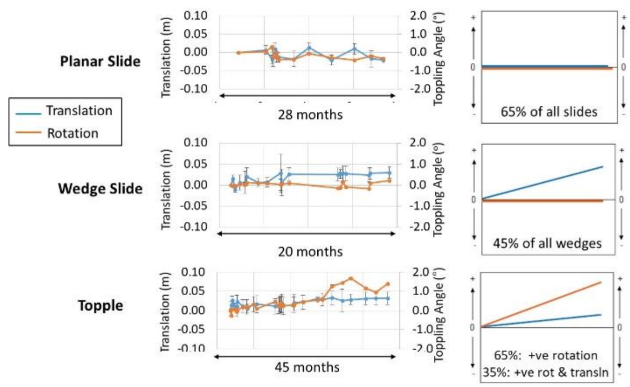

Figure 7: Consideration of the block motion and magnitude of deformation relative to failure mode (from Rowe, 2017).

Combining the individual rockfall events into a database permits detailed analysis of the rockfall history and characteristics, including the frequency and magnitude dependent upon the lithology. This information can be used to prioritize slope mitigation activities across a complex slope.

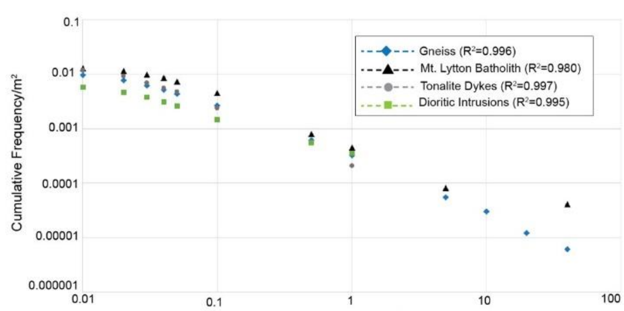

Figure 8: Frequency – magnitude of rockfall events, by rock type in the White Canyon (from van Veen, 2017).

As the data base is further developed over time, with a longer record, the influence of weather on the events can be considered. A general data trend can be seen in Figure 9, from the Goldpan rock slope also located along the Thompson River, where the frequency of events is highest during the periods when freeze-thaw cycles are more active and when there is more precipitation. This analysis, however, must be considered within the context of when the scanning was conducted. At a minimum, site visits have been conducted every three to four months, weather permitting, as the scanner cannot be operated in wet weather or freezing temperatures. The data is not continuous, and therefore, the data presented in Figure 9 is not reflective of the specific timing of all of the rock slope failures.

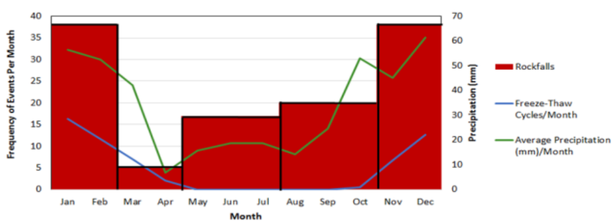

Figure 9: Relationship between rockfall events and weather (from Kromer, 2017).

When one considers the design of a scanning program, it is also important to think about the frequency of scanning from the perspective of the volume of loss recorded. In Figure 10, the left-hand image shows the volume of loss indicated by change calculated between LiDAR scans collected 15 months apart. During this period, six distinct scans were collected, with dates shown in the right-hand image. A number of the apparent larger volume events shown on the left, are in fact comprised of a series of smaller volume events occurring across a spatially contiguous section of the rock surface as seen on the right. The frequency of data collection can have a significant influence on the data collected, and the resultant frequency-magnitude relationships, depending upon whether individual and temporally distinct rockfall events are merged together as a result of less frequent scanning.

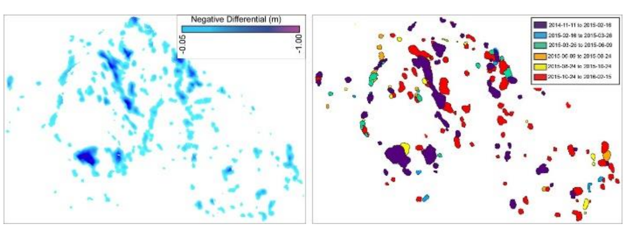

Figure 10: Identification of rockfalls, considering: left) the distribution and volume of detached blocks over a 15 month period, and right) the spatial distribution of the block failures from seven sequential LiDAR scans (from van Veen, 2017).

A number of researchers are developing continuous monitoring programs, which also have the advantage of providing near-real time warning of impending instability events (Kromer et al, 2017). This is particularly useful where there is an impending failure (based on our site knowledge, rockfall history, etc.), in order to detect small precursors and deformation in real time. It isn't feasible, nor is it necessary, to do this all the time at every slope.

5 SITE SCALE ANALYSIS – TALUS MOVEMENT

Time-sequential data analysis can be used to develop a more detailed understanding of rock slope talus movement, morphology and triggers. Analysis of change detection results for talus slopes, as shown in Figure 11, permits the detection of rockfall events onto talus slopes, and the volume and spatial extent of movement events including the change in the source area higher on the slope and the accumulated debris at positions lower on the slope.

One of the significant challenges with this type of analysis is that the bedrock base of each talus channel is rarely exposed, so the total volume of retained material is not known. In addition, talus can be entrained during the movement episode, with the result that talus flux volume calculations and projections are approximate.

The movement of the talus can be triggered by a rockfall event disturbing the underlying talus, by weather related triggering events, or possibly both. Preliminary analysis of weather influences on the slope stability is shown in Figure 12, where it can be seen that talus volume increases during the summer and fall months. The timing and volumes mobilized are an important consideration for infrastructure operation and management of maintenance.

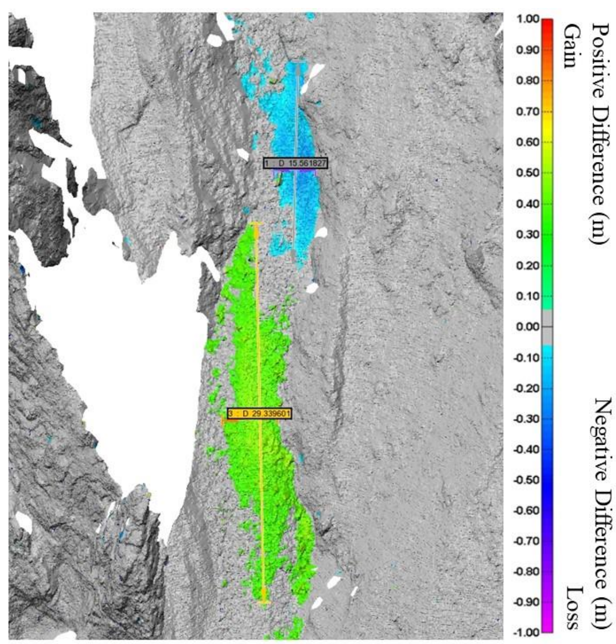

Figure 11: Position of the talus on the rock slope, showing loss and gain of material (from Bonneau, 2017).

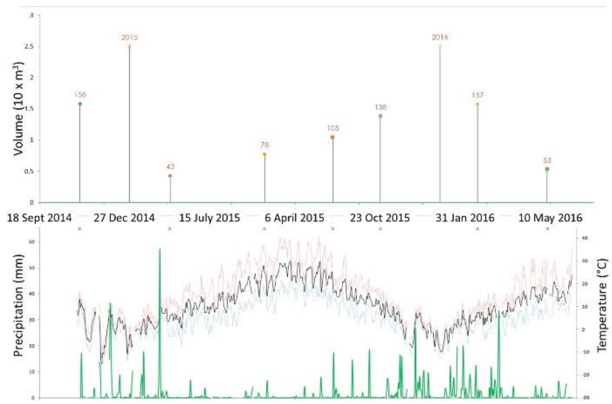

Figure 12: Relationship between talus volume accumulation (upper) and weather events (lower) (from Bonneau et al, 2018).

6 INFRASTRUCTURE HAZARD ASSESSMENT - EVENT SIMULATION

The application of remote sensing techniques, and change detection to evaluate slope detachments, accumulations and movements, provides valuable information for rockfall event simulation. With more frequent scanning, single events can be identified, including source volume and location, evidence of impact points, as well as accumulation volume and location at the toe of the slope. High-resolution remote sensing datasets allow us to simulate rockfall using highly-detailed slope and rockfall geometries, better incorporating measured surface roughness, as well as rockfall shape and size.

The analysis of a 1.4 m^3 failure event is shown in Figure 13. The source zone is located in gneissic host rock approximately 25 m above track level and cross-cut by tonalite dykes (a). Change detection of the event (b) was used to identify the source zone, extract the back and front surfaces of the failure (c), and map visible structure in the source zone (d). This information can be used to simulate slope failures which disaggregate along modelled discontinuities (e), comparing simulated trajectories (f) to identified accumulations and impact points from the change detection. Work investigating the performance and accuracy of these simulations is ongoing, and now includes processes such as talus-debris interaction.

7 CONCLUSIONS

Remotely sensed data for rock slopes provides an unprecedented suite of high quality data, which can be used for a variety of different analyses, focused on managing the hazard to underlying infrastructure. On a network scale, ALS data and orthoimagery can be used to identify potentially hazardous slopes which require a focused effort. TLS data can be used at the slope scale to assess rockmass conditions and identify slope failures and talus movement. Detection of the rockmass conditions, source and impact locations, volume and shape permits development of a detailed database of events, including failure mechanics which can be used to calibrate rockfall simulations. permitting analysis of the detachment mechanics, frequency and magnitude of events, and provides cases for rockfall trajectory simulation calibration. When weather triggers related to detected rockfall deformation or talus accumulation can be discerned, rock slope work and infrastructure maintenance (Figure 14) can be further optimized and the outcomes tracked and assessed. Assessment of pre-failure rock deformation can be used to develop deformation thresholds for a given slope or failure style. Where slope failures are imminent, these methods can be combined with higher-frequency or continuous monitoring to provide warning to the railway operators.

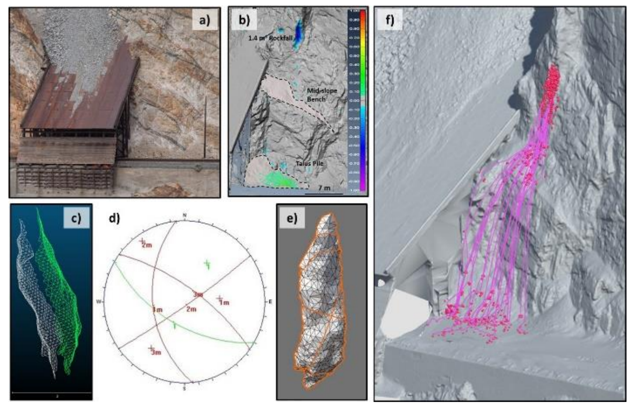

Figure 13: Validation of rockfall modelling tools using LiDAR derived data (after Sala, 2017). a) photograph of section of slope where failure occurred, b) LiDAR data showing slope morphology, c) model of the failed rock from before and after scans of the rock slope, d) visualization of the rock block including location of joint planes in Blender, and e) results of rockfall simulation of the failure event described.


Figure 14: Ditch maintenance – White Canyon slopes.

8 ACKNOWLEDGEMENTS

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