A Comparison of Rockfall Models Calibrated Using Rockfall Trajectories inferred from LiDAR Change Detection and Inspection of Gigapixel Photographs

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ABSTRACT
Light detection and ranging (LiDAR) technology can be used in the study of rock slopes to characterize rock face conditions, classify discontinuity sets, and monitor slope activity. Monitoring through change-detection analysis allows for the measurement of rockfall scar volume, determination of detachment areas, and the measurement of deposition volume and location. This study uses high resolution LiDAR data to infer rockfall path and breakup and uses this information in the comparison and calibration of three rockfall simulation programs. In this paper, we focus on one 18 m^3 rockfall event. The modelling software Rocfall and RockyFor3D, are industry-standard simulation programs; we used them in two forms. First, using an estimation of the rock parameters gathered from gigapixel photography and LiDAR data, we compared the run out distances and the trajectories predicted by each model. We also tested a third model using the Bullet Physics engine, which provided a full 3D representation of the surface and allowed for the most realistic simulation of the block dynamics. We found that change detection allowed us to accurately interpret the rockfall path and fragmentation of a rockfall event and that the full 3D representation of the rockfall using Bullet Physics most accurately matched the interpreted paths.

RÉSUMÉ
Light detection and ranging (LiDAR) de la technologie peuvent être utilisés dans l'étude des pentes rocheuses à caractériser les conditions de visage de roche , de classer de discontinuités , et de surveiller l'activité de la pente . La surveillance par l'analyse du changement de détection permet de mesurer le volume des chutes de pierres cicatriciel , la détermination des zones de détachement , et la mesure du volume de dépôt et l'emplacement. Cette étude utilise les données LiDAR à haute résolution de déduire chemin chutes de pierres et de la débâcle et utilise cette information dans la comparaison et l'étalonnage des trois programmes de simulation les chutes de pierres . Dans cet article , nous nous concentrons sur un 18 m3 cas de chutes de pierres . Le logiciel de modélisation Rocfall et Rockyfor3D , des programmes de simulation standard de l'industrie ; nous les utilisons dans les deux formes . Tout d'abord, en utilisant une estimation des paramètres de roches recueillies auprès gigapixels photographie et données LiDAR , nous avons comparé les distances s'épuiser et les trajectoires prévues par chaque modèle .. Nous avons également testé un troisième modèle en utilisant le moteur de Bullet Physics , qui a fourni une représentation 3D complète de la surface et a permis la simulation plus réaliste de la dynamique de blocs. Nous avons constaté que la détection de changement nous a permis d'interpréter avec précision la trajectoire de chutes de pierres et de la fragmentation d'un événement chutes de pierres et que la représentation 3D complète de l'éboulement utilisant Bullet Physics identifié plus de précision les chemins interprétés.

1 INTRODUCTION

Rockfalls are one of many geohazards that affect Canadian railways, especially in Western Canada's Cordillera region, causing damage to infrastructure and service interruptions (Keegan, 2007, Lan et al., 2010). The use of terrestrial light detection and ranging (TLS) is becoming state of practice in evaluating rockfall hazard on rock slopes, see Jaboyedeoff et al. (2012) for a complete review. TLS can be used for kinematic and structural analysis of rock slopes (Oppikofer et al. 2008; Sturzennegger and Stead, 2009; Lato et al., 2009), for hazard mapping and trajectory modelling (Lato et al., 2009; Lan et al., 2010) and for monitoring rock slopes (Rosser et al. 2005; Lim et al. 2005; Lato et al. 2009; Abellán et al. 2010).

Hazard assessments of rock slopes can be improved using high resolution LiDAR data. It permits enhanced analysis of slope topography, rock block geometry, rock travel paths and breakup. An important consideration in rockfall hazard assessment is the evaluation of trajectories of detached blocks. Rock fragmentation along this trajectory is also relevant because of the possibility of the fragments following much different paths than that of the original intact block. The purpose of this study is to leverage the information contained in high-resolution datasets to calibrate and compare three rockfall simulation methods: Rocfall (Rocscience, 2013), RockyFor3D (Dorren et al., 2014) and the Bullet Physics Engine (Coumans, 2010). We completed this comparison for one 18m^3 rockfall event, identified during a monitoring campaign in May 2013 of the Thompson River British Columbia. The model was calibrated using it's the path and breakup of the block from its source area to its area of deposition, interpreted from LiDAR data collected over successive dates at the site.

1.1 Site Description

The White Canyon is located approximately 4 km North-East of Lytton, British Columbia, along the Thompson River (Figure 1). The north side of the river at White Canyon is traversed by CN railway (mileages 93-95 Ashcroft subdivision), a single track on a 10-20m wide bench cut into the toe of the slope. The slope itself is up to 500 m tall characterized by a highly variable morphology composed of vertical outcrops of competent rock and eroded gully features partially filled with talus deposits that lie at an average angle of 35 degrees. A short tunnel section through a prominent ridge of more competent rock separates the 2.5 km length of track into two segments, east and west. The rock outcroppings are composed of fractured, foliated amphibolite and quartz feldspathic schist with intrusions of tonalite, quartz diorite and granodiorite (Brown, 1981). The intrusions commonly form vertical spires, which are prone to rockfall events. The rockfall event of interest in this study was located at approximately mile 94.3 at height of 41.3 m above the tracks (Figure 2) and occurred at some time between May 8th and May 11th.

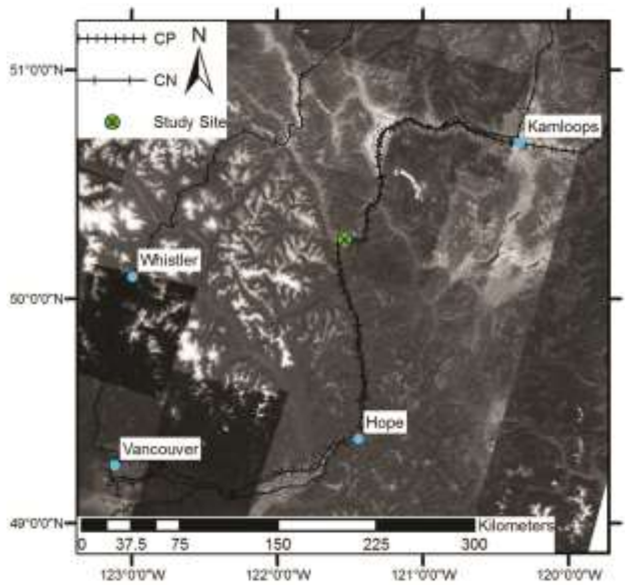

Figure 1: Location map of the study site.

2 METHODS

In this study, an Optech Illris 3D-ER laser scanner was used to collect high spatial resolution point measurements of the north slope of the White Canyon from a single station located on a terrace on the opposing end of the river valley. To avoid superposition of events, only LiDAR point clouds obtained directly prior and after the observed rockfall event were used for change detection analysis (May 8th and May 11th). Mean distance to the area of interest was 325 m with a mean point spacing of 0.1 m.

Data processing was performed using Innovmetric Polyworks V12 (Innovmetrics, 2013) according to standard change detection methodology (Rosser et al., 2005; Lim et al., 2006; Oppikofer et al., 2008; Lato et al., 2009).The IMAlign module was used to align point clouds obtained from successive scans. This was done by first using a rough alignment by picking similar point pairs in-between scans followed by a best fit algorithm which implements the iterative closest point algorithm (Besl and McKay, 1992; Chen and Medioni, 1992). Triangulated surfaces of each point cloud were computed in the IMerge module in which the Delaunay triangulation was implemented (De Smith et al., 2007). Surface comparisons were conducted in the IMInspect module using the shortest distance comparison. A colour map was generated to visualise the distances between both surfaces. Volumes were calculated in the IMInspect module of Polyworks using the surface to plane command.

Figure 2: Site photo of the location where the 18 m^3 failure occurred.

To complement the high resolution LiDAR data, a high resolution gigapixel panorama was collected on May 24th. Gigapixel panoramas consist of stitched high resolution photos of individual sections creating a single high resolution panorama. Photographs were collected using a Nikon D800 camera, equipped with a 135 mm lens. The camera was mounted on a tripod with a GigaPan brand robotic head from the same scan station used for LiDAR data collection. Stitching of photographs was done using GigaPan's 'Stitch' software. Detailed description of the use of gigapixel photography in engineering geology can be found in Lato et al. (2012).

2.1 Modelling Procedure

We applied two different rockfall modelling methods (Rocfall and Rockfor3D) and a novel approach using the Bullet Physics engine. The rockfall models both require a classification of the material distributed on the slope in order to realistically replicate the rockfall trajectories. We completed this classification using the Gigapixel photography of the area and locating the different lithologies and the different impact areas. There are four different zones that we classified on the slope (Figure 3):

1. The bedrock material and source area: Outcrops composed of gneiss including the source area. The source area block consisted of a vertical spire feature.
2. Ledge features: Ledge that is steeper than the friction angle of the talus material resulting in no accumulation.
3. Talus Accumulations: Areas shallower than the friction angle of talus material. These areas have higher rockfall penetration depths and a rockfall impact would result in loss of material.
4. Ditches: High accumulation of talus and low restitution. These areas are designed to catch material resulting from rockfall.

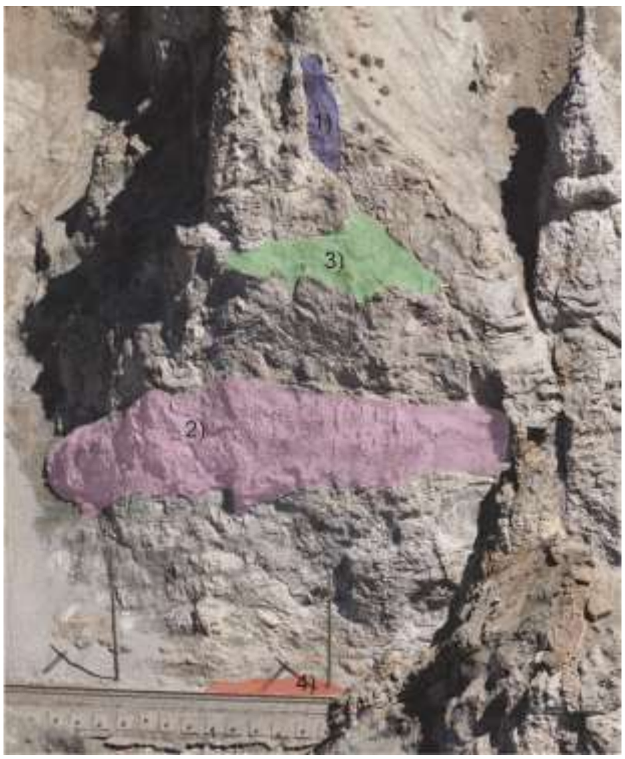

Figure 3: Gigapixel image of the site identifying characteristic areas: 1) Bedrock Material and Source Area; (2) Ledge features; (3) Talus Accumulations; and (4) Ditches. The non-coloured area was modelled as bedrock or was outside the scope of the model.

For the modelling, these areas were treated as different zones and were given different restitution values corresponding to the expected behaviour. The source zone was assumed to occur as a single event. We have completed the models using two different source block sizes: the first one equaling 18 m^3 (5 m x 2.4 m x 1.4 m) and the second set being a square block of 0.125 m^3 (0.5 m x 0.5 m x 0.5 m) to account for breakup upon failure, since none of the models have fracturing built in.

The Digital Elevation Models (DEM) were obtained from either the LiDAR point cloud data or the Triangular Irregular Network (TIN) which was created from the point clouds using ArcGIS (ESRI, 2013). The lines taken for Rocfall were determined from the LiDAR data, discussed in Section 3.1 as well as a line taking the steepest path. The resolution of the 3D model was on average 0.25 m and the resolution of the DEM used for the RockyFor3D model was 0.2 m. The Rocfall model used sections from the point cloud, which had an average point spacing of 0.1 m. However in a few cases the points were located too close together and had to be removed to eliminate the artifacts in nodal connections and to keep the program stable.

3 RESULTS

3.1 Change Detection

The results of the change detection analysis on the LiDAR data can be seen in Figure 4. Areas of loss are represented by a negative change and areas of gain are represented by a positive change. The volume of the detached block had a calculated volume of 17.9 +/- 0.2 m^3 and the volume of gain located in the ditch along the tracks had a calculated volume of 17.7 +/- 0.2m^3. In addition to the detached block, areas of loss on less steep ledges can be seen, which were used as impact points to calibrate the model.

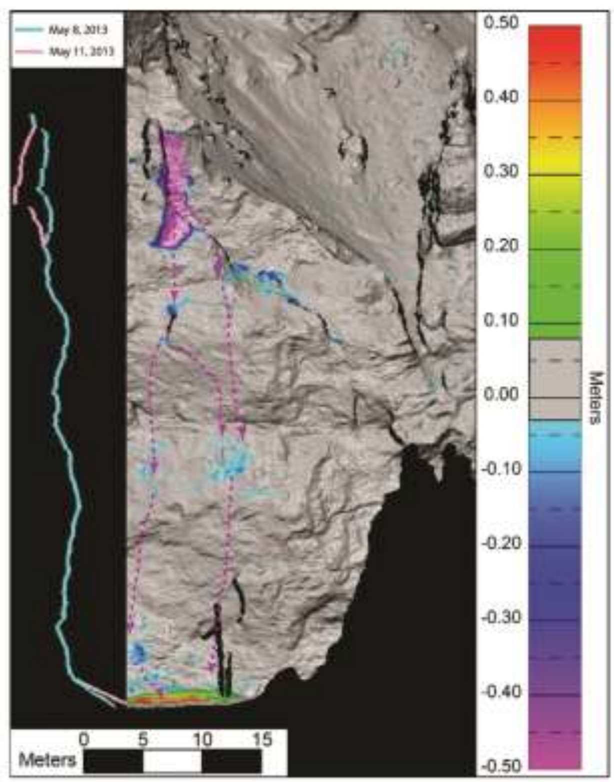

Figure 4: LiDAR change detection and probable paths of rockfall

3.2 RocFall

The modelling shows that the actual size of the block modelled has little effect on how the block travels down this slope. Rather, there is a difference in the run out distance, where the larger blocks have a higher average pass height. In this type of 2D analysis it is not possible to determine if the distribution across the slope face is accurate. However, there are enough impacts where the ledges were identified in Figure 3 that the outcome is similar to what was observed at the site. Figure 5 shows the location of the impact sites and where a change in the pass heights occurs.

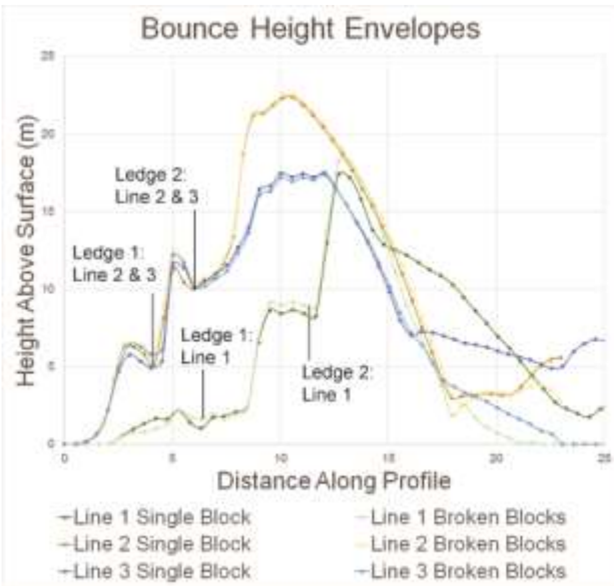

Figure 5: Height profiles of the three lines used in the rockfall model. Line 1, follows the right most path, line 2 follows the steepest path and Line 3 follows the left most path. Shown in Figure 4.

3.3 RockyFor3D

The 2.5D model provided by the RockyFor3D simulation program shows relatively similar pathways for the rockfalls (Figure 8), all continuing down the steepest path of the slope with a high number also falling to the left of the main pathway. These pathways show a very similar model to that which was observed in the LiDAR data, including the upper portion following the extension crack down the top of the slope towards the right hand side of both the LiDAR and the modelling images (Figure 6).

Roughness was omitted in the RockyFor3D modelling due to its high impact on the outcomes, wherein the majority of the modelled rocks stopped on the ledges and did not make it down the slope. The very fine resolution of the DEM accounted for the majority of roughness changes in the slope. The model does not account for the deposition observed in situ, with the majority of rockfalls passing over the tracks, even with the lowest possible restitution values in place. However, this could be attributed to the errors generated from the occlusion of the ditch. Where the interpolated surface is flat due to the triangulation algorithm and there being no measured points within the ditch. A comparison using an estimated ditch width and depth is being completed currently.

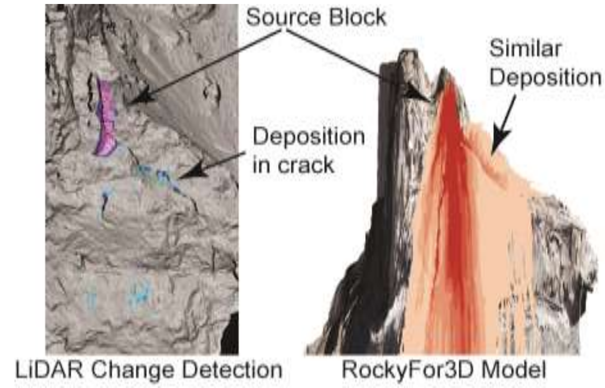

Figure 6: Images showing deposition near the source area

Two different surface parameters were modelled. The first using what the estimated ground parameters were (explained in section 2.1) and the second using only bedrock, or a constant high restitution value. With the increase in restitution the pathways become more defined, seen especially clearly in the larger block model (Figure 8). This was completed to determine if there was a significant effect on the model outcome due to the restitution values on the ledges.

3.4 Bullet Physics Model

The 3D bullet physics model used model parameters that assumed a perfectly elastic system and the model was completed with no other defined parameters. Therefore, the entire system was controlled by the gravitational forces on the block and the impact calculations upon interaction with the slope. The path of the block is as follows: the block topples off of the ledge, impacts the slope at the highest ledge (Figure 7, a), continues down the slope with the now increased angular acceleration and impacts the slope at the second observed location (Figure 7, c) until the block reaches the final location at the bottom of the slope in the ditch before the tracks. The impact locations all occur on the observed ledges and the geometry of the block shows significant importance in the fall behaviour.

4 DISCUSSION

4.1 Change Detection

Rockfall trajectories were interpreted based on the change detection results shown in Figure 4. Areas of loss along the rockfall path are interpreted as impact areas. The impact of the original rock block caused smaller rockfall events and dislodged loose surface material on the ledges. The impact areas grew in size further downslope. This is interpreted as being the result of the successive breakup of blocks after each impact. The breakup of the rock block is dependent on its geological characteristics (Nocilla and Evangelista, 2009). The highly fractured, weathered nature of the bedrock material at the White Canyon indicates that falling blocks are more susceptible to fragmentation. The studied rockfall likely started fragmentation at its source area. Good correlation between source and deposition area volume indicates that there are no superimposed events.

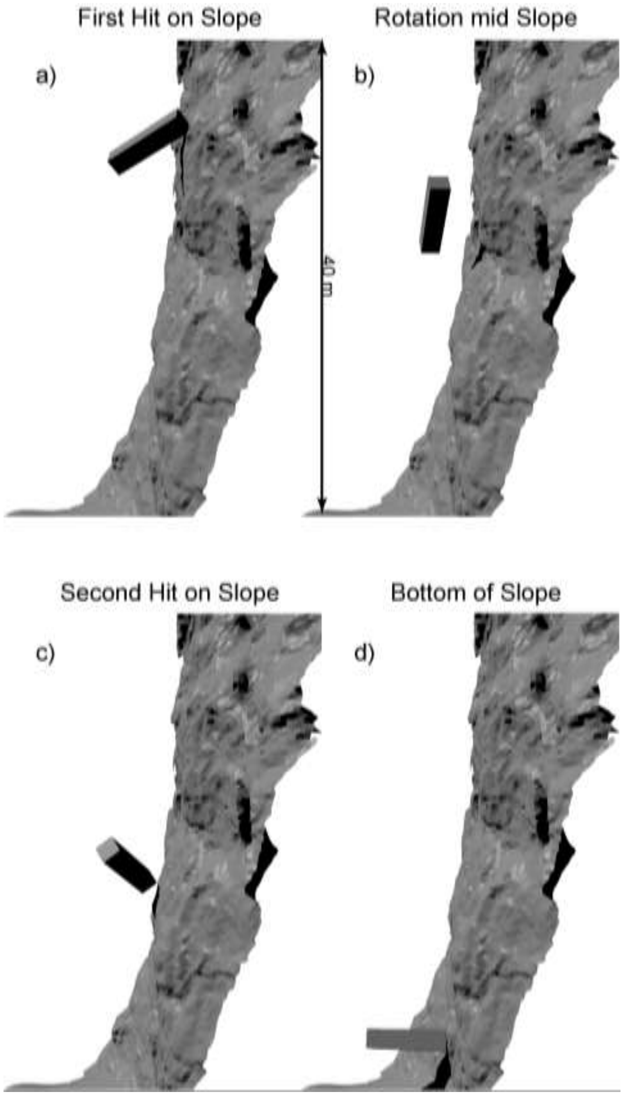

Figure 7: Bullet Physics model, impact sites and path down the slope. The initial fall location was above the cut off of the images and the track is just visible at the bottom of each model.

4.2 Rockfall Modelling

We saw results from all three of the models that showed that the path of the majority of the falling blocks modeled followed a similar profile to that which we observed in the LiDAR data. The 2D lumped point model provided the least accurate re-creation of the data and the full 3D model provided the most similar model to the interpretation of the LiDAR data. Neither of the two conventional models showed a significant difference when a multitude of small rockfalls were assessed as compared to a single large failure. The mass of the two different block models varied significantly. The only major change that was observed was a small increase in pass heights and a change in the way the larger blocks tended to funnel in the 2.5D model. This is expected from the 2D rockfall model since it does not account for the shape or the size of the rockfalls, where a change in the size will only affect the energy calculations. In comparison, the 2.5D model does account for the size which may explain the model showing more defined pathways since the larger blocks would not be affected by the small changes in topography. The impact collisions are still limited to a spherical shaped block (Dorren, 2012) which may be influencing the way in which the blocks travel down this very steep and topographically complex slope.

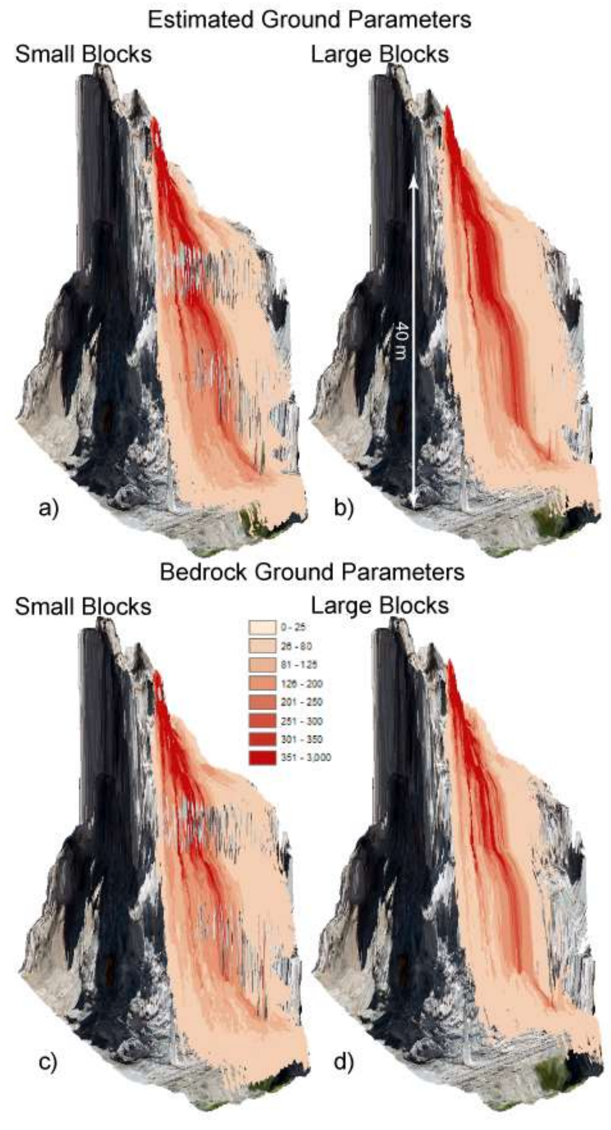

Figure 8: 3D visualization of pathways generated by RockyFor3D modelling (Darker red indicates more passages and lighter red is less)

The most interesting result came from the full 3D model; even with no variation in surface parameters and the use of the default impact parameters, the outcome was very similar to the interpreted rockfall path, impacting in the same locations and with enough velocity to likely cause rockfalls to occur in that area. The high resolution slope and the elastic impact was enough, omitting the widely accepted restitution angle to show a very promising modelling result with no other calibration from the user. A similar method of using a constant impact coefficient for the entire slope was also applied to the 2.5D model. In this case, modelling with a mean restitution value of 0.53, the pathways become more defined (Figure 8, c) following more closely the estimated pathways shown earlier (Figure 4). We therefore suggest that the rockfalls are almost entirely controlled by the shape of the slope. In practice the slope has a very low restitution parameter, however, the impacts are prone to causing material to fall off the slope rather than significantly altering the pathway or stopping the rocks mid slope due to the slope angle and associated friction angle of the falling material.

Another issue presented with the two classical rockfall models is observed at the bottom of the slope profile. It is known that the rockfalls in this area become very fragmented during their journey down slope and that the ditch, especially in the area that was modelled will catch almost all of the rockfall that occurs. This was also observed in the LiDAR data where the volume of gain at the bottom of the slope was measured to be very similar to the volume of loss that occurred at the top of the slope. The position of the scanner across the risver from the slope results in occlusion or loss of information about the ditch itself. As such the base of the ditch is assumed to be level with the elevation of the tracks. The models therefore give an unrealistic outcome for the distribution of the fallen material, and the ditch should be incorporated or the TLS data merged with ALS data to give a better representation of the true nature of the slope. These models could then be analyzed to determine the effect of the restitution value in this very vertical and high velocity impact area.

5 CONCLUSION

Through this study we have shown that the pathway of a rockfall can be accurately identified using change detecting analysis using LiDAR data, and that the fractured nature of the slope lends itself well to this analysis. All three modelling methods compared provide similar results to the interpreted rockfall paths. The full 3D modelling method provides the most accurate representation of how a falling rock interacts with the slope and has promise to show surface slope interactions. We have also shown that rockfall models that use high resolution DEMs are not sensitive to specific surface parameters. That is, rockfall paths in this case were almost entirely controlled by the shape of the slope and surface parameters had little effect on the pathways.

Further work on the modelling of individual rockfalls, similar to that which we expect to occur in the canyon is being completed using the same 3D model to compare the outcomes of a full block versus that of multiple small blocks.

ACKNOWLEDGEMENTS

The Railway Ground Hazards Research Program (RGRHP), a collaborative effort funded by NSERc, CN Rail, CP Rail, and Transport Canada supported this research. The Kumsheen Rafting Resort provided access and logistical support during fieldwork.

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