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ABSTRACT: Natural and man-made rock slopes are numerous along the southernmost 260 km of the railroad linking the port of Port-Cartier to the mine site near the northern town of Fermont, in the province of Québec. The aim of the Para*Chute* research project is to integrate a variety of technologies into a common approach to manage work prioritization and data related to slope stability over large areas. This paper presents how rockfall simulations were integrated into a rock slope classification system to identify and rate remote natural cliffs. Rock cuts were rated using a different methodology that is not address in this paper. The semi-automatic rockfall simulation carried out over the entire study area allowed us to recognize all natural slopes from which a rockfall could reach the railway. These slopes are often not apparent from the ground. After identifying these natural rock slopes, we ran a second set of simulations to evaluate the reach potential of the identified remote rock slopes. These results are used as one of the parameters of the rating system. The proposed methodology allows an effective characterization of natural rock slopes, because all inputs of the rockfall simulations are derived from a digital elevation model.

INTRODUCTION

Knowing where problematic rockfalls originate, and why they do, not only helps, but also is crucial to properly manage and mitigate the associated risk (Turner and Jayaprakash, 2012; Corominas et al., 2014). The Rockfall Hazard Rating System (RHRS; Pierson, 2012) was developed in the early 1990's to help manage rock slope mitigation programs. This system offers a way to compare and rate rock cuts to recognize the most hazardous ones along a transportation corridor. Subsequently, many organizations adapted the system to their needs (Pierson and Turner, 2012). This and other systems commonly ignore natural rock slopes that are farther away and not visible from highways and railways.

To improve the characterization of rockfall sources and causes, we propose a methodology to extend the RHRS for use with natural rock cliffs that are commonly located farther away than human-made rock cuts (more than 20 m away from the rail track). We will call these rock slopes, the remote rock slopes in the rest of this paper. Our approach is based on the use of remotely sensed data, including airborne laser scans (ALS) and unmanned aerial vehicle (UAV)-based photogrammetry.

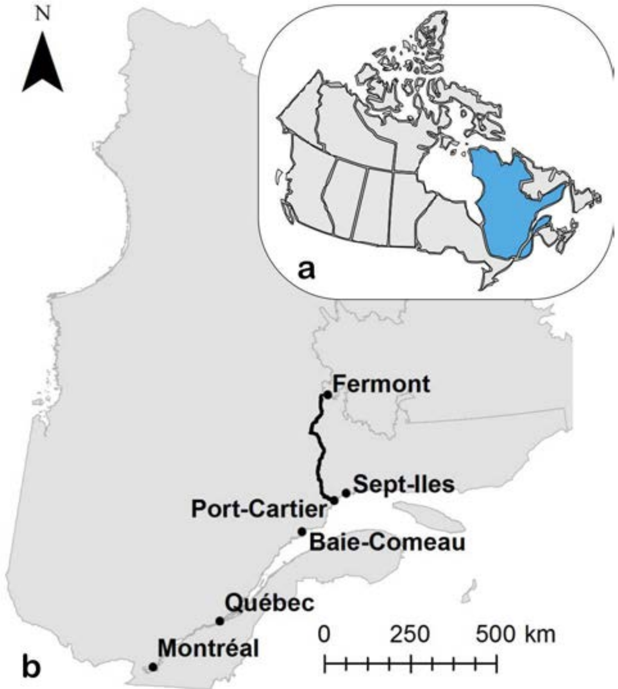

Figure 1. a) The province of Québec in Canada b) Location of the studied railroad

The methodology was developed and implemented in a regional study of railway linking the coastal town of Port-Cartier to mining sites near Fermont, Québec, Canada (Fig. 1) (Cloutier et al., 2015). To conduct this research project, which we named Para*Chute*, researchers from Université Laval collaborated with the Ministère des transports, de la mobilité durable et de l'électrification des transports du Québec and ArcelorMittal Infrastructures Canada. One of the project's objectives was to limit time-consuming and expensive field work and decrease uncertainty around the different parameters of the RHRS by optimizing the use of GIS and digital elevation models (DEM) in order to develop a customize RHRS methodology.

A major challenge in such work is the size and large number of both natural and human-made rock slopes along the railway. Few of the natural rock slopes were inspected before this study, consequently the rock slope inventory resulting from the work presented in this paper is more complete, enabling improved recognition of the rockfall hazard.

Not all natural rock slopes located along the railway need to be included in the rating system. The screening of remote rock slopes is based on the potential of a rockfall from a particular slope reaching the railway track (the 'potential of reach') (Noël et al., 2015). If such a potential exists, then we evaluate the rock slope using a systematic rating system. The identification of rock slopes and the evaluation of their potential of reach rely on systematic 3D rockfall simulations, which are the main focus of this paper. Their susceptibility to generate rockfall is then evaluated from visual characterization using UAV and helicopter based photos and 3D models.

In this paper, we first describe the general concept of our proposed modified RHRS system. We then outline the methodology for identifying and rating the potential of reach of natural rock cliffs, and finally discuss the results.

GENERAL CONCEPT

The parameters used to score rock slopes in the RHRS fall into three categories: 1) the susceptibility of the slope to produce rockfalls (frequency, volume and rock condition), 2) the potential of reach (ditch effectiveness, height and inclination of slope), and 3) the vulnerability of the infrastructure or users to a rockfall (e.g. sight distance, traffic density). These components are elements of the risk equation (Fell et al., 2005), in which they are multiplied. Unlike the risk equation, the final RHRS score of a slope is obtained by summing the different parameters scores.

We developed two rating methodologies, one for remote natural cliffs and another for rock cuts. In both cases, potential of reach, rockfall susceptibility and vulnerability are rated from 0 to 1, and the values are multiplied to give the final score. This approach is similar to other classification systems, e.g. New York State System in Pierson (2012); Pritchard et al. (2005); Lato et al. (2016).

In the fall of 2014, we acquired aerial photographs (0.1 m pixels) and aerial laser scans (ALS) along the entire length of the railway and over a width large enough to evaluate any possible rockfall hazard, corresponding to the drainage bassin. The aerial photographs were assembled into a mosaic of orthophotos, and the ALS were used to produce a digital elevation model (DEM; two resolutions are used in this paper, 1x1m and 0.5x0.5m cells), from which information on topography and landforms was extracted. Mobile laser scans were also acquired from a vehicle travelling on the railway line.

The inventory of rock cuts is based on remote sensing data. For all rock cuts, we identified discontinuity sets from analyses of point clouds obtained with mobile laser scans (Jaboyedoff et al., 2009; Cloutier et al., 2015). Kinematic analysis run on stereographic plots is done to evaluate the likelihoods of toppling, planar and wedge failures (Norrish and Wyllie, 1996). Dimensions of ditches and the height, inclination and orientation of the rock cuts were also obtained from the point clouds. We then visited all rock cuts, partly to validate the point clouds analyses, but mainly to rate other parameters, such as infilling material, opening of joints, the presence of unstable blocks and the presence of blocks in the ditch. Moreover, all rock cuts were photographed systematically to generate 3D point clouds. These point clouds are generated on demand and if needed, e.g. to revise the rating of some parameters, to evaluate the volume of falling rock after scaling work or rockfall event, to plan stabilization measures, etc. The potential of reach was evaluated from the geometric characteristics of the rock cut, and the rockfall susceptibility was estimated from parameters rated visually, similar to what is done in the RHRS. For some rock cuts higher than 25 m, videos and photos were acquired from a UAV to document the higher part of the slopes that cannot be seen from the track.

For natural rock slopes located farther from the railway, their identification and evaluation of their potential of reach rely on 3D rockfall simulations. Their susceptibility to generate rockfalls is evaluated visually from air photos, laser scans, photogrammetry point clouds or videos acquired with an UAV or from a helicopter. The UAV was fly from the railway track, for about 10 of the 74 remote rock slopes.

The remainder of this paper focusses on the estimation of the potential of reach from remote cliffs. The methodology relies entirely on the DEM generated from ALS, because ALS is now commonly acquired in projects covering large areas. We developed informatics tools to facilitate the application of the methodology over large areas by generating input files and running the simulations by batch processing. The general approach requires 1) the identification of slope crests, which we use as locations of rockfall sources, 2) systematic rockfall simulations, which provide information on where rockfalls trajectories might cross the railway track, 3) identification of potentially problematic rock slopes, and 4) rockfall simulations done sector-by-sector which allow us to evaluate the potential of reach for a specific rock slope. Identification of rock slopes from which a rockfall might reach the rail line is helpful to target acquisition of photos and videos to rate their rockfall susceptibility.

METHODOLOGY

Preliminary rockfall simulations as a screening tool of remote rock slopes

We ran rockfall simulations over the whole study domain using conservative values (Noël et al., 2015; Noël, 2016). 3D rockfall simulations allow falling rock to move sideways and thus allow for the characterization of lateral dispersion of rockfall paths (Agliardi and Crosta, 2003; Li and Lan, 2015), and to identify channels where blocks could concentrate. The software used in this study is RockyFor3D (RF3D) (Dorren 2015). The choice of this software was motivated by its compatibility with other tools, its ability to run simulations by batch processing, and most importantly, the ability to deal with large areas efficiently.

In RF3D, the input parameters are 1) the topography of the terrain, for which we used the ALS DEM with 1x1m cells, 2) the characteristics of slope materials, 3) the rockfall source locations, and 4) block density, dimension and forms. The script developed in MatLab generates the ten required input files by RF3D automatically. The methodology does not require fieldwork, which makes it a very useful preliminary screening tool.

Identification of rockfall source locations for simulations

In our study, the rockfall source locations are automatically located at slope crests, which are identified by interrogating the DEM with a script that looks for slope break, which was developed especially for this use. A cell is identified as a crest if its inclination is above a certain threshold and if the inclination of the cell above (the neighboring cell in the opposite direction than the orientation of the elevation gradient) is below the threshold. Rockfall sources are identified with no consideration of the stability of the slope.

In gridded data, steeply inclined rock cliffs are represented by a lower number of pixels than a more gentle rock slope of the same height (Fig. 2). If, all the pixels with a slope over a certain threshold, for example 50°, were identified as rockfall sources, then, two sources would be identified in Figure 2a, and five in Figure 2b. It would result in more simulated trajectories on the gentler slope. The number of rockfall sources would not be representative of the real slope area (Fig. 2). Using slope crest as slope locations reduces this bias, but does not remove it completely. For example, a higher number of rockfall sources will be attributed to a cliff that has multiple slope breaks adjacent to each other than a very high cliff with only a single crest (Fig. 3). This becomes important when comparing slopes in terms of the number of trajectories reaching the railway.

Three threshold values were used to identify crests: 40°, 60° and 80°. An example, shown in Figure 4b, illustrates how the threshold value impacts the identification of the DEM cells. Fewer cells are identified as slope crests for the 80° threshold, compared to the 40° threshold. The 60° threshold provides the best results in most sectors studied in the Para*Chute* project, but in general the threshold value should be chosen according to site-specific topography.

Other input parameters

The DEM is used without modification in the simulation program. Thus, lakes and rivers are represented by flat surfaces, meaning that rockfall could propagate over water bodies. This is not a problem in our study, because there are few water bodies between the railway and rock cliffs.

Terrain parameters are linked to the DEM cells based on their slope angle. This approach is based on the hypothesis that the material forming a flat slope will most likely dissipate more energy than the material forming a steep slope. In the study area, valley bottoms are filled with glaciofluvio sediments and steeper ground is either bare rock or rock mantled with a thin veneer of till.

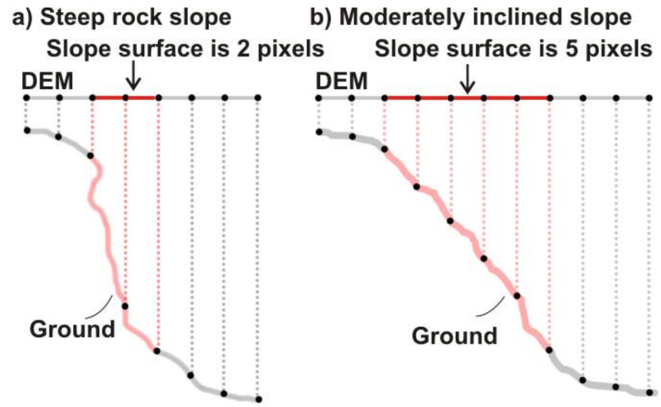

Figure 2. Steeply inclined slopes take fewer cells in a DEM than a gentler one of the same height.

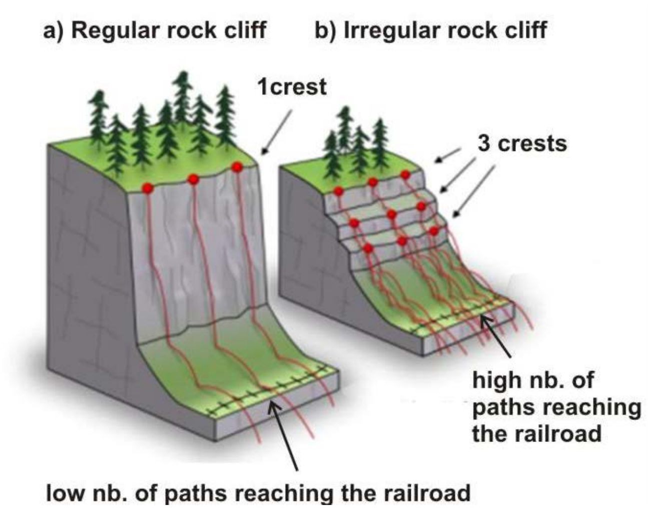

Figure 3. Illustration of the effect of using slope crests as rockfall source locations on the number of trajectories simulated for two types of cliff geometries.

Slope inclination thresholds of 2°, 7°, 25° and 45° were used; the parameter values are shown in Figure 5. The slope material parameters in RF3D are not the commonly used coefficients of restitution, which are defined as the ratio of the energy of the block after an impact with the ground and the energy before the impact. Instead, a soil type and the slope surface roughness encountered for 10, 20 and 70% of the rebounds are specified. These values, which represent the height of the obstacles, should be measured in the field. The tangential coefficient of restitution is computed according to the impact velocity and the size of the falling particles related to the soil roughness. For more details, the reader is referred to Dorren (2015) and Noël (2016).

The equivalent tangential and normal restitution coefficients were computed and are shown in Figures 4c and 5. We chose upper range values to ensure the propagation distances are not underestimated. Our rationale was to recognize cliffs farther than 20 m away from the railway that could potentially generate rockfalls that would reach the railroad. At this stage, we did not want to eliminate too many slopes. An example of a natural rock slope that was identified in this manner is shown in Figure 4a.

For each cell identified as a slope crest, ten fictive cubical blocks of 40 ± 12 kg were simulated. RF3D imposes an initial horizontal speed of 0.5 m/s and a -0.5 m/s vertical speed.

Output of the rockfall simulations

A variety of output files are generated by RF3D; two are used in the methodology presented in this paper: the end point locations of the rockfall paths and the number of trajectories passing through each cell (Fig. 4d). From the latter result, the number of paths was extracted from the pixels crossed by the railway centerline, yielding the number of rockfall paths crossing the railway line.

Recognition of crests from which rockfall can reach the railway tracks

The number of rockfall paths crossing the railway track highlights those sections of the railway that could be reached by a rockfall. However, these results do not allow us to evaluate the potential of reach of a specific slope for the following reasons:

(1) The number of paths crossing the rail line depends on the number of sources above the railway.

(2) The number of paths is linked to the rail line, not to the rock slopes. The goal of the methodology is to rate rock slopes according to their potential to generate rockfalls that could interfere with railway operations.

(3) The rockfall paths cannot be manipulated separately to link them to their sources (Fig. 6).

(4) At this stage, paths from rock cuts and natural rock slope are not differentiated when they are located above each other (Fig. 6).

We carried out a manual interpretation of the rockfall path maps (Fig. 4d) to identify natural rock slope crests and regroup them into sectors. The manual interpretation rates the slope crests from 1 to 4 according to the number of paths crossing the railway track below (Fig. 4e). The thresholds separating the four categories are arbitrary (Noël, 2016), thus the result is subjective, but it forces the operator to consider every source location and, if desired, regroup them into sectors. Through this process, we differentiated crests of rock cuts from crests of natural slopes, and then carried out additional rockfall simulations sector-by-sector to compare and rate slopes.

During this manual operation, we also examined airphotos and ALS point clouds in 3D to identify different parameters relevant to rockfall activity, such as the presence of a talus slope, rockfall debris, corridors of broken trees, fractures and scarps of rockslides. All the observations are entered into a GIS environment and attributed to a natural rock slope sector. They are used to evaluate the susceptibility of specific rock slope sectors to generate rock instabilities.

Evaluation of a sector's potential of reach

Rockfall simulations were carried out sector by sector to quantify their probability of reach. We used RF3D and slope material parameters in the same way as in the preliminary simulations (Fig. 5). Source locations are identified using the 60° slope threshold identified during the manual interpretation. Only slopes that are natural were included; sources located on the top of rock cuts were eliminated. We then generated new DEMs for each sector from the ALS with a pixel size of 0.5 x 0.5 m.

For a given sector, the number of end points of rockfall paths (Fig. 7a) that stopped on or beyond the rail line was extracted from the results. We developed a different method to extract end point locations for the five sectors where natural cliffs are located above a tunnel and have source locations on both sides of the track. The ratio of rockfall trajectories reaching the railway and the total number of simulated trajectories defines the sector's potential of reach.

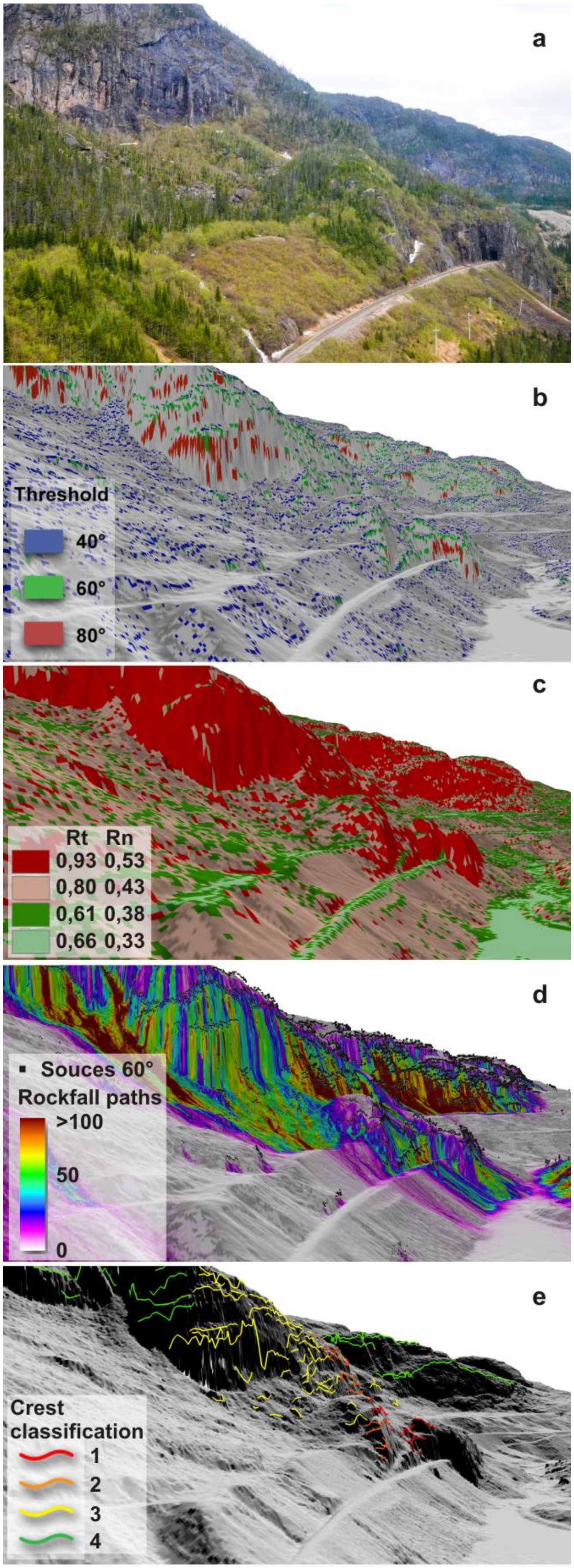

Figure 4. Steps and input parameters of the preliminary simulation methodology for a specific sector, photographed in a) comprising a high natural rock cliff and a tunnel; railway at the bottom of the image. b) Slope crests, which are used as the rockfall source locations in the simulations. c) Coefficient of restitution values are attributed based on the DEM cell inclination. Rn: Normal coefficient of restitution and Rt: Tangential coefficient of restitution. d) Rockfall simulations results presented as the number of rockfall paths passing through a pixel. e) Results of the manual classification of source locations.

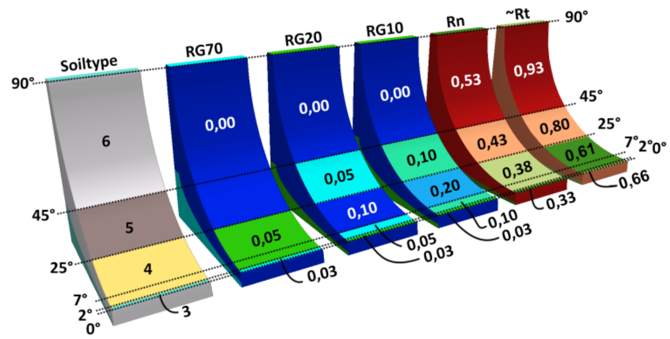

Figure 5. Six forms illustrating the range of inclination used to determine material properties. Soil type, RG70, RG20 and RG10 are terrain parameter inputs for the simulations in RF3D (Dorren, 2015). They represent the slope surface roughness that is encountered 70%, 20% and 10% of the time, depending on the soil type specified. The equivalent Rn and Rt are computed.

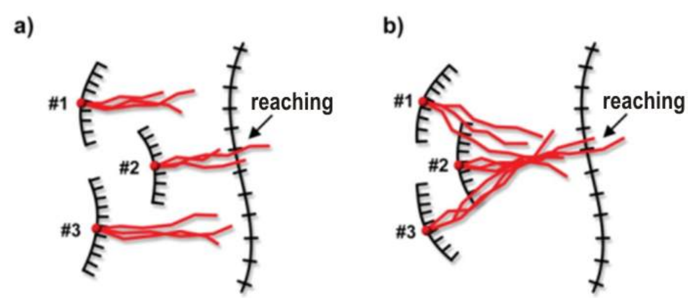

Figure 6. a) Non-overlapping and (b) overlapping rockfall trajectories. In the case of overlapping rockfall trajectories, the operator cannot differentiate the slope crest from which they originated. In the outputs of the software RF3D, the rockfall paths cannot be manipulated separately.

RESULTS AND DISCUSSION

We completed the preliminary rockfall simulations for the entire study domain (260 km of railway) and for three scenarios of rockfall source locations, which consist of crests with thresholds of 40°, 60° and 80° (Fig. 4b). The maps resulting from the three sets of simulations were integrated into a GIS database. The user can display the rockfall path density (Fig. 4d), the number of paths reaching the transportation corridor, the rockfall source locations, the slope material parameters, inclination and orientation of the terrain, and the DEM. We analyzed the results from the three sets of simulations to identify natural rock slope sectors from which a rockfall might reach the rail line.

A large number of simulated trajectories that cross the rail line indicate that the topography is favorable for the propagation of rockfalls towards the railroad and that a large number of slope crests are located above it. The numbers of slope crests in four categories (Fig. 4e) also provide an indication of this likelihood. The results show that 33 km of the rail line out of the 260 km studied could be affected by rockfalls from remote rock slopes.

Seventy-four sectors of natural rock slopes with sources at the 60° threshold were identified for simulations. Between 61 and 17,794 trajectories were simulated for each sector. An example is shown in Figure 7 (this is the same region shown in Figures 4a to 4e, but the simulations were run only for those rock slopes not eliminated by the screening process and regrouped to form one of the remote slope sectors. Slopes in the background of Figure 4 form a different sector). No rockfall sources are located at the crest of the rock cut in Figure 7a. For this particular sector, 12 230 trajectories were simulated. From these, 10% reached the railway track. This sector's potential of reach is 10%.

We ran the simulations with a finer-gridded DEM with a higher rugosity. As a consequence, the trajectories propagate a shorter distance than in the simulations run using a 1-m² cell DEM.

The percentage of trajectories reaching the railroad can be used as the score in the proposed modified RHRS system. Because the methodology is systematic, sectors can be directly compared with one another (Fig. 8). However, the rockfall simulations should not be used alone for the design of retaining infrastructure, because they were not calibrated for their specific sector.

The preliminary rockfall simulations, which was run over the entire study area, was used as a screening tool, to identify all natural rock slopes from which a rockfall could reach the railway track. The remote slopes eliminated at this stage will not be evaluated in the rating system. It also means that they will not be considered for mitigation work. To make sure we don't eliminate slopes to quickly and also because we have no way of knowing if we missed a slope or not, terrain parameters are chosen in their upper range to, somewhat, exagerate the rockfall run out. Moreover, trees, that could help to reduce rockfall run out, are not considered, yielding also to longer run out distances.

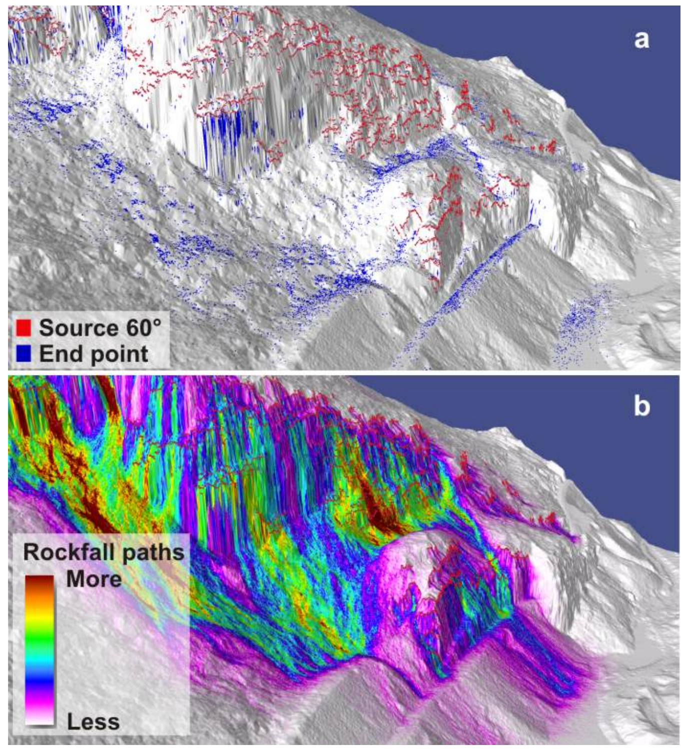

Figure 7. Results of simulations from one of the 74 sectors of natural slopes. a) Starting and ending location of trajectories. b) Number of rockfall paths passing through each pixel of the DEM.

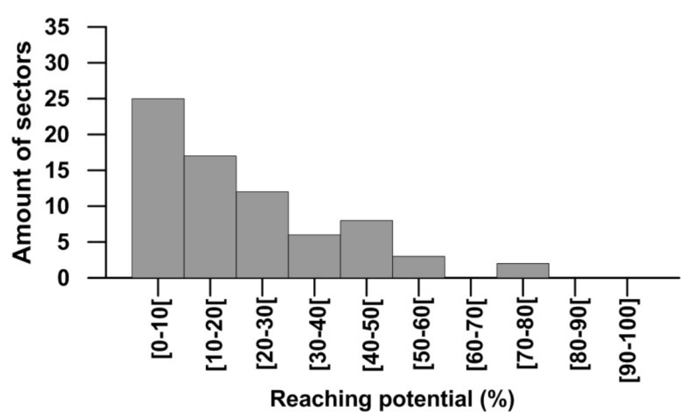

Figure 8. Distribution of the potentials of reach of the 74 natural slope sectors.

CONCLUDING REMARKS

We believe that the systematic application of a modified RHRS system that includes natural cliff will help to manage the rock slopes and diminish the losses related to rockfalls and increase safety and efficiency of railway operations.

74 sectors of natural rock slopes from which a rockfall could reach the infrastructure were identified from the preliminary rockfall simulations. Most of these rock cliffs were not included in previous inspections. The potential of reach was then evaluated for these sectors by running a second set of simulations, this time sector by sector. This methodology is entirely based on a DEM and requires no field work.

In this study, rockfall simulations were carried out systematically before field work and were used to target field work and specific data acquisition.

To complete the rating of the 74 sectors of natural rock slopes, the susceptibility to generate rockfalls was evaluated by rating parameters from visual characterization. This is similar to what is done in the RHRS. The methodology rely on air photos and point clouds obtained from ALS and from UAV-based photogrammetry. The final score of the sector are obtained from the multiplication of the reach potential and the rockfall susceptibility values.

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