2 **Rockfall Activity Index (RAI):**
3 **A Lidar-Derived, Morphology-Based Method for Hazard Assessment**

4
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8 **Abstract:** In this paper, we introduce the Rockfall Activity Index (RAI), a point cloud-derived,
9 high-resolution, morphology-based approach for assessing rockfall hazards. With the RAI
10 methodology, rockfall hazards are evaluated in a two-step procedure. First, morphological
11 indices (local slope and roughness) are used to classify mass wasting processes acting on a rock-
12 slope. These classifications are then used with estimated instability rates to map rockfall activity
13 across an entire slope face. The rockfall hazard is quantified as the estimated annual kinetic
14 energy produced by rockfall along 1-m length segments of a slope face. Field assessment of the
15 RAI method at multiple study sites indicates that the morphology-derived classification and
16 hazard assessment routines provide results that closely match the observed behavior and
17 performance of rock slopes.

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19 **1. Introduction**

20 Rock slopes are geologically active features of the landscape that can be hazardous to people,
21 property, and infrastructure. Often they are steep, which makes them susceptible to rockfall—a
22 mass wasting process involving detachment, fall, rolling, and bouncing of rocks (Hung et al.
23 2014). These rocks may range in size from gravel- to boulder-sized fragments (~centimeters to
24 ~decimeters) to large rock blocks (~meters) [Higgins and Andrew 2012]. Once released, rocks

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can travel at high velocities across long distances, sometimes causing fatalities to those in the path of moving debris (Katz et al. 2011).

Rockfall is a chronic slope hazard along transportation corridors in mountainous areas of North America, where tens of millions of dollars (US\$) are spent annually on rock slope maintenance and mitigation works (Turner and Jayaprakash 2012). They pose similar threats to transportation routes in many other parts of the world (e.g., Baillifard et al. 2003, Guzzetti et al. 2004, Katz et al. 2011, Michoud et al., 2012). In transportation geotechnics, it is common to assess rock slope hazards using rock mass classification (e.g. Pantelidis 2009) or rockfall hazard rating (e.g. Pierson 2012) systems. These and other similar assessment systems rely on visual inspections and simple calculations to develop a relative ranking of potentially hazardous rock slopes. Such rankings help public agencies and owners prioritize needs and allocate resources for rockfall hazard mitigation (Pierson 2012).

One of the most common rock slope assessment schemes is the Rockfall Hazard Rating System (RHRS), originally developed by Pierson (1991) for the Oregon (USA) Department of Transportation. The RHRS has since been adopted by other transportation agencies in North America (FHWA 2013), and worldwide (Bunce et al., 1997; Chau, Wong, and Lee, 1998; Ilinca, 2008; Youssef & Maerz, 2009). The RHRS uses information on rock mass features (e.g. block size, discontinuity properties), morphology (slope height), environmental factors (climate, surface water runoff, and infiltration), and facility use and protection measures (e.g. road occupancy, width, and sight distance; rockfall catchments) to assess the dangers that rock slopes pose to motorists and other facility users. An alternative system, the Rockslope Deterioration

Assessment (RDA), was developed by Nicholson (2004) to capture in greater detail the effects of finer-grained, shallow weathering and deterioration processes on rock slopes. The RDA uses information on rock mass, morphology, and environmental factors to determine a relative rockfall hazard rating.

The RHRS, RDA, and other similar assessment schemes are established methods for identifying, assessing, and rating rock slope hazards and risks along transportation and infrastructure corridors. However, these methods are often highly qualitative in nature (Budetta and Nappi 2013) and have a coarse spatial resolution. Today, remote sensing technologies such as light detection and ranging (lidar, or laser scanning) allow rock slopes to be imaged and visualized at unprecedented, cm-scale resolution (Jaboyedoff et al., 2012; Abellán et al., 2014). Moreover, lidar allows investigators to safely capture data from slopes that produce rockfall or may be otherwise inaccessible (Kemeny and Turner, 2008). Capitalizing on this and other related advancements in remote sensing, we developed the Rockfall Activity Index (RAI), a point cloud-derived, high-resolution, morphology-based method for assessing rockfall hazards. Although lidar has been used extensively for rock slope change detection (e.g., Jaboyedoff et al. 2012; Abellan et al. 2014; Kemeny and Turner 2008; Rabatel et al. 2008; Girardeau-Montaut 2016, Kromer et al. 2015), rockfall volume characterization and associated magnitude-frequency distributions (e.g. Lim et al. 2012, Barlow et al. 2012, Santana et al., 2012, D’Amatao, 2014, Olsen et al. 2015), cliff monitoring (e.g., Rosser et al. 2007, Lato et al. 2009, Olsen et al. 2009, 2015) and hazard and risk forecasting (e.g., Rosser et al. 2007b, Stock et al. 2012, Collins et al. 2012, Royan et al. 2013), the engineering geology research and practice communities currently lack a *hazard rating methodology* that is tailored to terrestrial laser scanning (Lato et al. 2012).

The RAI method involves a two-step evaluation of high-resolution (cm-scale), three-dimensional point clouds. In the first step, morphological indices (local slope and roughness) are used as an indicator to classify erosion and mass wasting processes acting on rock slopes. In the second step, the slope morphology classifications are used with estimated instability rates to map rockfall activity across a slope face. The RAI method has been implemented as a simple and computationally efficient algorithm, which makes it repeatable and easy to apply across rock slopes of virtually any size. After describing the basis and formulation of the RAI method, we present detailed results from two field study sites to demonstrate the efficacy of the approach. Field comparison at these two sites and nearly a dozen other sections of rock slope indicate that the classification and hazard assessment routines provide results that closely match the observed performance of the slopes.

2. The Rockfall Activity Index (RAI) Method

The RAI method was developed as a simple but high-resolution approach for mapping and assessing rockfall hazards across large areas (e.g. at the scale of road corridors). The method provides an estimate of rockfall kinetic energy release (i.e., the rockfall activity index, RAI) along 1-m rock slope segments as well as a detailed mapping of rock slope morphology and kinetic energy release areas. The RAI serves as a measure of *rockfall* activity along a slope. There is no recognized upper volume limit to rockfall, but the maximum size is usually related to the scale of the individual rock fragments (Hungr et al. 2014). The RAI does not consider large, structurally controlled failures such as rock slides or topples (Hungr et al. 2014), which are typically assessed using limit equilibrium analysis procedures (e.g. Wyllie and Mah 2004). The RAI is expressed as annual cumulative delivery of rockfall kinetic energy (kJ) at the base of a

unit length (1-m) slope. We adopted kinetic energy as a metric because it is strongly correlated to a landslide's destructive potential (e.g. Lee and Jones 2014). Although this quantitative formulation suggests a high degree of engineering precision, we recognize that variability and uncertainty exist in the parameters used to compute the RAI. We thus selected the term *index* to emphasize the method's intended use as a measure of rockfall activity, rather than an exact predictor of annual energy release from rock slope. This is later discussed at a more practical level in the context of rock slope assessments at two field study sites.

The RAI method utilizes 3D point clouds representing the topography at high detail, capturing overhangs and other features. This differs from a common "2.5D" digital elevation model (DEM), which provides only a single value of elevation at a given latitude/longitude location and thus is unable to simultaneously capture the upper and lower elevation points of overhanging rock. We derived high-resolution (2-5 cm spacing) point clouds from Static Terrestrial Laser Scanning (sTLS) [i.e., lidar] of rock slopes. Lidar serves as an ideal remote sensing technology for this work because many objects obscuring rock-slopes (e.g. vegetation, street signs, passing vehicles) can be filtered and removed from the point cloud. However, it must be recognized that substantial obstructions such as dense vegetation can result in significant gaps or lower resolution in these areas when there is limited visibility, resulting in portions of the model that may not be suitable for the RAI calculations. Notably, the RAI method requires only a point cloud and is thus independent of the remote sensing technology used in the field to collect topographic data. Therefore, any method that produces a high-resolution (cm-level) point cloud data, including mobile terrestrial laser scanning (mTLS) and Structure from Motion (SfM), could, in principle, be used with the RAI method.

The following sub-sections describe topographic data acquisition and point cloud processing, rock slope morphology mapping, and calculation of the RAI.

2.1 Topographic Data Acquisition and Point Cloud Processing

Static Terrestrial Laser Scanning (sTLS) data were acquired for two study areas located in the State of Alaska, USA. The data were then georeferenced following the methodology described in Olsen et al. (2009 and 2011). Before processing, the data were cropped to include only the exposed cliff face and vegetation was removed through manual editing so that morphological features could be evaluated for the bare cliff surface without vegetation biases.

For efficient computations and topological consistency, the point cloud was organized into a grid structure following the procedure outlined in Olsen et al. (2015). The grid structure was contained within the best-fit plane of the point cloud to best preserve features on the cliff face. The centroid coordinates of all points contained within each cell were then computed. The centroids of neighboring cells were then triangulated using the centroid triangulation connection described in Olsen et al. (2013). 3D surface normal vectors were then calculated for each triangle via the vector cross product. The normal vector for each cell centroid was calculated as the average of the normal vectors for each triangle connected to that cell. The 3D surface area for each cell is calculated by summing the area of each triangle connected at that cell divided by three since it is shared with three centroids.

Utilizing a grid format has drawbacks since it will distort features (such as overhangs) that are perpendicular to the grid plane. However, these issues were accounted for in the algorithm design by determining 3D areas for computations to account for the fact that cells in these situations represent a larger surface area. Other issues such as data shadows (Olsen et al. 2015) were also considered; however, these were found to affect only a small number of cells within a cloud. A sensitivity analysis showed that these did not significantly change outcomes.

A key consideration with this approach is the optimal grid cell size, which depends on the resolution of the input data. With sTLS, the point sampling can be highly variable across the cliff face since scanners sample on angular increments, and multiple scan positions are combined to fill in occlusions. The typical point spacing for the original scans collected on this project was between 0.02 and 0.03 m on the cliff face. However, for modeling and analysis purposes, a grid cell size of 0.05 m was used to balance the preservation of detail with adequate sampling to minimize data shadows and noise through the centroid smoothing process. The algorithm can potentially be applied to datasets of lower resolution, although adjustments and calibration of the RAI formulation may be needed.

2.2 Rock Slope Morphology Mapping

Rock slopes evolve in response to instabilities within the rock mass and from deterioration of the rock slope face. Instability of rock slopes is largely governed by structural controls within the rock mass (e.g., orientation and strength of discontinuities) and initiating factors such as antecedent precipitation (leading to increased groundwater pressures), seismic loading, and removal of supporting rock mass due to erosion or prior rockfall. In contrast, deterioration is a

shallow phenomenon involving progressive physical and chemical alteration of rock material culminating in their detachment and removal (Nicholson 2004). These mass wasting processes ultimately govern the shape and form of a rock slope and thus are reflected in a slope's morphology (Selby 1993). Accordingly, the first step in the RAI method involves classification and mapping of the principal morphological features across a rock slope. These morphological classifications not only reflect local features of the rock slope but also indicate the mass wasting processes acting on different regions of the slope face.

In formulating the morphological classification scheme, we sought a balance between complex categorizations that encompass the full spectrum of slope behavior and highly simplified classifications that omit key slope processes. At our field study sites, and in our experience at other places, we observed several fundamental rock slope morphologies that were adopted for our classification scheme. Our most common observations pertained to rough, jagged slope morphologies reflecting discontinuous masses of rock across a range of scales. We also observed areas comprised of relatively intact rock, overhanging rock, and zones of talus accumulation. These morphologies (and related rock material) are associated with different slope processes, each having unique rates of activity.

We ultimately chose seven morphological classes that have unique styles of topographic and geomorphic expression.

Discontinuous rock involves intact blocks or fragments of rock separated by joints, bedding, or other planes of weakness. Mass wasting in discontinuous rock typically occurs through the release of one or more rocks leading to rockfall. Rates of activity in

discontinuous rock vary as a function of rock mass characteristics and environmental factors (e.g., precipitation, freeze-thaw cycles). Recognizing that discontinuous rock occurs across a range of scales, we assigned sub-classifications depending on discontinuity spacing:

(1) *widely to moderately spaced discontinuous rock* (D_w) typically has a joint spacing of 30 cm or greater,

(2) *closely spaced discontinuous rock* (D_c) typically has a joint spacing in the approximate range of 10 cm to 20 cm, and

(3) *fragmented discontinuous rock* (D_f) typically has a joint spacing less than 10 cm.

It is worth noting that while the discontinuous rock classifications do not explicitly consider the orientation of discontinuities relative to the slope face (i.e., dip or anti-dip slopes), this factor may be expected to be indirectly captured in the instability rate, which is introduced in the section below.

Intact rock (I) involves rocks that have only a few or relatively minor discontinuities. Well-indurated *intact rock* is commonly among the most stable material within a rock slope, while softer and weaker *intact rock* (such as argillaceous rock) can be highly susceptible to disintegration, surface erosion, and raveling.

Overhanging rock is commonly the outcome of differential erosion between rock units resulting in the formation of cantilevered slabs (e.g., Paronuzzi and Serafini 2009). Rock in these settings often fails by tensile fracture, which typically results in sudden,

catastrophic release of rock debris. Susceptibility to fracture varies as a function of geometry, with horizontal (or subhorizontal) overhangs being more cantilevered and thus less stable than steeply inclined overhangs. Accordingly, we sub-classified rock slope morphologies in these settings as either (5) *cantilevered overhang* (O_c), whose lower portion is inclined at 150° or greater, or (6) *steep overhang* (O_s) [Figure 1].

Finally, we recognize areas of debris accumulation, or (7) *talus* (T), which is often located near the toe of a slope or on benches along slope face. Mass wasting of talus typically occurs by erosion and raveling. The morphological classes are summarized in Table 1.

Commensurate with the goals of developing a repeatable rockfall assessment technique, we sought to implement the RAI method as a simple logic tree algorithm. To accomplish this, we developed simple rules to classify slope regions based on the seven morphological classes (Table 1). To ensure clarity in the classification procedure, we opted for a rules-based approach involving common morphological parameters over potential alternative approaches such as machine learning or other similar artificial intelligence-based techniques. As surface roughness is strongly correlated to geomorphological features (e.g. Frankel and Dolan; 2007, Berti et al. 2013), we adopted this parameter along with local slope as the key decision parameters (Table 2). The slope was computed for each cell of the point cloud derived grid based on the 3D normal vector. Slope values range from 0° (horizontal) to 90° (vertical) to 90°-180° for overhangs (these angles are measured clockwise from horizontal for slopes that dip to the right in profile). Roughness was computed over two scales (35- and 85-cm windows; i.e., R_{35} and R_{85}) to capture

both fine-grained surface characteristics as well as larger-scale rock slope surface features. There are multiple ways to compute roughness (e.g., Shepard et al. 2001); however, for this work, we adopted standard deviation of slope because this approach has been shown to provide a simple and reliable measure of this parameter (Grohmann et al. 2011; Berti et al. 2013).

Figure 2 shows the classification algorithm. The slope is first used to identify rock overhangs, which are then sub-classified based on their inclination (O_c or O_s ; Figure 1). Fine-grained roughness is used to identify relatively smooth material ($R_{35} < 6^\circ$), which are then sub-classified as talus (T) or intact rock (I) based on slope. We adopted a threshold slope value of 35° as this is the typical angle of repose of talus, which largely consists of rock fragments and gravel. A material having a high degree of fine-grained roughness ($R_{35} > 11^\circ$) is sub-classified as either widely to moderately spaced discontinuous rock (D_w) or closely spaced discontinuous rock (D_c). Intermediate cases ($R_{35} = 6^\circ$ to 11°) are further classified based on larger scale roughness as either T or I ($R_{85} < 12^\circ$), or for large-scale roughness ($R_{85} > 12^\circ$), as fragmented, discontinuous rock (D_f). The logic tree was initially formulated based on field observations of rock slope morphology and mass wasting processes in different geologic settings. We then iterated and further refined the parameter thresholds (specifically, R_{35} , and to a lesser degree, R_{85}) until an optimal classification performance was achieved. We qualitatively assessed and verified classification performance at 15 field sites based on both accuracy (correct classification of morphologies observed in the field) and resolution—that is, ability to delineate contacts between morphological classes. The classification performance of the model is discussed for two rock slopes later in the paper.

2.3 Rockfall Activity Index (RAI)

The rockfall activity index (RAI) is computed for each 1-m length segment of rock slope as:

$$\sum_{i=1}^n \frac{1}{2} m_i v_i^2 r_j \quad (1)$$

Where $(\frac{1}{2}mv^2)$ represents the kinetic energy of a falling rock, n is the number of rock slope cells within a 1-m segment, i is the cell number, r is the instability rate for each morphology classification, and j is the number of morphology classifications within a 1-m segment.

Mass is determined as the product of rock volume and specific gravity G (where G is typically assumed to be ~2.6; Goodman 1989). Volume is a representative size for rock for each morphological classification (Table 1). The estimated volume is based on the cell area multiplied by the depths presented in Table 1, which represent typical per-cell values that were determined based on annual change detection data collected at the field study sites. Note that the volumes adopted for the non-overhanging morphologies (i.e., D_w , D_c , D_f , I , and T) reflect the scale of the rock fragments associated with each respective classification. Rock overhangs (i.e., O_c and O_s) have significantly higher volumes, which reflects both the large failure masses and the comparatively high ratio of rock volume to surface area of the overhang's lower face.

Velocity computations are based upon assumed free fall distance between the point of release and the toe of the rock slope (along transportation corridors, the latter typically corresponds to the elevation of the road surface). The free fall assumption allows us to make a simple estimation

of velocity without the need to consider energy losses resulting from the impact of rock fragments with the slope surface once a rock is in motion. Velocity is computed using Newton's first law of motion as $v = (2gh)^{0.5}$. Here, h is the vertical distance between the point of release and toe of the slope, and g is the acceleration due to gravity (9.8 m/s^2).

The instability rate (r) is the fraction of the cells within a morphologic unit that are expected to fail over a typical one-year period. We estimated r based on sTLS-derived annual change detection data collected at the study areas (Table 1). Hence, the values presented in Table 1 reflect the average number of cells within a morphological class that changed over the ~1-year change detection period. Note that the overhangs (O_c and O_s) exhibit the highest rates of activity (or instability). By contrast, the more stable I and T morphologies have comparatively lower rates of activity. We recognize that high-resolution change detection data is not available for most common projects, and therefore we have provided estimates of what we believe to be realistic ranges of r for each morphological class based on our collective experience with change detection monitoring at several rock slope study sites worldwide. Nevertheless, it should be recognized that r represents rock slope activity rates, which vary based on rock type, weathering, subsurface characteristics (e.g., discontinuity orientation, groundwater level), and environmental conditions, among other factors. Therefore, when selecting r based on our range estimates, it should be understood that these values are associated with a high degree of variability and uncertainty.

3. Application of RAI Method to Field Study Sites in the State of Alaska, USA

The RAI method was applied to field study sites in southern Alaska, USA (Figure 3). Rock slopes at these sites were selected for this research because of their high rates of activity, their proximity and access to major roadways, a relative absence of vegetation, and the lack of rock slope mitigation works. In total, 15 individual stretches of rock slope located throughout southeast and central Alaska were evaluated in the research; however, for brevity, we will focus on two sites with different rock types and slope morphologies. The lower portion of Alaska is situated within an active subduction zone, and the geology of the region is largely a product of ongoing terrain accretion. Rock slopes at these study sites were excavated during construction of State Highway 1 (locally known as "Glenn Highway"). Glenn Highway follows a glacially cut valley through the Matanuska and Chickaloon geologic formations, which mainly consist of sedimentary material of continental origin that were eroded during uplift of local mountain ranges and subsequently deposited in the region (Trop and Plawman 2006). The sites have a long history of rockfall due largely to the combination of the region's extreme climate (and associated freeze-thaw cycling), steep artificial cuts, and unfavorable structural controls within the rock masses. The rock slope faces were free of direction stabilization measures (e.g., rock bolts), which could artificially modify their behavior. Where employed, rockfall mitigation measures were limited to narrow roadside catchments.

3.1 Rock Slope Study Sites

Rock slope A is an approximately 60 degree, ~8-m-high road cut located near milepost 85.5 of Glenn Highway (Figure 4). Rock at Site A consists of fine- to medium-grained, moderately weathered gray and tan hard sandstone of the Chickaloon Formation. The rock mass includes three approximately orthogonal discontinuity sets that produce well defined ~10 to ~30 cm rock

blocks. Seepage was not observed at the site during several summer seasons of the fieldwork. Mass wasting of the rock slope occurs through release of these blocks resulting in numerous small rockfalls.

Rock slope B is located several km away near milepost 87; it consists of a ~10-m-high road cut inclined at approximately 50 degrees (Figure 5). The site includes soft argillaceous rocks (carbonaceous siltstones) of the Chickaloon Formation that have been intruded by hard, well-indurated mafic sills (basalt). A major anti-dip (i.e., dipping into the slope, with favorable structural control) discontinuity set is defined by the orientation of the contact with the intrusive basalt unit. This dominant set, along with other irregular joint sets in the sill material, produces rock fragments having maximum dimensions in the range of ~20 to ~200 cm. The significant contrast in strength between the siltstone and sill (basalt) material has resulted in differential erosion features including cantilevered overhanging rocks. Once again, seepage was not observed at the site during the fieldwork. Mass wasting along the lower portion of the slope occurs through erosion, disintegration, and raveling of the soft siltstone. Along the upper portion of the slope, mass wasting occurs both through the release of rocks defined by discontinuities in the sill material, as well as through tensile fracture and collapse of the cantilevered sill rock.

3.2 Results

Figure 6 shows the sTLS-derived shaded relief image, morphology classification, and source mapping for Rock Slope A. The blocky structure of the rock mass is apparent in the shaded relief image, as are rock overhangs along the upper part of the slope. The overhanging rock is highly cantilevered and localized along the right (east) portion of the slope. Below this is a large,

continuous area of relatively smooth material. To the west, the morphological classification shows a patchy network of both steep (O_s) and cantilevered (O_c) rock interspersed by variably sized discontinuous rock (D_w , D_c , and D_f) across almost the entire face of the slope. An apron of talus is found across the bottom of the slope. Toward the east, the morphological profile is more continuous, where intact rock (I) is shown below a localized overhang. Panel C provides a color intensity diagram showing the areas making significant contributions to the RAI (shown in orange to red hues). The diagram indicates that along the western portion of the rock slope, areas making large RAI contributions are distributed across the full height of the slope face, while to the east major contributing areas are significantly more localized along the top of the slope. The RAI segment profile (Panel D) indicates a relatively high rockfall hazard (i.e., high RAI values) to the west, which becomes more moderate further to the east. The RAI values properly trend toward 0 near the margins of the rock slope.

Figure 7 shows different spatial patterns for Rock Slope B. The shaded relief image clearly reveals the differential erosion processes acting near the sill intrusion, which has led to a series of highly cantilevered overhangs that traverse almost the entire length of the slope. This is also reflected in the morphology classification (Diagram B), which shows west-to-east rock overhangs (mostly O_c) interspersed by largely continuous areas of intact material (I). A smaller, patchier network of discontinuous rocks is also present across the slope. Diagram C shows that the rock overhangs are almost fully responsible for the RAI segment score, and thus the rockfall hazard. This is particularly true in the upper reach of the slope, where the dark red hues indicate high RAI contributions that result from the combination of the large volume of overhanging rock and the height of the overhang above the road surface. The RAI segment profile is relatively

consistent, but high RAI values are shown along several local stretches where multiple overhangs are present over the vertical profile.

The RAI 1-m segment values can be summed to provide a relative hazard assessment for the entire length of a rock slope. For example, the total RAI value (i.e., area under the Panel D curves) for Rock Slopes A and B are 699 and 1369 kJ, respectively. (By comparison, a single 5 kg rock dropped from a height of 5 m delivers 50 kJ of kinetic energy to the road surface.) The larger total RAI value for Rock Slope B reflects its size (i.e., face area), which is about twice as large as Rock Slope A.

4. Discussion

Qualitative comparison of the study site photographs and shaded relief images with the morphological mapping indicates that the automated classification routine of the RAI method is performing well at the field study sites. This was further supported by our field assessment and verification at 15 additional rock slopes studied as part of the research. The morphology classification and mapping is particularly valuable because it can be used to infer localized processes acting on rock slopes. For example, the automated morphological mapping of Rock Slope B suggests that erosion of the intruded, intact material located directly beneath the sill is controlling the development of the critical rock overhangs. The intact classification (*I*) indicates that few if any, major discontinuities exist in this area of the rock slope, and therefore mass wasting at this location is likely to occur as an ongoing erosive process involving the release of small rock fragments, rather than by rock fall involving larger blocks. In fact, this is the active process we observed in the field, with soft carbonaceous siltstones gradually, but continuously,

eroding. As this process continues, the capacity of the stronger sill units (overhangs) will be exceeded leading to sudden collapse and release of a large volume of rock debris. The historic record of Glenn Highway maintenance operations, the patchwork of fresh rock scars visible in the road surface, and the volume of debris in the catchments together suggest this to be the case. At the other study location (Rock Slope A), the morphological classification and mapping suggest that the western portion of the rock slope will evolve through the ongoing release of small to large rocks across the full height of the slope. The eastern portion, which consists of intact rock and talus, will evolve through raveling and shallow erosion of the rock face. Once again, we observed this active process during our fieldwork.

The RAI mappings (panel C) together with the RAI segment profiles (panel D) are valuable for identifying precisely the areas that make the most significant contributions to the rockfall hazard and for understanding the relative size distribution of rockfall events. For example, at Rock Slope A, RAI "hotspots" (shown with red hues) are distributed across the full height of the western portion of the slope but become more localized towards toward the east. These hotspots correspond to local areas that tend to release large volumes of rock (e.g., rock overhangs) and rockfall source areas that are located well above the base elevation of a slope and thus are capable of producing large amounts of kinetic energy. Local areas contributing somewhat less to the rockfall hazard (shown in orange hues) may also be important in some settings. At a more practical level, the RAI mapping may also be used to identify slope segments warranting more detailed assessment and to inform rockfall mitigation strategies. For example, the mapping of Rock Slope A suggests that face meshing or rockfall catchment may serve as optimal rockfall mitigation techniques along the western portion of the slope, while toward the east, scaling of the

localized overhang may be a more effective approach. In addition to the RAI mapping and segment scores, the total RAI values for each site serve as a useful indicator of relative hazard level and could be used to identify rock slopes requiring further evaluation and if appropriate, mitigation actions.

When computing the RAI for a rock slope, the most significant source of uncertainty is the estimated instability rate r , which is a function of setting and may be expected to vary temporally in response to climate fluctuations. Still, in simple parametric trials, we found that the RAI is not highly sensitivity to this parameter. Instead, the RAI is largely governed by factors directly related to kinetic energy: release location and mass, both of which are relatively well constrained. In preliminary studies involving three sTLS surveys over a two-year period at several of the sites, we found annual r values to vary by no more than 20%, suggesting only a modest difference over the study period.

Finally, it should be recognized that similar to other rock slope systems, the RAI method was developed to address chronic rockfall hazards that exist under aseismic conditions. In its current formulation, the RAI method will not specifically address seismically induced rock slope failure, which can also contribute to rockfall risk at some locations.

5. Conclusions

Rockfall causes property damage and human losses in mountainous regions of the world. The impacts of rockfall are especially severe along transportation corridors, where many tens of millions of dollars are spent each year on rockfall hazard mitigation and maintenance works. In

transportation geotechnics, it is common to assess rock slope hazards using one of the several available rockfall hazard rating systems. While these systems can help public agencies and owners identify hazards and prioritize mitigation efforts, they are often highly qualitative in nature (Budetta and Nappi, 2013) and have a coarse spatial resolution. Capitalizing on recent developments in high-resolution remote sensing technologies, we have introduced the Rockfall Activity Index (RAI), a point cloud-derived method for assessing rockfall hazards. The RAI method has been implemented as a simple and computationally efficient algorithm, which makes it repeatable and easy to apply, even for large rock slopes.

When applying the RAI method to rock slope study sites located in Alaska, we found that the morphology-derived classification and hazard assessment routines provide results that closely match the observed performance of the slopes. The morphology classification mapping is valuable since this can be used to infer localized processes acting on rock slopes, while the RAI activity mapping is useful for identifying precisely the areas that make the most significant contributions to the overall rockfall hazard at the site. This information can be used to identify slopes requiring more detailed assessment and to inform rockfall mitigation strategies.

We continue to monitor our study sites in Alaska and are also applying the RAI methodology at additional locations worldwide to test and assess its efficacy in other geologic settings. Future research will focus on the use of point clouds developed using other geomatics technologies (e.g. mTLS and SfM) and also investigate temporal variability of the instability rate r at the test sites in Alaska and at other locations.

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Figure Headings

Fig. 1 Overhanging rock sub-classifications. (A) cantilevered overhang (*Oc*), whose lower portion is inclined from 150° to 180°. (B) steep overhang (*Os*), whose lower portion is inclined from 90° to 150°.

Fig. 2 Point cloud-derived rock-slope morphology classification algorithm. Morphology parameters and threshold values are indicated in black and blue, respectively, while morphological classes are indicated in red.

Fig. 3 (A) Location of field study sites in southern Alaska, USA. (B) Location of rock-slopes A and B along Alaska State Highway 1 (“Glenn Highway”).

Fig. 4. (A) Rock-slope A is an approximately ~8-m-high road cut that includes zones of talus accumulation (B), closely spaced and fragmented discontinuous rock (C), and overhanging rock (D).

Fig. 5 (A) Rock-slope B is an approximately ~10-m-high road cut that includes zones of intact rock (B), overhanging rock (C) and closely spaced and fragmented discontinuous rock (C), and closely to widely spaced discontinuous rock (D).

Fig. 6 (A) sTLS-derived shaded relief image of rock-slope A. (B) RAI method morphology classification. (C) RAI source mapping. (D) RAI 1-m segment profile.

Fig. 7 (A) sTLS-derived shaded relief image of rock-slope B. (B) RAI method morphology classification. (C) RAI source mapping. (D) RAI 1-m segment profile.

A. Cantilevered Overhang (Oc)

B. Steep Overhang (Os)

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Table 1: RAI method morphological classes and associated failure mass depths and instability rates

Morphological Classification	Description	Estimated depth of failure mass (m)¹	Instability rate (<i>r</i>) [%]²	Estimated typical range of instability rate (<i>r</i>) values³
<i>Widely to moderately spaced discontinuous rock (D_w)</i>	Intact blocks or fragments of rock separated by discontinuities typically spaced at ~30 cm or greater	0.3	0.71	0.4 to 3.0
<i>Closely spaced discontinuous rock (D_c)</i>	Intact blocks or fragments of rock separated by discontinuities typically spaced between ~10 cm and ~20 cm	0.2	0.34	0.2 to 2.0
<i>Fragmented discontinuous rock (D_f)</i>	Intact blocks or fragments of rock separated by discontinuities with a typical spacing of less than ~10 cm	0.1	0.18	0.1 to 1.0
<i>Intact rock (I)</i>	Rockmass with few or relatively minor discontinuities	0.05	0.1	0.02 to 0.3
<i>Cantilevered overhang (O_c)</i>	Overhanging rock whose lower portion is inclined at less than 120° [see Figure 1]	0.5	1.98	1.0 to 5.0
<i>Steep overhang (O_s)</i>	Overhanging rock whose lower portion is inclined at greater (i.e., steeper) than 120° [see Figure 1]	0.75	1.97	1.0 to 5.0
<i>Talus (T)⁴</i>	Mass wasting-derived rock fragments (debris) accumulated at the base of a slope, or along benches within a slope	0.025	0	0 to 0.4

1. Estimated depth of the failure mass is based on annual change detection data collected at the field study sites. The resulting failure volume for each 5-cm by 5-cm slope face cell is computed by multiplying the cell area (i.e., 25 cm²) by the estimated depth of the failure mass.

2. The instability rate *r* is computed as the fraction of the cells within a morphologic unit that failed (eroded) based on annual change detection data obtained at the field study sites in Alaska, USA.

3. The typical range of *r* values is estimated based on the authors' involvement with change detection studies at rock-slope sites worldwide. The values vary based on a variety of factors including rock type, weathering, subsurface characteristics, and environmental conditions with lower bound values correspond to relatively stable conditions while upper bound values pertain to highly active rock-slopes. Note that these values are associated with a high degree of variability and uncertainty.

4. The *r* value represents erosion and raveling of talus.

Table 2: Point cloud-derived morphological parameters used in the RAI method (point cloud spacing = 5 cm).

Morphological Parameter	Units	Description
Roughness over 35 cm square area (R_{35})	Degrees	Standard deviation of slope over a 35-cm by 35-cm square window of cells (i.e., 7 cells by 7 cells)
Roughness over 85 cm square area (R_{85})	Degrees	Standard deviation of slope over a 85-cm by 85-cm square window of cells (i.e., 17 cells by 17 cells)
Slope	Degrees	Slope computed from the 3D normal vector for each cell. Values range from 0° (horizontal) to 90° (vertical) to 180° (overhang)