DOI: https://doi.org/10.68732/27723e3e814e4006

ISBN: 978-9989-2053-6-1

Novel approaches for the evaluation of the roughness of discontinuities and failure surfaces in landslides and rock slopes

O. Chang
XRGeo Technology Inc, Burnaby, Canada
omar.chang@xrgeo.com

D. Stead
Simon Fraser University, Burnaby, Canada

D. Donati
Alma Mater Studiorum – University of Bologna, Bologna, Italy

Abstract

The evaluation of surface roughness has several important applications in the field of engineering geology. Discontinuities, such as joints and faults, control the stability of potentially unstable rock mass volumes at various scales. At the outcrop- and bench-scale, surface asperities contribute to the shear strength of discontinuities, angle of friction and apparent cohesion defining the stability of discontinuity-bounded blocks. At the slope scale, the roughness waviness of basal and lateral release surfaces has a significant impact on both the overall stability and the kinematics of rockslides. On the surface of large landslides, spatial variations in morphological roughness represent subsurface changes in orientation of the basal surface.

The importance of geological surface roughness has long been recognized; however, the methods routinely used for its evaluation still employ fixed orientation, and two-dimensional approaches. Field-based assessments are not fully exploiting high-resolution three-dimensional datasets collected through remote sensing methods. In this work, we demonstrate the application of a suite of innovative digital tools developed to allow the characterization of surface roughness across different spatial scales, using datasets from both internationally renowned landslides and typical rock slopes. The proposed algorithms provide a detailed roughness analysis of discontinuity and topographic surfaces that can be applied both at the outcrop scale and the landslide scale. As numerical modelling and 3D remote sensing become standard in engineering geology, high-resolution characterization of surface roughness at multiple spatial scales will become increasingly important. This work lays the foundation for the enhanced fidelity of complex numerical modelling and improved methodologies for risk assessment and slope stability analysis.

Keywords

Surface roughness, Landslide, Rockfall, Digital reconstruction, Remote sensing.

1 Introduction

In the field of engineering geology, surface roughness represents a key consideration in assessing the stability and evolution of rock slopes at various scales. At the centimetre-scale discontinuities (e.g., single joints), surface roughness controls the shear strength and resistance to sliding of blocks and rock mass volumes and can be quantified using the joint roughness coefficient (JRC). Surface roughness along a rupture surface can spatially vary based on discontinuity set characteristics as well as presence of failed rock bridges (Elmo, 2023). In the field, it can be estimated using profilometers and alloy disks of varied sizes (ISRM, 1978). At larger, meter- or multimeter-scale, overall waviness of the surface can control both shear resistance and landslide kinematics. Landslides moving along bi- or multi-planar sliding surfaces require internal deformation and damage to occur before the unstable volumes are displaced. The resulting damage surface reflects the internal deformation of the landslide body, which in turn is controlled by basal surface morphology and displacement direction (Donati et al., 2021). The introduction of remote sensing methods, such as photogrammetry and laser scanning, for the digital 3D reconstruction of surfaces has enabled more accurate assessment of surface roughness (Tatone and Grasselli, 2013; Zou et al., 2023; Chang et al. 2024). However, methods routinely used for its evaluation still employ statically anchored reference values and restricted two-dimensional resolution approaches. This paper aims at bridging this gap, demonstrating the use of a suite of innovative digital tools that allow surface roughness to be qualitatively and quantitatively measured across different spatial scales, orientations, and conditions, from rockfall scars to the ground surface of major landslides. The tool is tested at two sites in British Columbia (Canada), namely the Stawamus Chief and the Downie Slide.

2 Background information

With the rapid advancement of remote sensing technology, the ability to create digital twins from large scale to small scale applications have become increasingly available (Chang et al, 2024). This rapid advancement has resulted in an influx of high resolution and multi-sensor datasets that are currently being underutilized. For geological analyses aimed at assessing surface roughness, geoscientists can rely on a number of dataset types that can be classified based on the spatial dimension. Two-dimensional datasets (2D) are profiles or imagery which only contain two axes (e.g., photographs or profiles). Two and half dimensional datasets (2.5D) are 2D representations that carries a single value per cell or point (e.g., contours, DEM). Three-dimensional datasets (3D) provide perspective and relativity, allowing observations along different orientations and visualization of complex geometries. The visualization of these datasets in a digital space provides the user the ability to switch between different dimensional domains and datasets. This dimensional fluidity has improved user's capability to visualize complex structures and datasets and allowed the derivation of simplified 2D and 2.5Ddatasets that can be used for quantitative measurements, pattern recognition, and spatial reasoning that remains challenging using fully 3D datasets, inherently characterized by greater complexity. However, the simplification of geospatial data also leads to constraints. Many techniques and methods, such as JRC, were developed for field or laboratory use. The simplification or roughness through the derivation of 2D measurements was due to practical necessity, as acquiring multi-orientation data was largely unfeasible, due to limited surface accessibility and time constraint, resulting in errors due to inhomogeneity caused by orientation and scale (Barton and Choubey, 1977).

Over the past two decades, there have been significant improvements in 3D data collection and numerical capabilities, yet, data collection and interpretation procedures have remained largely unchanged, with standard field protocols being applied to higher resolution, digital datasets. As a result, digital and virtual mapping and numerical modelling procedures are also affected by the same pitfalls and restrictions of field methods, preventing the full exploitation of sophisticated 3D datasets. The growing capability to acquire rich 3D datasets therefore demands a fundamental shift in standardization: rather than adapting 3D data to fit legacy 2D workflows, new robust and systematic standards should be built around 3D representation.

3 Methodology

This study aims at i. demonstrating digital tools used to investigate the role and impact of roughness orientation and scale in geomechanical interpretation and ii. preliminarily testing such tools at two

unstable rockslopes located in British Columbia, Canada, namely the Stawamus Chief and the Downie Slide.

By defining surface profiles through software developed in-house, reference dependency is highlighted. The impacts of location and orientation of the roughness profiles are outlined and discussed by comparing differently oriented profiles from the same location and surface The manner in which the profiles are depicted mirrors the conditions under which standards such as JRC are typically applied, i.e. where orientation is commonly evaluated either down dip or arbitrarily picked, rather than systematically analysed and optimized for the study site. A new procedure is proposed that helps in eliminating orientation bias in profile determination by systematically investigating roughness indifferent directions at each location and allowing roughness orientation sensitivity analysis to be undertaken. The proposed technique can represent the basis for the creation of roughness directionality maps, that can be used to highlight how roughness and asperities vary spatially and directionally across surfaces at various scales.

3.1 Case study 1: The Stawamus Chief

Stawamus Chief, often colloquially referred to as "The Chief" is a granitic monolith located immediately east of the town of Squamish, 30 km north of Vancouver (BC, Canada).The monolith is constituted by a competent, high quality, massive rock mass, with ubiquitous surface-parallel sheeting and exfoliation joints (Coughlan, 2024).The slopes of the Stawamus Chief have been affected, over the last decade, by several rockfall events. In 2021, the most significant recorded rockfall occurred along the "Grand Wall", in the southern sector of the monolith, and involved a volume of 3000 to 3500 m^3 (Ashwood and Manicke, 2021). The Grand Wall is characterized by a prominent, arc-shaped overhang that represents one of the most active rockfall sources of the rock slope. 3D laser scanning data was collected before and after the rockfall allowing a detailed study of the Grand Wall (Chang et al., 2024).

3.2 Case study 2: Downie Slide

The Downie Slide is a 1 billion m^3, slowly moving rockslide located on the western slope of the Revelstoke Reservoir (Columbia River valley, BC, Canada), about 70 km north of Revelstoke dam. The instability extends 3.3 km across and 2.4 km along the slope, between elevation 507 m a.s.l. and 1520 m a.s.l., and has a maximum thickness of 250 m (Kalenchuk et al. 2013). The landslide affects the metamorphic succession of the Monashee Complex, consisting of schist, gneiss, quartzite, and marble of Proterozoic to Lower Paleozoic (Read and Brown, 1981).The landslide surface gently slopes towards the east with an average slope angle of 18°, increasing to 40° in the lower part, near the shore of the Revelstoke Reservoir. The ground surfaceis characterized by lineaments and fractures that are controlled by rock mass discontinuities, displacement trends, and basal surface morphology (Donati et al., 2021) and in turn control morphological roughness (Westin, 2015). Based on the geomorphic characteristics of the landslide ground surface, various domain subdivisions have been proposed for the landslide. In the present study, we consider the subdivision proposed in Donati et al. (2021), in which domains are defined based on intensity and orientation of surface slope damage features.

4 Results

4.1 Case study 1: The Stawamus Chief

Two perpendicular series of 2-m spaced, parallel profiles were traced along a photogrammetric 3D model of the Grand Wall (Fig. 1a), with the objective of detecting topology differences, morphological features and anomalies (Fig. 1). The spacing of the traces and the normal angle between profile sets were arbitrarily defined. Profiles were obtained to the left (PL) and right (PR) of the anchor profile (P-0) and then stacked to visualize topological variations across profiles (Fig. 1c,e). Topological variance was evident based on location and orientation. Variation is indicative of rock mass structures, failure surfaces, changes in rugosity, rock bridges, and inhomogeneity.

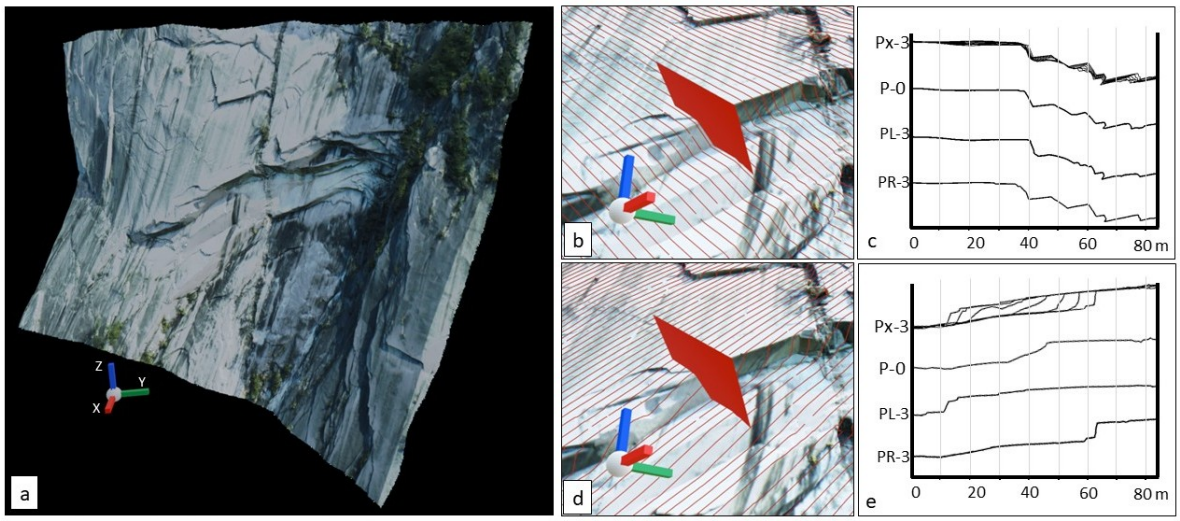


Fig. 1 Profile analysis for the Grand Wall of the Stawamus Chief. (a) Photogrammetric 3D model, with traces of profiles parallel to the reference plane (20 m x 20 m, red plane).Spacing between profile traces is 2m. Traces are constructed (b,c) parallel or (d,e) perpendicular to the reference plane. Derived traces are then stacked (Px -X) where "X" determines the number of stacks in respect to the left (PL) and right (PR) of the reference plane (P-0).Each trace is also examined individually (e.g., PR-3 = Three profiles to the right of P0).

Characterizing orientation dependency and inhomogeneity of the rock mass along the entire surface of the outcrop may not easily allow the identification of spatial variation in surface roughness. A radial sampling approach (referred to as "coral" analysis), in which the mesh is evaluated across a wide range of orientations, is therefore proposed to investigate three-dimensional roughness variability in various parts of the model, at the same time minimizing the orientation bias (Fig. 2). In this sense, choosing appropriate interval angles ensures that no orientation is overlooked, providing a complete geometric envelope for subsequent analysis (Chang et al., 2026).

The radial roughness approach can provide a quantitative depiction of the slope surface roughness in different orientations and locations. A visual analysis of the Grand Wall of the Stawamus Chief shows topological variations controlled by the ubiquitous presence of sheeting and exfoliation joints. Variations in the selected length of the radial profiles can also affect the results, emphasizing the importance of scale on roughness quantification.

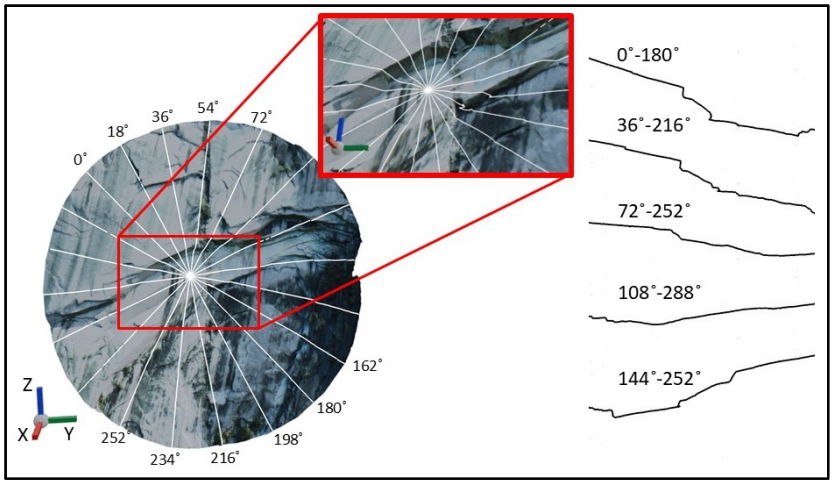


Fig. 2 Overview of the Stawamus Chief analysis, showing a portion of the 3D mesh investigated using a coral approach, and a set of profiles determined in a radial manner to remove orientation bias.

4.2 Case study 2: Downie Slide

The slope damage domains outlined in Donati et al. (2021) are characterized by the presence of morphological features, such as tensile fractures, depressions, scarps, and hummocky regions, the spatial distribution and orientation of which is controlled by the morphology of the basal surface and, in turn, the displacement orientation (Fig. 3). To qualitatively assess the changes in landslide surface roughness and its directionality, a radial set of profiles was traced within each of the identified slope damage domains.

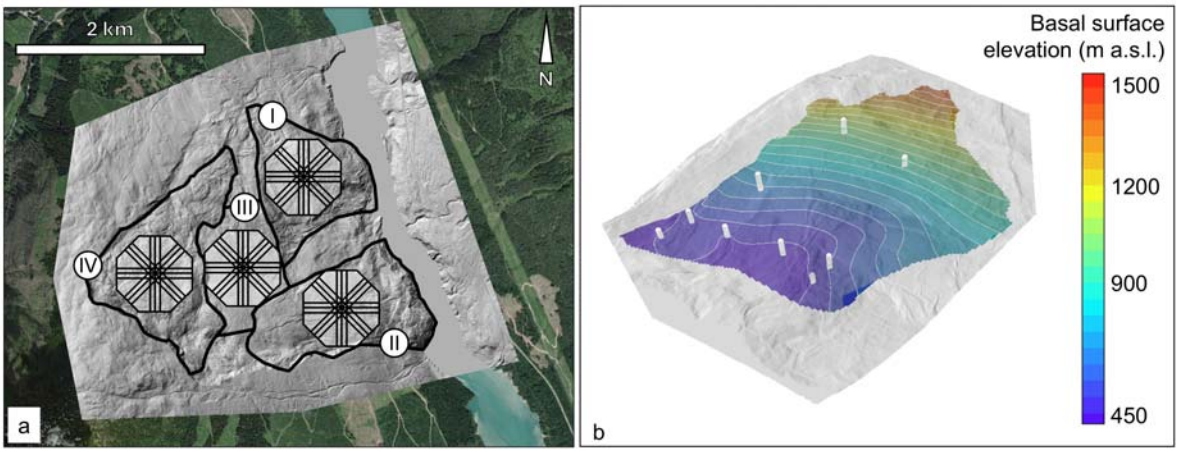


Fig. 3 Downie slide. (a) Hillshade map of the Downie Slide area. The slope damage domains described in Donati et al. (2021) are outlined in black and identified with roman numerals (cfr. fig. 6). Corals used for analyzing each domain are overlaid on the map. (b) 3D view of the basal surface of the Downie Slide, which has been recognized to control the distribution and orientation of surface damage features. The white lines show the depth at which the basal surface was identified within in-hole inclinometers.

For the radial profiles, a length of 400 m was selected, corresponding to the dimension that could fit all domains, to enhance comparison between the different profiles. Four orientations were investigated, with 45° angular offset. For each direction, three parallel profiles, spaced 55m apart, were traced. Therefore, a total of 12 profiles is obtained for each domain. The lowermost part of the basal surface of the Downie Slide is characterized by significant changes in orientation, which control the occurrence of N-S tensile cracking in the central part of the "North knob" (Domain I in Fig. 4), and E-W oriented lineaments and scarps in the "South knob" (Domain II in Fig. 4). The profiles show a marked directionality, with relatively rougher profiles in the N-S (0°-180°) and E-W (90°-270°) directions, respectively. The "Central domain" (domain III in Fig. 4) is characterized by a relatively smooth surface, due to the presence of a locally planar basal surface that allow displacement without little internal deformation and surface damage. Profiles for all directions display such smooth morphology, except for a limited area at the northernmost limit of the domain. The "Upper hummocky region" (domain IV in Fig. 4) progressively formed through block accumulation following landslide head scarp retrogression. Due to its blocky nature, the domain is characterized by the absence of significant directionality in morphological roughness.

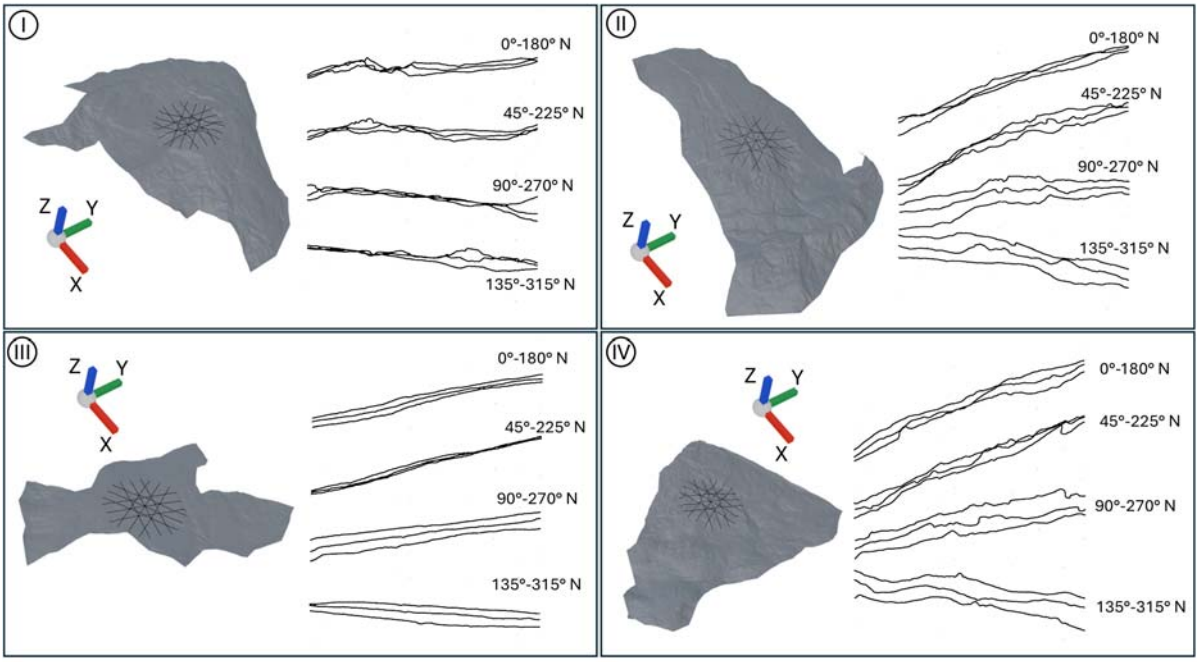


Fig. 4 Overview of the radial profiles traced across the slope damage domains at the Downie Slide. For each domain, a 3D view of the radial profile and the stacked sets of profiled for each direction is shown. The horizontal length of all profile is 400 m. Note the smoothness of profiles in the 90°-270° direction in domain I and in the 0°-180° direction in domain II. See text for additional preliminary interpretation and Figure 3 for the location of domains and radial profiles (corals).

5 Outlook and future development

In this paper, new tools, currently under development, for assessing the spatial variability of surface roughness at various scales were introduced. With more data input and refinement, these tools presented have the potential to significantly reduce orientation bias that has long been embedded in conventional engineering geological practice by relying on a single orientation. The implication of this shift extends across scale and application. Future development will focus on expanding validation datasets, incorporating a broader range of failure mechanisms, geological settings, and data acquisition methods. This represents a standardized orientation sensitivity analysis that is applicable at all scales. Moreover, the use of radial profiles across large surfaces can allow the creation of directional roughness maps that can assist geoscientists and engineers in the identification of geomorphological domains across landslide surfaces and rock slopes.

References

Ashwood, W, Manicke, H (2021) Preliminary Rock Fall Assessment, The Black Dyke - Grand Wall, Stawamus Chief, Squamish, B.C.021-134. Westrek GeotechnicalServices Ltd.

Chang, O, Stead, D, Elmo, D, William-Jones, G (2024) Application of mixed and virtual reality in deep mining, Deep Mining 2024: Proceedings of the 10th International Conference on Deep and High Stress Mining, Australian Centre for Geomechanics, Perth, pp. 867-878, https://doi.org/10.36487/ACG_repo/2465_54

Chang, O, Stead, D, Donati, D (2026). New approaches to the characterisation of discontinuity roughness and landslide failure surfaces.Geohazard9, Edmonton (AB, Canada), 1-3 June 2026 (in press).

Coughlan, BT (2024) Rockfall hazard assessment of the Stawamus Chief using multi-temporal remote sensing analysis. MSc Thesis, Simon Fraser University.

Donati, D, Westin, AM, Stead, D, Clague, JJ, Stewart, TW, Lawrence, MS, Marsh, J (2021) A reinterpretation of the Downie Slide (British Columbia,Canada) based on slope damage characterizationand subsurface data interpretation. Landslides 18:1561–1583. DOI: 10.1007/s10346-020-01601-5

Elmo, 2023. The Bologna Interpretation of Rock Bridges. Geosciences13(2), 33. https://doi.org/10.3390/geosciences13020033

Fofonoff, S, Schlotfeldt, P, Wyllie, D (2015) Preliminary Geotechnical Review,Angels Crest Rock Fall, Stawamus Chief, Squamish, BC. GeoPacific ConsultantsLtd.

ISRM (1978). Suggested methods for the quantitative description of discontinuities in rock masses. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 15 (6), 319–368

Kalenchuk KS, Hutchinson DJ, Diederichs MS (2013) Geomechanical interpretation of theDownie Slide considering field data and three-dimensional numerical modelling.Landslides 10:737–756.

Monger,JWH, McNicoll VJ(1993) New U-Pb dates from southwestern coast belt, British Columbia: radiogenic age and isotopic studies: report 7, Geological Survey of Canada Paper 93-2, pp. 119-129.

Piteau DR, Mylrea FH, Blown IG (1978) Downie Slide, Columbia River, British Columbia, Canada. In: Voight B (ed) Rockslides and avalanches, volume 1. Developments in Geotechnical Engineering 14(A):365–392

Read PB, Brown RL (1981) Columbia River fault zone: southeastern margin of the Shuswap and Monashee complexes, southern British Columbia. Canadian Journal of Earth Science 18:1127–1145.https://doi.org/10.1139/e81-108

Tatone, B, and Grasselli, G (2013) An investigation of discontinuity roughness scale dependency using high-resolution surface measurements. Rock Mechanics and Rock Engineering 46, 657–681. https://doi.org/10.1007/s00603-012-0294-2

Zou, C, Li, J, Wu, Y,Yatao, Y, Li, J (2023)2D and 3D evaluation of joint roughness exposed by rock cores. Bulletin of Engineering Geology and the Environment 82, 316. https://doi.org/10.1007/s10064-023-03325-x