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RIDIM: Unveiling Rock Instabilities through Hierarchical Segmentation of 3D Point Clouds

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SUMMARY: RIDIM (Rock Instability Detection and Inventory from a point Cloud Method) (Guiotte et al., 2023) has been developed to map out sections of large, towering rock cliffs that are prone to failure. This method leverages a hierarchical segmentation approach, analysing 3D point clouds using watershed tree method. RIDIM was devised and validated on a lava cliff in Reunion Island. The results not only enable the identification and mapping of unstable blocks but also facilitate discussions regarding the necessary preventive measures to mitigate risks posed by rockfalls along the studied cliff.

Keywords: rockfall, 3D point clouds, hierarchic segmentation, impact energy.

Introduction

Rockfalls pose significant financial and safety risks to both people and infrastructure, necessitating proactive prevention strategies. Conducting expert analyses is crucial for understanding the potential changes in rocky terrains and for evaluating the risks associated with rockfalls. Such analyses involve identifying areas susceptible to rockfalls, establishing stability criteria informed by the lithology of the cliff faces, assessing the likelihood of instability over time, pinpointing areas where rockfalls are likely to extend, and calculating the kinetic energy that could be released by falling rocks.

A rock mass, typically stable, may have its equilibrium disturbed by exacerbating factors. The likelihood of block falls within this mass is closely associated with its shape and intrinsic discontinuities.(Hudson and Priest, 1983).

Traditional rock face stability assessments, conducted through expert analysis, suffer from subjectivity and low spatial resolution. 3D scanning imagery for rocky cliffs emerges as a promising alternative, offering higher spatial resolution and broader coverage (Abellán et al., 2014; Battulwar et al., 2021). Despite progress in automatic or semi-automatic approaches for discontinuity identification within 3D point clouds or ortho-rectified image analysis, these methods demonstrate lower efficiency for highly discontinuous or lower quality rocks such as volcanic formations, and their effectiveness is contingent on the quality and resolution of the reconstruct topographic images. These formations, especially in tropical contexts, exhibit significant anisotropy from thermal cooling fractures and rapid weathering, deteriorating their geomechanical properties.

Hierarchical segmentation algorithms facilitate object delineation and classification in 2D raster images add parent-child topological relationship (Beucher, 1994; Perret et al., 2019). Various approaches and techniques for hierarchical segmentation have been developed (Nguyen and Le, 2013; Richter et al., 2013), among which watershed segmentation (ws) stands out adapts well to rough rock surfaces. Ws effectively identifies regional boundaries, groups neighbouring regions, and enables multi-scale analysis by construction, making it a robust choice for identifying overhanging blocks on volcanic cliffs.



This study aims at applying hierarchical watershed segmentation to a volcanic cliff to outline overhanging blocks and describe their shape, hence supplying metrics to propose suitable safety measures. **Study site**

The interior of Réunion Island is served by mountain roads that are very prone to rockfalls. The RN5 is the only road leading to the Cilaos, home to about 5,700 residents, and is a major tourist destination on the island. Almost 25km of this road, bordered by 200m high rock cliffs, are highly susceptible to rockfalls. The Aloès cliff, stands over 200 m high and spans more than 200 m in length. This cliff exhibits a morphology characteristic of the cliffs that line the RN5

The Aloès Cliff comprises layers of massive olivine basalts, ranging from metric to plurimetric in scale, with variable vesicularity, interlayered with scoriaceous layers. The basaltic flows are intersected by numerous vertical joints outlining flow prisms formed during cooling, with scoriaceous levels averaging over 50 cm thick. The rock displays multiple levels of alteration and numerous fractures. Given its geological nature, the cliff is subjected to differential erosion and weathering of geological formations, resulting in phenomena such as exfoliation joints, opening of pre-existing fractures, creation of new fractures, undercutting, and others (Collins and Stock, 2016). The basaltic flow flew parallel to the outcrop face, without any downstream-tilt component towards the void.

Data and methods

The 3D point cloud for this study was produced using UAV-based Structure-from-Motion (SfM) photogrammetry. Images were captured with a ZenMuse X5s camera mounted on a DJI drone, maintaining a flight distance of approximately 40 meters from the cliff. This distance was strategically chosen to optimize the Field of View (FOV) of the drone's camera, achieve the desired image resolution, and obtain the optimal angles of incidence. A total of 249 photographs were taken, incorporating both orthogonal and oblique angles to comprehensively image the cliff, yielding a point cloud with an average density exceeding 300 points/m².

Vegetation was removed from the point cloud in CloudCompare by leveraging the geometric characteristics of the points: sphericity, planarity, and connectivity.

The estimation of block overhang utilized a saliency criterion, achieved by subtracting the vegetation-filtered point cloud from a smoothed point cloud adjusted to align with local minima perpendicular to the cliff's main orientation.

Segmentation was carried out on the inverse raster of 'saliency' using the watershed hierarchical method. In this technique, areas in overhang are depicted as depressions (watersheds), with the watershed boundaries defining their contours. The regions are organized hierarchically by area, meaning the tree's lowest level represents the initial segmentation of the 'saliency' raster along watershed boundaries. Each level of the tree indicates a stage of adjacent region fusion, with regions at each level characterized by an area within a specific range of saliency. The apex of the tree symbolizes a unified region covering the entire cliff face. Following segmentation, several statistical and morpho-mathematical parameters were analyzed to describe the tree's elements, including area, perimeter, and compactness.

Results

Some of the watersheds delineated by the morpho-mathematical analysis contour actual overhanging blocks. To extract those contours from the watershed-tree, shape descriptors metrics need to be thresholded.

To determine the thresholds, we cross-reference the matrix of manually mapped rocky overhangs with that of automatically mapped overhangs, enabling us to assess the percentage



of overlap. The mapping is also visually evaluated by overlaying the overhang map onto orthophotographs. It is observed that with the selected criteria described in Table 6, 86% of the pixels identified on the orthophotos as belonging to overhangs are mapped. The unidentified 14% consist of areas where there are no points on the 3D point cloud, pixels located on the periphery of an overhang, or areas where the saliency is not sufficient. Only 4% of pixels manually identified as overhangs but in fact belonging to vegetation patches.

Due to their geological nature, blocks from basaltic flows are fractured along their cooling fractures. A strong assumption is made to retain rock blocks with a W/H ratio ≤ 1 , where W represents the width of the block and H , its height. Therefore, polygons with a width 1.1 times greater than their depth are disregarded. This filtering might result in the exclusion of contiguous blocks, which with this method emerge as a single block, consequently possessing a W/H ratio >1 .

The median volume of blocks, estimated from “saliency” with a volume smaller than 10 m^3 is 0.045 m^3 . This implies that 50% of the blocks delineated by the method correspond to blocks of less than 50 liters (approximately 120 kg).

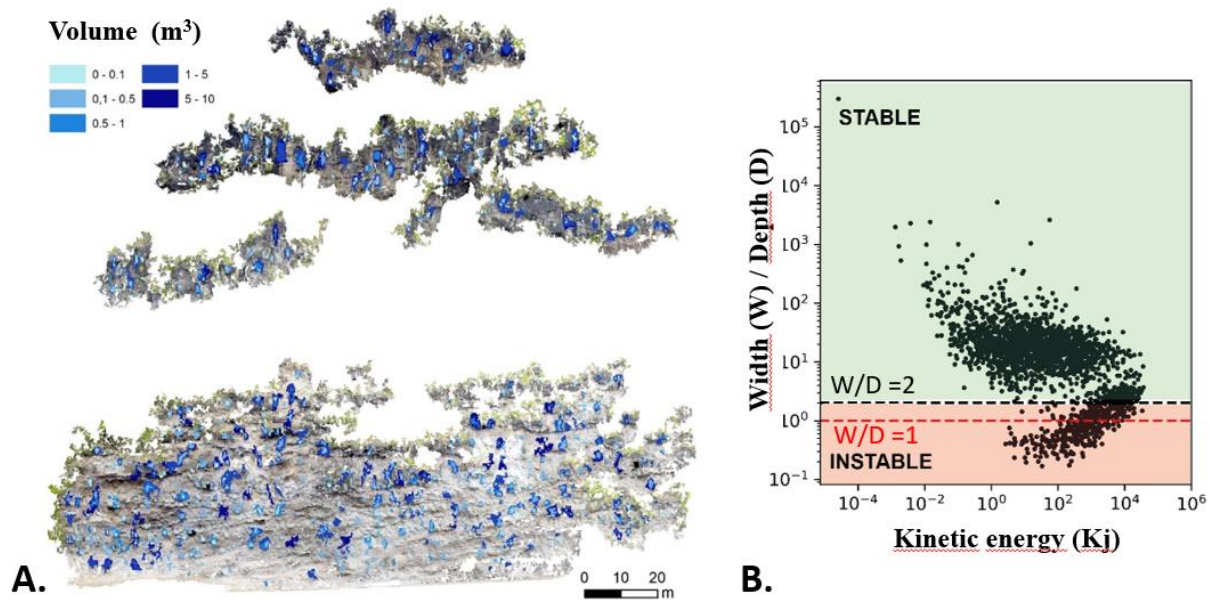


Figure 1. A. Volume of the delineated blocks determined through watershed hierarchical segmentation on the Aloès Cliff. B. Stability and kinetic energy of the delineated blocks.

Discussions

The stability of a rocky massif becomes compromised when the forces of traction, flexion, and shear, caused by geometric imbalance, exceed the resistance of the material. It is posited that in basalts, rocky blocks are primarily fractured by cooling fractures with pseudo hexagonal geometry and perpendicular to the flow surfaces (Aydin and DeGraff, 1988; Goehring and Morris, 2008). It was thus deduced that the width of the blocks visible in the outcrop could serve as a proxy for their depth. In scenarios where the dip direction is nearly coplanar with the wall direction, the bases of blocks are considered perpendicular to the wall. Hence, it is inferred that when the overhang depth (D) exceeds half the width (W), the center of gravity shifts beyond the overhang line rendering the block unstable (González De Vallejo et al., 2020). The identified unstable blocks ($W/D < 2$) constitute approximately 15% of mapped blocks, with volumes spanning from 10^{-3} to 10 m^3 .



Given their respective elevations compared to the elevation above the road, block energy upon impact can be estimated. The kinetic energy of mapped unstable blocks ranges from 2 kJ to 10⁴kJ. Half of these blocks exhibit kinetic energy beyond 594 kJ, and 95% possess energy under 6500 kJ. Such indications offer insights for selecting the appropriate rockfall protection system.

Conclusions and follow up

Employing watershed hierarchical segmentation on pre-processed 3D point clouds significantly enhances the ability to detect, isolate, and classify block sizes in densely fractured lava flow cliffs. The innovative RIDIM methodology provides a swift and systematic way to identify blocks at risk of dislodging across extensive rock cliff faces (Guiotte et al., 2023). Given its effectiveness, it is recommended that the RIDIM technique be further explored and adapted for various lithologies, offering a comprehensive, efficient, and straightforward solution for rockfall monitoring and the implementation of safety measures along cliff landscapes.

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