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Muon tomography, seismic noise survey and multi-scale topographic monitoring to assess rockfall hazard at the Maïdo Rampart (La Réunion Island)

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SUMMARY: Instable rock compartments at the 1000 m high Maïdo rampart threaten the few dozen inhabitants of the islet of Roche Plate in Mafate located downslope, as well as the cliff top which is the second most popular touristic site of La Réunion Island (>500 000 tourists/year). These rock compartments of a few tens of m³ to several hundred thousand m³ are pre-cut by fractures subparallel to the cliff as far as hundred meters from the cliff edge. In November 2020, reports of crack openings after an important bush fire raised fears of the imminent collapse of several hundred m³. The stability of other rock compartments was also considered worrying. In order to assess the stability of these compartments, a permanent multi-scale and partly automated system was installed to survey crack openings and surface deformations. This set up was completed by a seismic noise survey designed to qualify the degree of individualization of rock compartments. Finally, a muon tomography survey of the upper part of the rampart was deployed to image the extension of crack roots. The acquired data should make it possible to better understand rupture processes and kinetics, helping in characterizing and managing rockfall hazard at this site.

Keywords: Rockfall, Muongraphy, Seismic noise, Rampart, La Réunion

Introduction

At the Maïdo rampart (figure 1), the fracture network was mapped on the surface using orthophoto and LIDAR data, revealing an extension of cracks over tens of meters, with openings up to several meters. The complexity of the fracture network and its large extent (50,000m²) make difficult the assessment of rockfall hazard. In order to prevent possible rock collapses at this very exposed site, it is therefore necessary to better understand the geometry of instabilities (particularly at depth) and the kinematics leading to rupture.

Hereafter, we present three complementary experiments designed to gather information on the geometry of instabilities, qualitatively assess their degree of stability and survey signs of evolutions toward collapse. The extent and complexity of the site required adapting state of the art methods such topographic monitoring and ambient noise survey. In addition, BRGM with Iris Instrument chose to test an innovative method, a muography to remotely monitor the rampart, passively, with the hope to evaluate the depth of decompression cracks.

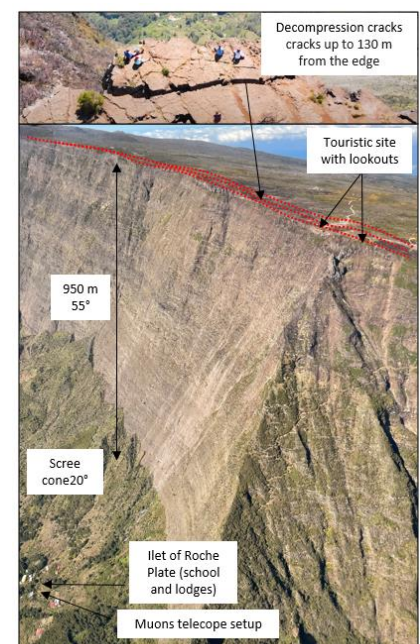


Figure 1: Maïdo rampart configuration



Topographic monitoring

The surface to be monitored is particularly large (50,000 m²) and makes it complex to detect topographic changes, knowing that stable sectors can be very far from measurement points. Devices such as extensometers might only measure the local component of the deformation. In order to overcome this problem, these instabilities are carefully monitored on behalf of the local authorities using multi-scale and partly automated topographic monitoring. The monitoring system was deployed in February and March 2022 and consists of :

- A geodetic reference system covering an area of 50,000 m², with semi-annual measurements of 22 control points using a total station, achieving sub-centimeter precision.
- Continuous monitoring equipment, including 12 extensometers (figure 2a) and an inclinometer with measurements taken every 4h, along with 40 displacement gauges. Additionally, an inclinometer was placed on the fissures delineating unstable compartments at the cliff's edge.
- 4 photogrammetric surveys conducted on the upper cliff near the tourist area to track erosion in rocky compartments at the cliff's edge, potentially linked to collapse triggers. The diachronic analysis of these data, only evidenced very small scattered rockfalls, with a maximum volume of 20 m³, located outside of the area of interest.

During the initial two years of monitoring, precision assessment and the study of daily and seasonal variations were conducted. These variations were attributed to material expansion and contraction, including rock, measurement instruments, and fastenings, due to temperature fluctuations. Importantly, only reversible movement with a maximum amplitude of 2 mm displacement signaling an ongoing destabilization process was recorded during the first year of monitoring, extending until September 2023.

Seismic noise survey

A seismic noise survey was carried out to assess the degree of individualization of rock compartments. Over the past ten years, such method proved efficient for unstable volumes of a few thousand to hundreds of thousands of cubic meters and in different contexts (volcanic or sedimentary rocks, various compartment geometries, etc.; Lévy, 2011; Burjānek et al. , 2012; Bottelin, 2014; Burjānek et al., 2017; Colombero et al., 2018; Valentin, 2018). The principle is as follows: unstable rock compartments vibrate preferentially at certain frequencies which are characteristic of their geometry, their mass, the rigidity of the rock, but also the degree of attachment to the stable massif.

At the Maïdo, the survey consisted of seismic noise records at locations distributed according to a dense spatial grid for several hours (2 to 4 hours) between 08/04/2021 and 08/06/2021. In total, 40 measurement points were carried out spread over 30,000m². The seismometers are CMG6-TD with recording velocities along 3 directions for frequencies between 0.33 Hz and 40 Hz. The sampling frequency was set at 200 Hz. For the duration of the experiment, a reference sensor located in the stable area, 150 m from the edge of the rampart, also recorded data.

13 sensors, located near the edge of the rampart, have an average amplification ratio relative to the reference station greater than 5 in the horizontal direction perpendicular to the rampart on the frequency band [0.5 24] Hz (figure 2b). These observations are also consistent with those of Burjanek et al. (2012) which showed that the relative amplification between the reference



stations located on the stable massif and the stations located on the unstable structures always presents a preferential direction, with a maximum amplification generally observed in a direction perpendicular to the cracks found at the surface.

For a small group of compartments (6) considered to be the most unstable on the site, the amplification ratio relative to the reference station is greater than 20 at certain frequencies, with an observed maximum of 30 for one sensor. Thus, measurements confirmed the presence of unstable rock compartments and allowed to qualitatively compare their degree of instability. However, we do not have any information providing an estimate of the probability or time of rupture.

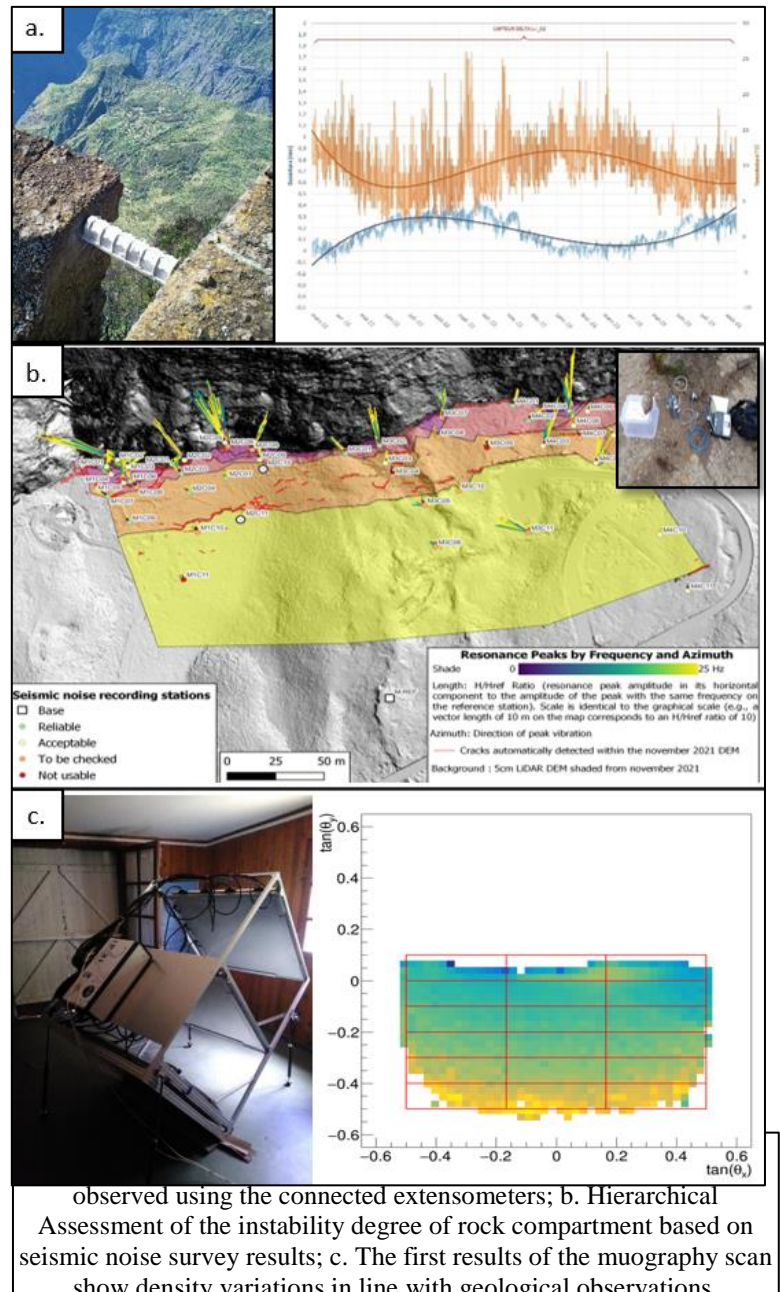
The performed analysis was relatively easy to set up and allowed to process and compare a large volume of data. This method is therefore operational for future studies of the rampart stability. It will be interesting to perform again this type of measurement in the future decade, in order to detect changes in the vibrations which might be linked to ongoing destabilization.

Muon tomography

In this scientific study, muography, a passive technique using natural cosmic muons, was employed to create a 3D map of the average density of the Maïdo rampart. Similar to radiography, the technique measures the attenuation of muon radiation as it passes through different materials (Procureur, 2018). The muon telescope used for this experiment utilized scintillator technology and featured three planes with high spatial resolution.

The primary goal was to establish a comprehensive 3D density map of the rampart and to study temporal variations in muon flux, which could provide insights into potential instabilities. The telescope was strategically positioned in Roche-Plate, 1,000 meters below the Maïdo rampart, and data collection occurred from November 2021 to August 2022.

Preliminary results indicate observable lithological differences, particularly the presence of thick basaltic flows (figure 3c). Nonlinear density variations with depth hold promise for estimating the depths of





fissure networks. However, limitations related to depth and rock traversed should be considered, as uncertainties increase with depth.

Additionally, the study noted the challenge of assessing the distance of fissures from the wall using the frontal view and suggested potential improvements using a telescope configuration with an upper wall incidence. It's worth mentioning that the monitoring period was affected by Cyclone Batsirai in February 2022, although this meteorological event did not significantly impact the recorded muon flux.

Conclusion

Beyond its immediate significance in alerting systems, topographic monitoring provides insights into the thermo-mechanical behavior of rocks and rupture processes. The proposed analysis of passive seismic data allows for the characterization of rock compartment disintegration levels qualitatively. This approach may potentially improve from systematic estimation of the first resonance frequency and associated damping.

The first global monitoring of high rock walls through muography yields promising initial results in characterizing the depth of root fissures in decompression zones. However, data collected by the muon telescope is already on exploration.

The data collected through diverse monitoring methods have enabled qualitative assessments of detachment levels and the identification of unstable compartments at various scales.

Overall, the combination of both conventional and innovative monitoring techniques holds significant promise for advancing our understanding of Maïdo edge rampart stability and guides the authorities in the management of geological risk at this high-stakes site

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