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Coastal erosion process at Calhetas parish, São Miguel island, Azores

Processus d'érosion côtière dans la paroisse de Calhetas, île de São Miguel, Açores

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ABSTRACT: The coastal cliffs on the north coast of the São Miguel Island, between Capelas and Rabo de Peixe parishes, due to its geology, composed by alternated fractured basaltic lava flows with breccia and/or unconsolidated pyroclastic deposits, are naturally predisposed to rock falls. Sea waves, meteorological agents and the anthropogenic activity that takes place near the cliffs are the main factors responsible for the erosive dynamics, with estimated retreat rates of up to 0.40 m/year. In this context, the urban settlements closest to the coastline are cyclically affected by landslides and rock falls. These geomorphological processes are responsible for the retreat of the cliffs, with the consequent loss of land, buildings and roads. Calhetas parish, in the municipality of Ribeira Grande, is one of those places that has recently been most affected by geomorphological instability. Since February 2023, a reactive phase of the cliff has been underway, with a consequent retreat of its crest. This paper describes the process that has affected this sector of São Miguel Island coast in recent years, with a particular focus on the phase that is currently underway. Displacements data are presented, obtained by fixed marks, as well as the measures that have been taken to mitigate the risk to the population. Finally, a discussion is presented on the solutions that are considered most appropriate for the problem.

RÉSUMÉ: Les falaises côtières de la côte nord de l'île de São Miguel, entre les paroisses de Capelas et Rabo de Peixe, en raison de leur géologie, composée d'alternances de coulées de lave basaltique fracturées avec des brèches et/ou des dépôts pyroclastiques non consolidés, sont naturellement prédisposées aux chutes de pierres. Les vagues de la mer, les agents météorologiques et l'activité anthropique qui se déroule à proximité des falaises sont les principaux facteurs responsables de la dynamique érosive, avec des taux de retrait estimés jusqu'à 0,40 m/an. Dans ce contexte, les agglomérations urbaines les plus proches du littoral sont cycliquement touchées par des glissements de terrain et des éboulements. Ces processus géomorphologiques sont responsables pour le retrait des falaises, avec pour conséquence la perte de terrains, de bâtiments et de routes. La paroisse de Calhetas, dans la municipalité de Ribeira Grande, est l'un des endroits les plus touchés récemment par l'instabilité géomorphologique. Depuis février 2023, une phase réactive de la falaise est en cours, avec pour conséquence un retrait de sa crête. Cet article décrit le processus qui a affecté ce secteur de la côte de l'île de São Miguel au cours des dernières années, avec un accent particulier sur la phase en cours. Les données de déplacements sont présentées, obtenues par notes fixes, ainsi que les mesures qui ont été prises pour atténuer le risque pour la population. Enfin, une discussion est présentée sur les solutions considérées comme les plus appropriées au problème.

Keywords: Geological risks; geomorphological instabilities; volcanic coast; cliff instability; coastal protection.

1 INTRODUCTION

The coastline of São Miguel Island, between the parishes of Capelas and Rabo de Peixe, has a morphology characterized by steep cliffs with heights between 10 and 20 m. From a geological point of view, these cliffs are made up of alternations of volcanic materials with different mechanical characteristics.

Maritime agitation, meteorological agents, and human activity that develop in the vicinity of these cliffs are mainly responsible for erosion dynamics, with estimates of the average retreat rate reaching 0.40 m/year (Borges, 2003).

Since the urban centres are located close to the crest of these cliffs, cyclically these villages are affected by retreat processes leading to the loss of land, buildings, and streets. The parish of Calhetas is one of these locations that periodically is affected by crises of geomorphological instability.

In February 2023, another geomorphological crisis began, and until December 2023, there have been several episodes of instability, three of greater dimensions and others of lesser importance.

During this crisis, some measures were implemented to mitigate the risk for the local

population. As part of this initiative, six pairs of marks were placed along two alignments of tension cracks that developed parallel to the crest of the cliff. These marks aimed to assess the rock mass kinematics and try to understand the dynamics of the process. The objective is, proactively, to anticipate potential cliff retreats and, consequently, promptly alert the population to ensure their safety.

2 CASE STUDY

2.1 Location and geological settings

The Azores archipelago is located at the triple junction between the Eurasian, African, and North American tectonic plates. Being recent volcanic islands, their rock formations are generally unaltered, and the soils are little altered. The cliffs present in São Miguel Island coastline between Capelas and Rabo de Peixe are characterized by being steep and made up of sub-horizontal layers of pomitic pyroclastic deposits without effective cohesion and/or by alternations of basaltic lava flows fractured with clinker.

The cliff under analysis in this study delimits the parish of Calhetas to the north and is around 20 m high, with a sub-vertical slope, with some of the strata partially suspended. The lower half of the cliff, geologically, is made up of soft formations, namely a level of pumice of trachytic nature, with interspersed ash of the same nature with variable thickness. The upper half is formed by lava flows of a basaltic nature (s.l.) with clinker intercalations. Finally, a small layer of surface soil (vegetable soil and/or landfill) can be seen. All these formations have varying thicknesses along the length of the cliff (Figure 1).

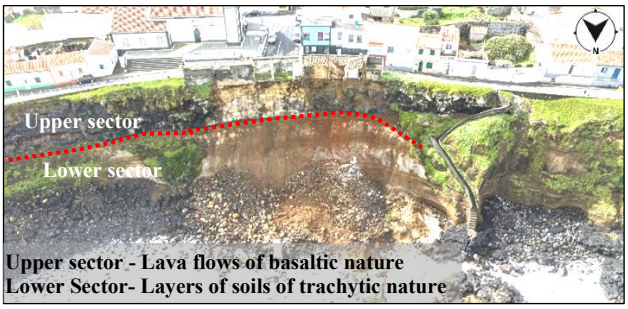

Figure 1. Geological constitution of the cliff at Calhetas.

In this sector of the coastline, close to the crest of the cliff and parallel to it, there are two streets with houses on the south side and some more scattered buildings on the north side over the crest of the cliff. With the inevitable progression of the cliff retreat process, the number of houses on the north side of the streets is increasingly reduced. Recently, the streets themselves have started to be threatened, restricting their use.

The erosion process in question consists of an intermittent phenomenon in time and space due to the intrinsic characteristics of the materials that constitute the cliffs and the action of triggering agents such as wave action, windstorms, intense precipitation, earthquakes, and anthropogenic actions (Di Crescenzo et al., 2021).

At the time of the beginning of this crisis, as the site was not being monitored, it was not possible to attribute any more intense meteorological phenomenon or any major anthropogenic action to trigger it, attributing its beginning to the progressive process of deformation of the massif and consequent increase in stress.

According to Borges (2003), who carried out quantitative studies of coastal retreat rates for the island of S. Miguel in the period between 1955 and 1999, the sector under analysis in this document points to values of average coastal retreat very heterogeneous cliff, varying between 0.1 m/year and 0.4 m/year.

Geologically, this cliff has a high propensity for the occurrence of these instability processes, considering that the base of the cliff is made up of material that is easily erodible by the action of the sea. So, periodically, the overlying basalt flows stay in cantilever. Furthermore, the alternation of basaltic flows with clinker levels, which are also quite erodible, leads to situations where the overlying strata also stay unsupported.

2.2 Description of occurrences

The current crisis began on February 2, 2023, at 8:00 pm, having destabilized an extension of the cliff measuring around 30 m and causing a retreat, which, in some places, reached 5 m (Figure 2).

In this episode, one of the affected buildings lost its back façade. It is important to note that the affected buildings were already vacant since the 2016-2017 crisis, except the structure located further west, which remained in use once it was a small warehouse.

After the first episode, the cliff became unstable again on March 1st, this time in a sector immediately to the west of the previous one, reaching a length of around 16 m and causing a retreat of around 2 m.

Figure 2. Affected areas on the Calhetas cliff: the alignment of existing cracks (dashed), the unstabilised areas (dotted) and the demarcation of demolished buildings / those affected by this crisis (continuous). Google Earth image (June 2022).

After this reactive phase, following a recommendation previously made by the Regional Laboratory for Civil Engineering, the four buildings located in the affected sector were demolished on the 24th, 27th, and 28th of March. This operation was done to relieve the load over the cliff and reduce the mass expected to become unstable once the cracks between the buildings and the adjacent sidewalk continued to evolve.

A few days before the demolitions began, it was found that the first and second alignment of cracks parallel to the coastline, already identified in 2016-2017, reactivated on the sidewalk and in the street pavement, resulting in an increase in the opening and the extension to the west of cracks. Furthermore, a new alignment of cracks further back was detected, the third (3rd) (Figure 2).

In March, the 2nd alignment (Figure 2) was located between 4.2 m and 6.2 m from the cliff crest, and the 3rd alignment was 1.6 m further back, thus compromising around 2/3 of the traffic lane.

On the night of April 7th, a few days after the demolitions had concluded, the cliff became unstable again. The sector now unstable was located immediately east of the initial one. With a length of around 50 m, it reached a retreat of 5 m in the sector of the demolished buildings (Figure 3).

Figure 3. The cliff after the instability of April 7.

After the instability of April 7th, the crest of the cliff retreated to the 1st alignment, becoming the 2nd alignment 2 to 3 m from the crest.

3 RISK MITIGATION MEASURES

3.1 Protection measures adopted

After the 2016-2017 crisis, when the retreat of the cliff reached the outer face of the road's guard wall, and the 1st and 2nd alignment of cracks appeared (Figure 2) parallel to the crest of the cliff, it was recommended that automobile circulation should be restricted on the affected extension of the road (70 m). It was also recommended to avoid activities or the presence of people and goods in the affected area until the 2nd crack alignment. For this purpose, it was suggested the placement of physical barriers like metal fences or blocks on the pavement. In addition, it was recommended the visual monitoring of the cliff quarterly, or after an abnormal worsening of weather conditions, to check for any retrogressive evolution of the site. In the case of activity, it was suggested the implementation of a monitoring system based on instrumental techniques to allow the detection of ground movements before the occurrence of instabilities. Although no movement was visually detected in the rock mass, marks were installed in the affected area, and the site was monitored for two years. Due to the movement being in its early stages or the limited accuracy of the total station used, no activity was detected, leading to monitoring discontinuation.

During the current crisis, and after the reactivation of the 2nd alignment and the emergence of the 3rd, it was recommended to increase the extension of the prohibited area for car traffic. This closure was extended to the west around 100 m, and in width, besides the entire sidewalk, 2/3 of the traffic lane was closed in the most critical area.

In May, after the crisis calmed down, six pairs of markers were placed along the two remaining crack alignments (2nd and 3rd) to evaluate its evolution weekly (Figure 4).

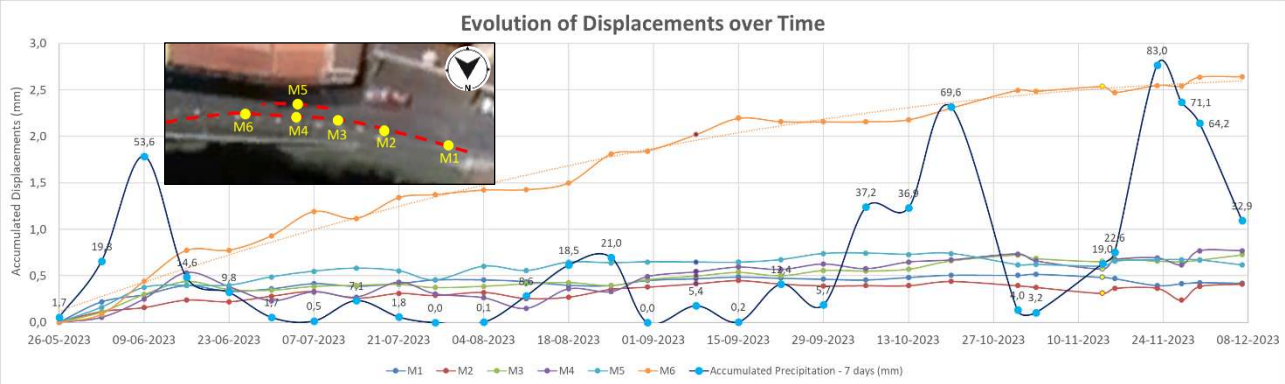

Figure 4. Evolution of the marks installed in the monitored cracks and precipitation.

3.2 Proposed solutions

To avoid the continued retreat of the cliff, it will be necessary to protect its base, which is made up of soft strata, as well as the stabilization of the overlying basalt flows that are fractured. For the lower sector, a rockfill prism adhering to the cliff can be done, which could serve as a base or foundation for the stabilization solution in the upper sector. Therefore, two possible solutions are proposed for the upper sector: one involves constructing an embankment along with small containment structures, while the other entails the installation of a reinforced concrete curtain anchored and nailed to the cliff.

At present, the authorities have granted a contract for the construction of a berm breakwater (a reshaping structure) for the base of the coastal cliff, without taking into account the solution to be implemented for the upper part. Even though the solution adopted isn't the one suggested, it has the advantage of needing smaller stones in the armour layer, making the construction process easier. Furthermore, although the project defines a reshapable berm, this intervention allows the execution of the solutions thought for the stabilization of the upper part of the cliff. Indeed, the breakwater has a wide stable crest, with a 15 to 23 m width.

In any case, until the entire cliff is protected and stabilized, new construction or rehabilitation should not be permitted on both sides of the street. Furthermore, it is essential to consider the necessity for new rehousing and relocation of structures, especially on the north side of the street.

4 CONCLUSIONS

The cliff that delimits the urban core of the parish of Calhetas to the north is cyclically plagued by crises of geomorphological instability.

The retreat of the cliff crest is the outcome of a natural process known as 'differentiated coastal erosion, occurring within various strata along the coastline.

In general, the occurrence of this type of phenomenon arises from the actions of different agents (e.g., high precipitation, intense maritime agitation, earthquakes, and vibrations resulting from human activity). Typically, there is a time interval of the order of hours or days between the request and the cliff's response to the action of the triggering agents in the rock mass.

During the current phase of the process, monitoring tension cracks near the crest of the cliff suggests that the mass rock does not react responsively to precipitation episodes, although, in the beginning, it seemed otherwise. Currently, this part of the cliff seems to have entered an inactive dormant state.

As this is a natural and irreversible process, there are two options: stabilization of the cliff or vacating the area near the ridge as the process progresses. In the latter case, proactive measures are necessary to minimize the exposed value. For this purpose, territorial planning tools are essential. Because both options have very high associated costs, each situation has to be viewed on a case-by-case basis. Regardless of the option adopted, it is essential to define clear policies to minimize losses and not create false expectations for the population.

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