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Geotechnical interventions to mitigate the geomorphological risk of the access road to Ribeira Quente parish - Azores archipelago

Interventions géotechniques pour réduire le risque géomorphologique de la route d'accès a la paroisse de Ribeira Quente - archipel des Azores

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ABSTRACT: The regional road no. 2-2ª is the only access to Ribeira Quente parish on the island of São Miguel (Azores). This road is approximately 5.5 km long and runs along the Ribeira Quente valley, with slopes that, in some cases, reach 450 m in height and with very steep gradients. The geology is very complex, with basaltic (*s.l.*) and trachytic (*s.l.*) lava flows, welded and non-welded ignimbrites, fall and flow pumice deposits, and slope deposits. Due to their geological, morphological, and hydrological characteristics, normally associated with episodes of intense and/or prolonged rainfall, the slopes often become unstable, isolating the population of Ribeira Quente parish from any kind of assistance by land. An example of this was the disaster that occurred on October 31, 1997, which left 29 people dead. Given the above, various consolidation works were carried out on the road's slope, of different types, namely: alteration of geometry, installation of external and internal drainage systems, ditches, application of shotcrete with nailing, and a semi-tunnel. This work presents the different interventions carried out along this regional road, as well as those that are planned to minimize and mitigate geomorphological risks. The aim is also to illustrate and emphasise the fact that any stabilisation solution needs to be properly dimensioned and have a maintenance plan after its implementation to guarantee its full functionality.

RÉSUMÉ: La route régionale n.° 2-2ª est le seul accès à la paroisse de Ribeira Quente sur l'île de São Miguel (Açores). Cette route, d'une longueur d'environ 5,5 km, longe la vallée de Ribeira Quente avec des pentes qui, dans certains cas, atteignent 450 m d'altitude et des dénivelés très importants. La géologie du site est très complexe, avec des coulées de lave basaltique (*s.l.*) et trachytique (*s.l.*), des ignimbrites soudées et non soudées, des dépôts de ponce de chute et de coulée et des dépôts de pente. En raison de leurs caractéristiques géologiques, morphologiques et hydrologiques, normalement associées à des épisodes de précipitations intenses et/ou prolongées, les pentes deviennent souvent instables, isolant la population de la paroisse de Ribeira Quente de toute forme d'assistance par terre. La catastrophe du 31 octobre 1997, qui a causé la mort de 29 personnes, en est un exemple. Compte tenu de ce qui précède, divers travaux de consolidation ont été réalisés sur le talus de la route, de différents types, à savoir: modification de la géométrie, installation de systèmes de drainage externes et internes, fossés, application de béton projeté avec clouage et un semi-tunnel. Ce travail présente les différentes interventions réalisées le long de cette route régionale, ainsi que celles qui sont prévues pour minimiser et atténuer les risques géomorphologiques. L'objectif est également d'illustrer et de souligner que toute solution de stabilisation doit être correctement dimensionnée, et disposer d'un plan d'entretien après sa mise en œuvre, afin de garantir sa pleine fonctionnalité.

Keywords: Geomorphological risks; slope instabilities; road protection; Azores.

1 INTRODUCTION

As a result of its volcanic-tectonic setting, the Azores archipelago has a wide variety of soils with different mechanical characteristics. The existence of slopes made up of volcanic deposits with different physical, mechanical, and hydrogeological characteristics are themselves predisposing factors to the occurrence of geomorphological instability processes, namely landslides, with consequences for people and property. Rainfall is one of the main factors triggering landslides in the Azores, as the increase in water in the materials leads to a decrease in shear strength, which can occur through the decrease in apparent cohesion (in unsaturated soils) or an increase in neutral pressures in the potential slip surface due the rise of the water table (Amaral, 2010 and Amaral *et al.*, 2010).

The regional road no. 2-2ª (E.R. 2-2ª), in the Ribeira Quente parish, on São Miguel Island (Azores), is flanked by slopes ranging in height from a few metres to approximately 450 meters, some with steep inclines. These slopes have a complex geological constitution, ranging from basaltic (*l.s.*) and trachytic (*l.s.*) lava flows, welded and non-welded ignimbrites, pomitic pyroclastic deposits of fall and flow and gravitational deposits. Given the above, these slopes are highly prone to slope movements, particularly landslides and debris flows, which are usually associated with heavy and/or prolonged rainfall.

Over time, numerous episodes of heavy precipitation have triggered slope movements, resulting in the blockade of the road, often at multiple locations. This, in turn, isolates the local population, cutting off access to assistance by land. The most notable event took place in 1997, when 29 people died in the Ribeira Quente parish, and the most recent was in June 2023. Therefore, it has become imperative to intervene geotechnically along this road. The carried-out interventions aimed the improvement of safety conditions; however, if they are not supported by geological and geotechnical studies and maintenance actions, they risk not being functional in the long term. This article presents some slope consolidation works carried out at Ribeira Quente Road. In addition, the aim is to illustrate why any stabilisation solution must be the subject of a study, which supports the project, and must also include a long-term maintenance plan, which must be adhered to guarantee the functionality of the solutions.

2 STUDY AREA

The E.R. 2-2ª access road to the Ribeira Quente parish, in the Ribeira Quente valley, is one of the areas most affected by slope movements in the Azores archipelago. This road is the only access route to the parish.

The existing water lines in the Ribeira Quente valley, as well as the presence of concave morphologies expressed in the slopes, with continuity upstream, represent flow channels favourable to the mobilisation of debris flows.

Considering the susceptibility of this location to the occurrence of slope movements, Marques (2013), based on the work carried out by Marques et al (2009), produced a map of susceptibility and propagation of slope movements for the municipality of Povoação, including the Ribeira Quente parish (Figure 1).

From this map, it can be seen that this road is very vulnerable to geomorphological instability processes. Based on this information, which justifies the phenomena that have occurred in this location, it became imperative to implement actions to minimise some of the most serious situations, intending to improve safety conditions for passers-by. It is important to emphasise that these measures do not completely eliminate geomorphological risk (as we can see in the most recent situation), but only contribute substantially to reducing it.

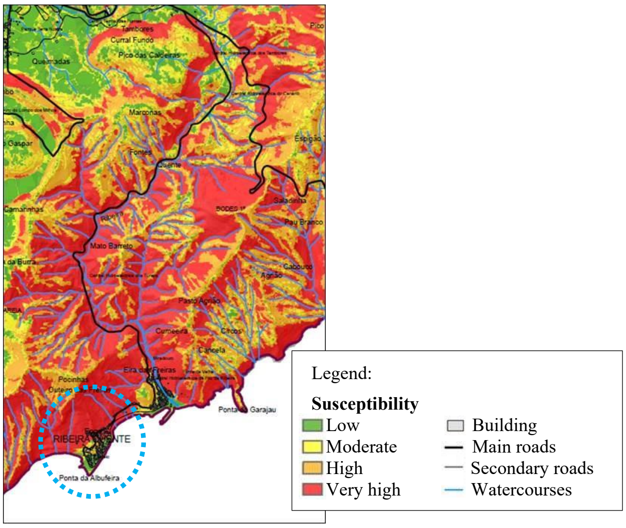

Figure 1. Map of susceptibility and propagation of occurrence of slope movements for the Ribeira Quente valley, outlined in blue (adapted from Marques, 2013).

3 RISK MITIGATION MEASURES

In recent years, 15 sites along the E.R. 2-2ª (Figure 2), which had been identified as critical, have been intervened. The risk mitigation measures to be implemented are: (1) re-profiling the slope, (2) a retaining wall with a ditch at the end, (3) construction of a semi-tunnel, (4) removal of rock blocks and (5) metal nets with nails and sometimes with shotcrete. This paper will present only 4 of the 15 sites intervened, corresponding to sites 4, 5, 12 and 14 (Figure 2), taking into account their representativeness in the overall context of the interventions.

Site no. 4 corresponds to a slope about 20 metres high and is made up of intercalations of trachytic pyroclastic deposits of different grain sizes. The intervention carried out at this site involves altering the geometry of the slope, softening its slope, and creating a bench at approximately half height (Figure 3).

The slopes adjacent to the E.R. 2-2ª usually have water levels. Evidence of this can be seen in the numerous springs and waterfalls that can be seen along the road. Despite this, no deep drainage system, such as sub-horizontal drains, has been installed at site no. 4. Thus, on the face of the slope, it is possible to observe signs of internal erosion caused by the outflow and accumulation of water, as well as gullies due to surface run-off (Figure 4 on the left). Apparently, no geological and geotechnical study or global stability analyses have been carried out on the slopes to be re-profiled to ascertain which tilt gives them stability.

Indeed, there have already been several surface geomorphological instabilities on the face of the re-profiled slopes. At site no. 6 (Figure 4 on the right), there was a superficial geomorphological instability on the face of the re-profiled slope.

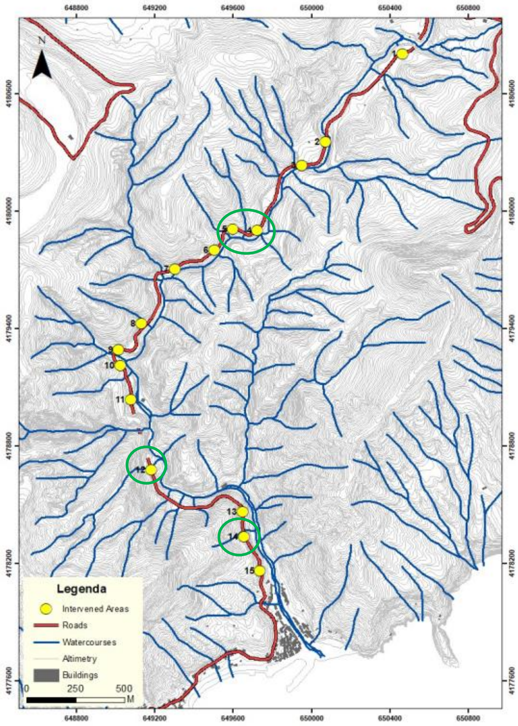

Figure 2. Location of the sections of the intervened areas. In green circles, the indication of the four sites presented in this work.

Figure 3. Site no. 4 - Slope re-profiling.

Figure 4. Site nº. 4 - Erosion on the slope face (on the left). Geomorphological instability at site no. 6 (on the right).

At site no. 5, a retaining wall was built with a ditch at its back, aiming to collect a large part of the material mobilised from upstream, preventing it from reaching the regional road platform (Figure 5). Over time, this measure has proved to be effective, as there have been several reports of these structures intercepting material that was heading towards vehicles travelling on the E.R. 2-2ª. However, these are measures that need to be maintained, in this specific case by removing the material that is trapped inside the ditch, so that it remains operational, a situation that does not always occur, as is the case at site no. 7 (Figure 5 on the right).

Figure 5. Site no. 5 – Waiting wall with ditch (on the left). Site no. 7 – No maintenance (on the right).

The slope adjacent to site no. 12 is 400 metres high. Taking into account the difficulty of implementing stabilisation measures there, a semi-tunnel was built, approximately 200 m long (Figure 6).

Figure 6. Site no. 12 – Semi-tunnel.

The length initially planned for the semi-tunnel was greater than that actually built. The initial extension was justified by the geological and morphological characteristics of the adjacent slopes. A heavy rainfall event in June 2023, which led to several landslides, debris flows, and debris avalanches, demonstrated this. In fact, in this event, the most serious situation occurred on the slope adjacent to the section of the semi-tunnel that was chosen not to be intervened on (Figure 7). The unstable material was deposited at the entrance of the semi-tunnel, causing its interruption and, once again, leaving the population of the Ribeira Quente parish isolated for a few hours.

Finally, the last site presented (site no. 14) corresponds to the application of nailing, metal mesh and shotcrete (Figure 8).

Figure 7. Geomorphological instability, of debris avalanche type, on the slope adjacent to the semi-tunnel.

Figure 8. Site no. 14 - Application of nailing, metal mesh and shotcrete.

4 CONCLUSIONS

The Ribeira Quente valley, where the E.R. 2-2ª is located, is one of the places that has been most affected by slope movements. The wide variety of volcanic materials, combined with adverse weather conditions, promotes the occurrence of different types of slope failures, with different modes of mobilisation and destructive potential, which is why risk mitigation measures have been taken.

The stabilisation solutions implemented in the sectors identified as most critical were conditioned by the geology and morphology of the slopes adjacent to the E.R. 2-2ª. These measures aim to minimise the geomorphological risk of this road and its passers-by, although they will not eliminate it completely. The solutions involved re-profiling the slopes, building retaining walls with a ditch at the end, constructing a semi-tunnel, removing rock blocks, and the application of metal nets with nails, sometimes with shotcrete.

Throughout the document, it was possible to see the importance of a prior study of the site to be intervened, with geological and geotechnical studies, as well as global stability analyses. In addition, all the works carried out require periodic maintenance, with cleaning and removal of debris, in order to guarantee their effectiveness. It should be noted that the main problems were observed in the places where the stabilisation solution involved slope re-profiling, with the occurrence of surface ruptures. Furthermore, places where retaining walls were built with a ditch at the end found a lack of cleaning of the ditches where the unstable deposits were trapped in that structure.

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