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An expedited assessment of slope instability on volcanic terrains in Azores archipelago

Évaluation rapide de l'instabilité des pentes en terrain volcanique dans l'archipel des Açores

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ABSTRACT: A project called MACASTAB (co-financed by the INTERREG Mac 2014-20 program) is being developed by a group of technicians from the Canarias, Azores, Madeira and Cabo Verde archipelagos. This project aims to prepare a methodological guide for the natural risk management produced by the instability of volcanic slopes and talus in Macaronesia archipelagos. One of its tasks is the development of charts to apply in the referred archipelagos in order to do an expeditious evaluation of slope stability.
Given the specificities of the geology of Azores islands, these charts were supported by limit equilibrium analysis methods (e.g. Morgenstern-Price) applied to slopes whose constitution is predominantly formed by soils (an unusual situation in the other archipelagos on the project). The results presented for shear strength parameters for volcanic soils on Azores archipelago are the result of triaxial compression tests and direct shear tests. An empirical correlation between friction angle and particle size distribution was determined with a coefficient of adjustment of 71%. That correlation shows a relationship between the angle of internal friction of a given material and the percentage of gravel and sand.
For the preparation of these charts, several stability analyzes were performed with different scenarios (slope gradient and heights, and shear strength parameters), in order to determine the safety factor (FS) of slopes in a simple and fast way in the field.

RÉSUMÉ: Un projet appelé MACASTAB (cofinancé par le programme INTERREG Mac 2014-2020) est actuellement développé par un groupe de techniciens des archipels des Canaries, des Açores, de Madère et du Cap-Vert. Ce projet vise à préparer un guide méthodologique pour la gestion des risques naturels produits par l'instabilité des pentes et des talus volcaniques dans les archipels de Macaronesia. Une de ses tâches consiste à élaborer des cartes applicables aux archipels mentionnés afin d'évaluer rapidement la stabilité des pentes.
Compte tenu des spécificités géologiques des îles des Açores, ces cartes ont été étayées par des méthodes d'analyse à l'équilibre limite (par exemple, Morgenstern-Price) appliquées à des pentes dont la constitution est principalement constituée par sols (situation inhabituelle dans les autres archipels du projet). Les résultats présentés pour les paramètres de résistance au cisaillement des sols volcaniques sur l'archipel des Açores sont obtenus par des essais de compression triaxiale et d'essais de cisaillement direct. Une corrélation empirique entre l'angle de frottement et la distribution granulométrique a été déterminée avec un coefficient d'ajustement de 71%.

Cette corrélation montre une relation entre l'angle de frottement interne d'un certain matériau et le pourcentage de gravier et de sable.
Pour la préparation de ces cartes, plusieurs analyses de stabilité ont été effectuées avec différents scénarios (pente et hauteurs de pente, et paramètres de résistance au cisaillement), afin de déterminer le facteur de sécurité (FS) des pentes de manière simple et rapide sur le terrain.

Keywords: Landslides; stability; slope; risk management; correlation.

1 INTRODUCTION

The Azores archipelago unlike the other Macaronesia archipelagos (Canary Islands, Madeira and Cape Verde) presents a great variety of volcanoclastic deposits resulting from a high range of eruptive styles and products emitted during effusive and explosive eruptions. Slope instability is a problem that affects several areas in Azores archipelago, causing considerable economic losses and human casualties.

Landslides promote material mobilization (soil, rock or debris) by gravity down a sloped section of land. On the other hand, depending on the involved mechanism, source zone, volumes, etc., they constitute an important source of geomorphological hazard for people and assets that live on the top and base of slopes.

Different methodologies can infer landslide occurrence (e.g., geomorphological, heuristic, statistical / probabilistic, or deterministic techniques). Bivariate (Yin and Yan, 1998) or multivariate statistical-based indirect mapping methods (Guzzetti et al., 2005) are the most used in the evaluation of landslide. These are deterministic methods based on physically based laws and are rigorous in detail studies at the slope scale when physical and mechanical properties of material terrain are known. These methods lose accuracy when spatial extrapolation is on a regional scale (Goth et al., 2008).

In order to minimize landslide hazard it is essential to analyse the stability of slopes under long-term conditions in order to prevent future accidents and mitigate the negative effects associated to this type of phenomena.

When slope instability occurs (eg, coastlines, roads, urban areas, proximity to water lines), technicians from various areas (Municipally services, Road services, Environment and Forest services) are convoked to assess the slopes stability in a short period. Detailed studies of geological and geotechnical characterization are incompatible with this short period to evaluate slope stability by limit equilibrium methods techniques or by stress/strain analysis techniques.

Thus, one of the many goals of this project for the Azores archipelago is the development of a fast field assessment form that allows assessing the slope stability of pyroclastic deposits with grain size particles that range from silts to gravel.

The purpose of this fast field assessment form is to serve as a preliminary tool to support field technicians for a simple and rapid evaluation of the stability of a given slope, in order to make a decision in geomorphological crises, and support slope protection measures in order to minimize landslide risk.

In order to support the elaboration of the field assessment form, slope stability analyses were performed using a limit equilibrium method to obtain the most critical slip surfaces. For this, different scenarios of morphological conditions (height and slope), geotechnical and water conditions, were taken into account. One of the inputs for stability analysis is the mechanical parameters (internal friction angle and cohesion) of soil. Through the information obtained by direct shear tests and triaxial tests it was possible to obtain an empirical function that allows the estimation of the effective internal friction angle with grain size.

This work intends to present an approach for preliminary evaluation of slope stability in a simple and fast way, based on geometric attributes of slopes and mechanical characteristics estimated empirically. The expedited assessment of the slope safety state will allow an early identification of safety measures that can be implemented in order to prevent human and material loss.

2 LOCATION AND GEOLOGICAL SETTINGS OF AZORES ARCHIPELAGO

The Azores archipelago is located in the triple junction between the Eurasian, African and North American tectonic plates, reflected in both seismic and volcanic activity (Figure 1). However, landslides are the most common type of geological hazard, conditioned by physical, mechanical and hydrological proprieties of volcanic deposits and by geomorphology (Marques et al., 2015). Seismic and volcanic activities are responsible for triggering landslides, however rainfall is of major importance in landslide occurrence in the Azores archipelago particularly on São Miguel Island.

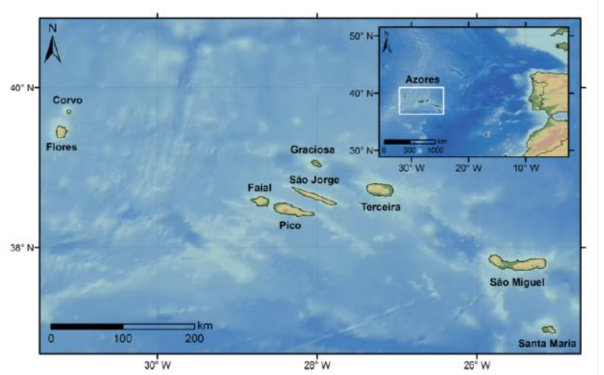

Figure 1. Azores archipelago location (in Marques et al., 2015)

The Azores islands are entirely of volcanic origin although, in some instances, sedimentary deposits are found, as is the case in S. Maria Island.

The geomorphologic instability processes triggered in Azores Archipelago generally occurs on steep hillslopes constituted by unsaturated cohesionless pyroclastic deposits. These volcanic materials consist of sandy gravel (pumice) or of silty sand (ash). Typically, these failures occur at less than 2 m deep, where the initial stress state is very low, and correspond to shallow translational slides. Under specific hydrological and topographical conditions, some lanslides evolve into debris flow forms (Figure 2).

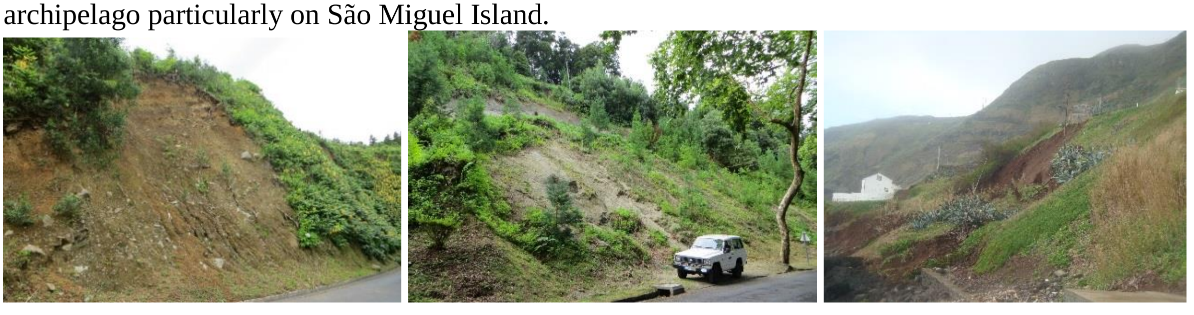

Figure 2. Examples of landslides occurrences in the Azores.

3 METHODOLOGY FOR SLOPE STABILITY

The safety factor, FS, for slope stability analysis is commonly defined as the ratio of the ultimate shear strength divided by the mobilized shear stress at the failure. From this point of view, a slope is considered as unstable if FS ≤ 1, due to the shear strength reduction or due to the increase of shear stress (Abramson et al., 2002). If the safety factor is between 1 and 1.5 the slope is considered marginally stable, and if FS$\geq$1.5 it is considered stable.

Engineers and researchers recurrently use the limit equilibrium methods that decompose the potential slip surface in slices for decades in order to evaluate the slope stability of natural slopes, excavation and embankments.

The global approach in order to obtain an indication of the slope stability is done by checking the possibility to develop a potential failure surface, determining the minimum factor of safety of the critical slip surface. For stability analysis by slice methods, it is necessary to know the geometry (topographic profile), the geological characteristics (stratigraphy) and geotechnical materials (physical and mechanical parameters), as well as the existing water conditions.

In this work, with the objective of creating intervals of safety factors according to different inclination / slope height scenarios, water conditions and shear strength parameters, stability analyses were performed using the Morgenstern-Price slice method to find the critical slip surface of the slope (with the minimum FS). Due to the large number of possible slip surfaces, a software was used to calculate the most critical slip surface (Slide - version 6).

Several stability analyses were performed in order to find the critical slip surface based on several scenarios - geometric (inclinations and heights), geotechnical (parameters of shear strength, particularly the fractional component) and water conditions - aiming to obtain information for the preparation of tables. The inclination of the slopes varied between 10º and 60º. The height of the slopes varied between 5 m and 40 m, and the internal friction angle between 20 ° and 45 °. The ground water conditions considered were: wet, ½, ¼ and ¾ height of slope, as well as fully saturated condition. For the conception of the tables, some premises were taken in consideration: 1) Cohesion values were not considered, due to the granular nature of most of the volcanic materials in the Azores archipelago. However, for calculation purposes and in order to avoid very shallow slip surfaces, a residual cohesion of 1 kPa was attributed. (2) The considered talus were constituted exclusively by granular soils. (3) The volumetric weight was kept constant, with a calculation value of 16 kN / m^3, which is obtained by the average saturated volumetric weights for pomitic deposits (Amaral, 2010); (4) The analysis was carried out in terms of effective stresses to evaluate the long term safety factor and assuming that a rupture occurs under drained conditions.

3.1 Slope stability

Figure 3 shows, for example, the variation of FS as a function of the various combinations related to slope, height and internal friction angles. A table with colour identification is also presented (Figure 4), to recognize the FS interval with different geometric conditions of slopes and geotechnics of materials: deep orange for FS <1, yellow for $1 >$ FS < 1.5, and green for FS > 1.5,.

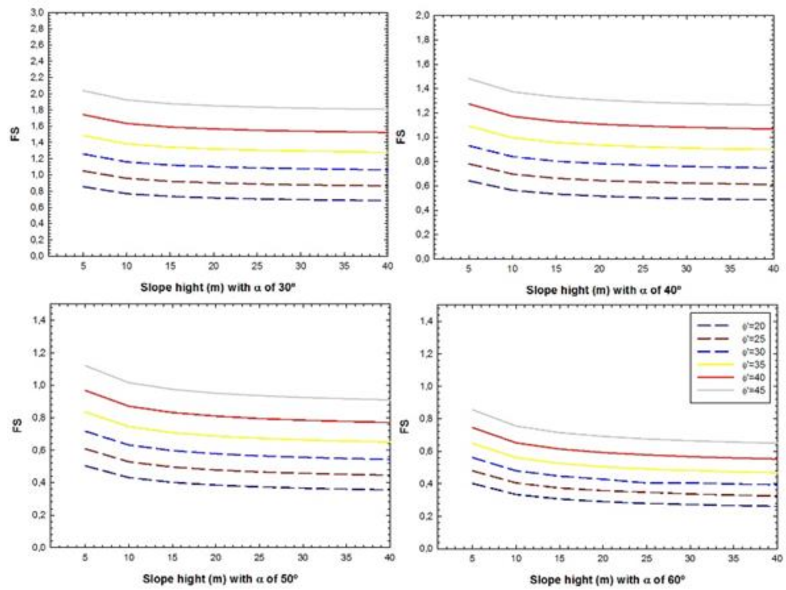

Figure 3. Example of the factor of safety variation in relation to different scenarios.

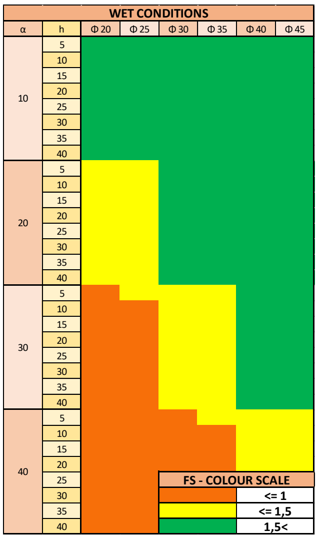

Figure 4. FS index table.

In order to obtain the FS in a more intuitively way, an FS index table was built (Figure 4). This example allows the technician(s) to evaluate in a early stage the stability of a slope according to its geometric and mechanical characteristics and ground water conditions. One of the inputs for the preliminary stability assessment, based on the use of the information obtained by FS index table, is the knowledge of the morphological characteristics of a certain slope. There are several ways to obtain this information, namely through topographic maps, topographical surveys, etc., so that the technician with appropriate tools can quickly obtains the necessary information.

As far as what concerns to geotechnical information, this information can be obtained either through laboratory tests (direct shear tests, triaxial tests) or through field-tests, by correlations (e.g. Standard Penetration Test). An empirical correlation was obtained from mechanical parameters and basic soil characteristics (granulometric fractions), in order to achieve this information in a simpler and faster way. This information is presented in the next section.

4 SHEAR STRENGTH PARAMETERS

4.1 Typical values of ϕ‘for soils in Azores

Geotechnical behaviour of volcanic soils has a particular behaviour. Generally, the materials have low dry density and unit weigth, high porosity and void ratio. Unit weigth ranges between 2.26 and 2.90 Mg/m^3, and dry unit weight ranges from 5 to 13 kN/m^3. Porosity ranges between 50 and 80%, and void ratio ranges from 1.02 to 3.87 (Amaral, 2010). The fine-grained components are characteristic of nonplastic or slightly plastic soils and the majority of the analysed samples have low clay content (<12%). Low-plasticity and nonplastic fine material have higher effective stress friction angles (Amaral, 2010).

Amaral (2010) performed several consolidated drained direct shear tests and results showed two distinctive families of shear envelope with the effective internal friction angle (ϕ') of 30º-35º for silty soils, and 35º-43º for sandy soils. Effective cohesion (c') ranges from 0 kPa to 9 kPa.

In this work the values for shear strength parameters were obtained from triaxial compression tests for pyroclastic deposits of fine matrix (soil) and coarse (pumice), welded and non-welded ignimbrites and slope deposits. Values for internal friction angles ranged between 33º and 42º and the effective cohesion values ranged between 0 to 24 kPa. The higher values found of shear strength parameters were on weathered welded ignimbrite.

Table 1 presents the range of values of cut resistance parameters for different materials found in the Azores archipelago.

Table 1. Range values of c´and ϕ´for different volcanic products. DPP, F – Silty pumice deposits; DPP,I and DPP, G – sand and gravel pumice deposits; SD – slope deposits; INS – non welded ignimbrite.

Litologia	c' (kN/m^2)	ϕ' (º)
DPP, F	0 - 6	30 - 37
DPP, I/DPP, G	0 - 2	36 - 43
SD	0 - 9	25 - 39
INS	16-24	35-37

4.2 Empiricall strength correlation for volcanic soils

A large number of correlations between shear strength and soil proprieties (grain size, Atterberg limits), density, confining pressure, SPT and CPTs have been reported in the literature (e.g., Lupini et al., 1981). Considering the physical and mechanical characterizations obtained by Amaral (2010) and the ones obtained for this work by triaxial tests, correlations were established between different basic soil parameters (for example the grain size distribution).

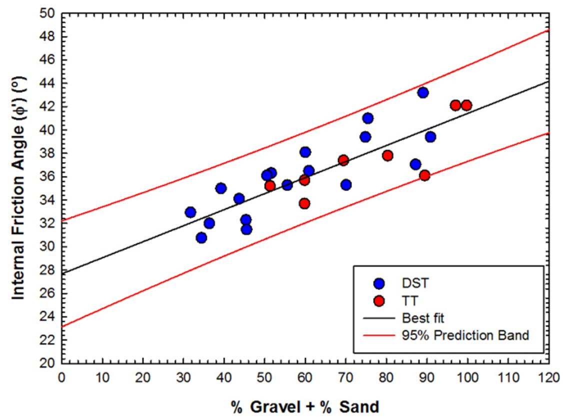

Figure 5. Variation of friction angle with the sum of gravel and sand percentage. DST (Direct Shear Test) – TT (Triaxial Test).

Figure 5 shows the correlation obtained between the effective friction angle and the sum of the gravel and sand percentage, which is expressed by equation (1), with a correlation coefficient of 71%.

$$\phi' = 0.138(\%Gravel + \%Sand) + 27.7 \qquad (1)$$

Where ϕ' is the internal friction angle.

Expression (1) allows to obtain the internal friction angle from a simple granulometric analysis, which can easily be performed in the laboratory or even in the field, so that its results can be used to analyse the stability of a slope in a simple and fast way.

5 CASE STUDY - APLICATION

The presented case study corresponds to a slope located near the regional road of access to the Furnas parish, on S. Miguel island, Azores archipelago. This slope has a height of about 30 m and a slope of nearly 40°. Its geological constitution is entirely of trachytic falling pyroclasts (pumice stone), resulting from eruptions in the Furnas polygenetic volcano. In 2009, in the slope shown in Figure 6, a translational surface slip occurred with a mean depth of rupture of about 1.5 m. Rotation surveys at the bottom of the slope confirmed the existence of deep pozzolan deposits and the absence of underground water.

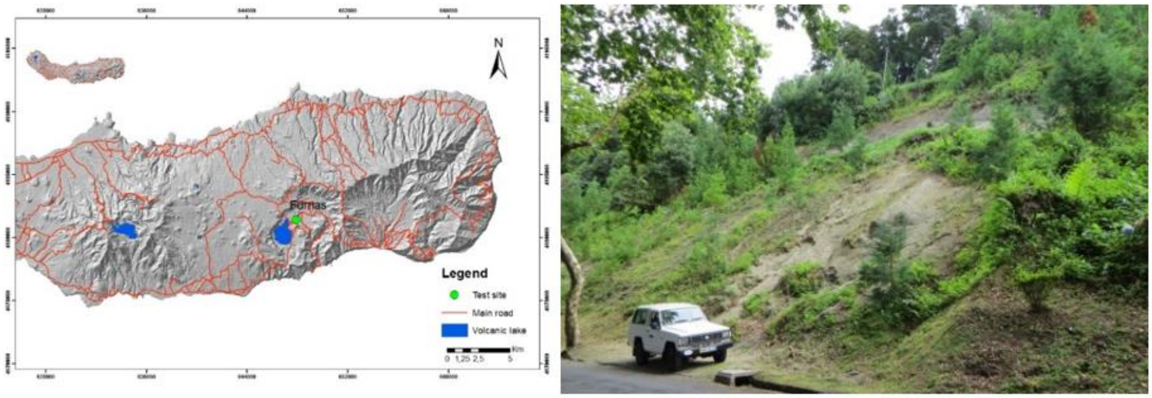

Figure 6. Slope situated on the access road to the parish of Furnas, São Miguel Island.

Moniz et al. (2016) performed triaxial tests on the materials of the slope and determined an internal friction angle between 39º and 43º. These materials are not cohesive. It is a well-graded GW-Gravel with sand, nonplastic, with 60% gravel, 37% sand and 3% fine elements (silts + clays). The dry weight is very low, with a quantity of 5 kN/m^3. The saturated volume weight is 12 kN/m^3.

Through expression (1) an internal friction angle of 41° was calculated in order to determine the slope stability. This value is very similar to the one obtained by triaxial tests (39º to 43º), fitting in the average of those values. Based on the information of the geometry (height of 30m), slope (40°), and the lack of a water level, a FS of proximally 1.12 was determined using the graphic shown in Figure 3. With the parameters obtained by the triaxial tests, a quantitative of the FS of 1.05 (for an internal friction angle of 39º) and an FS of 1.20 (for a friction angle of 43º) were obtained, meaning that the FS determined through the graph fits the average of these. From the topographic profile of the site, the FS calculated based on the software used and on the Morgenstern-Price slice method, obtained safety factors of 1.14, 1.22 and 1.30 for friction angles of 39°, 41° and 43°, respectively (Figure 7).

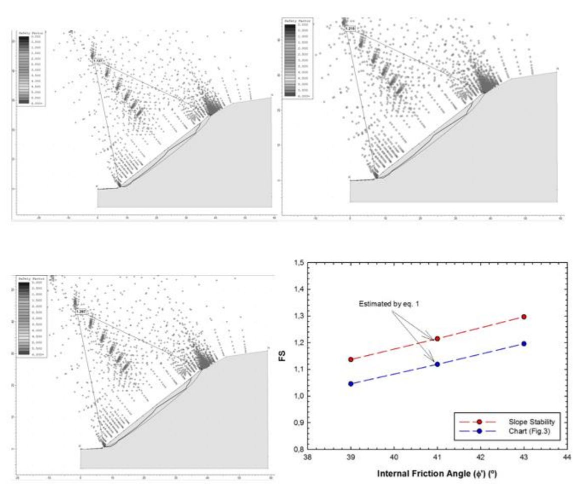

Figure 7. FS calculated for 39º, 41° and 43°. Comparison between the values found through the software and the graphic (of Figure 3).

It is observed that the position of the critical slip surface with the minimum FS shows a location very close to the breaking surface that occurred in 2009 in this slope. It is possible to see a reduction of 9% in relation to the stability analysis performed by the classical technique. This difference is considered not relevant for a situation of need for an expedited evaluation in the field, and as expected, the differences are minimal and reflect the morphological irregularities of the profile used in the classical analysis as opposed to the rectilinear geometry of the graphical component. On the other hand, the use of a 16 kN/m^3 constant weight is more conservative in terms of stability, increasing the weight of the potentially unstable soil mass.

6 CONCLUSIONS

The application of slope stability analysis techniques is an important tool for assessing the stability state, as it allows the determination of potential areas for initiation of terrain breaks, and thus to assess the need to implement stabilization measures to avoid problems for people and goods.

The aim of this work was to obtain a preliminary support tool for the evaluation of slope stability, serving as a preliminary analysis of stability conditions, essential in times of geomorphological crisis.

Thus, the information obtained in this work is a contribution to give a rapid response to the stability conditions of a given earth mass, and later this evaluation must be done with more accuracy and more time to obtain input information, as well as the analysis methods (eg. application of stress strain analysis).

7 ACKNOWLEDGEMENTS

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