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Geotechnical and Hydrological Modeling of a Landslide at Lajedo Parish – Flores Island (Azores Archipelago)

Modélisation géotechnique et hydrologique d'un glissement de terrain dans la paroisse de Lajedo - île de Flores (archipel des Açores)

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ABSTRACT: In November of 2016, a hydrological and geotechnical monitoring network was installed at three landslides (#L1, #L2 and #L3), using vibrating wire and standpipe piezometers, tiltmeters, inclinometers and a rainfall station. Based on the acquired data in the last 2 years at Lajedo parish, and the hydrological, physical and mechanical characterization of the deposits, through laboratory tests, for landslide #L2, it was possible to carry out an investigation by modelling the ground water infiltration process and pore water pressure variations using a finite element seepage analysis. The effects of these variations were the input to compute the slope stability analyses over the time in order to analyse the factors that promoted slope instability. This study is part of a research project known as Decisionlarm, whose main objective is to develop a multi-technical monitoring system to support decision-making based on alert and alarm levels in the unstable zone by evaluating the effect of precipitation and the oscillations of water level in the potential failure planes capable of triggering landslides.

RÉSUMÉ: En novembre 2016, un réseau de surveillance hydrologique et géotechnique a été installé lors de trois glissements de terrain (#L1, #L2 and #L3), utilisant des piézomètres à corde vibrante et de colonne montante, des tilthimètres, des inclinomètres et une station de précipitation. Basé sur des données acquises au cours des dernières 2 années à la paroisse de Lajedo et de la caractérisation hydrologique, physique et mécanique des gisements, par des essais en laboratoire, pour le glissement de terrain # L2, il a été possible de mener une étude en modélisant le processus d'infiltration des eaux souterraines. et les variations de pression interstitielle en utilisant une analyse d'infiltration d'éléments finis. Les effets de ces variations ont été utilisés pour calculer les analyses de stabilité de la pente au fil du temps afin d'analyser les facteurs favorisant l'instabilité de la pente. Cette étude fait partie d'un projet de recherche appelé Decisionlarm, dont l'objectif principal est de développer un système de surveillance multi-technique pour appuyer la prise de décision basée sur les niveaux d'alerte et d'alarme dans la zone instable en évaluant l'effet de la précipitation et des oscillations de le niveau de l'eau dans les potentiels plans de rupture capables de déclencher des glissements de terrain.

Keywords: Landslides, hydrological and geotechnical modeling, water pressure.

1 INTRODUCTION

The Azores archipelago presents a high variability of volcanic soils with different geotechnical, hydrological and geomorphological characteristics. These characteristics are predisposing factors to the occurrence of slope movements triggered by precipitation episodes.

Among the factors that affects slope stability, meteoric conditions are of primary importance, as a predisposing factor, and as triggering element (Wieczorek, 1996) due to the rapid increase of pore pressure or by loss of apparent cohesion in the soil and consequently reduction of the shear strength, favouring the instability of the system. Infiltration and the transient changes in the hydrological systems is the most common trigger of landslides, especially in steep slopes and granular soils.

The trigger mechanism of a landslide and subsequent behaviour are conditioned by the rheological proprieties of the material as well as by the hydrologic system inherent to the slope and the amount of water on the slope. The decisive amount of precipitation needed to determine slope failure depends on the morphology, on the mechanical and hydrological properties of the soil and on the vegetation that cover the slope (Crosta 1998, Van Asch et al., 1999).

Two general different approaches have been presented in literature to explain the relationship between rainfall and slope instability processes: (i) the empirical analysis of rainfall thresholds (e.g. Wieczorek, 1987; Aleotti, 2004; Marques et al., 2007); and (ii) physical based mathematical models (e.g. Montgomery and Dietrich, 1994). Concerning the last one, mostly of these models are based on the assumption for steady or quasi-steady water level and groundwater level parallel to hillslope, and by coupling the infinite slope model analyses to assess shallow landslide induce by hydrological conditions and land use. However, these assumptions cannot overtake transient response of pore water pressure due to the rainfall and the redistribution of pressure (Crosta and Frattini, 2003).

The relationship between the water level and the displacement velocity are object of study to be considered in land-use management (Malet et al., 2005; Corominas et al., 2005).

The present work is based on the study of a situation of geomorphological instability (# L2) with slow to very slow kinematic behaviour that occurs at Lajedo parish, Flores Island (Azores archipelago). Hydrological and geotechnical modelling was carried out in order to simulate the water fluctuation within the sliding and, for different precipitation scenarios, to verify the response of the safety factor and to define the critical precipitation capable of reactivating this system. The hydrological model in analysis was calibrated based on hydrological and geotechnical monitoring equipment installed at the site, which record the water pressure and the unstable mass movement.

The main objective of hydrological modelling was to understand the hydrological behaviour and its effect on stability for a meteorological event that provoked a reactivation of the system, verified by inclinometric measurements. In addition, after the calibration of the model, different precipitation scenarios were considered in order to verify their influence on the water level variation, causing the system to reactivate. This type of work is relevant when the stabilization remediation is not economically viable, and/or the relocation of people creates serious social problems.

2 STUDY CASE: LAJEDO LANDSLIDES ON FLORES ISLAND

Flores Island is part of the western group of Azores archipelago. Lajedo parish is located in the southwest coast of this island (Figure 1). In Flores Island, particularly in central zone, a microclimate is developed which includes a rainfall pattern that exceeds the amount of 2000 mm/year (Azevedo, 1998).

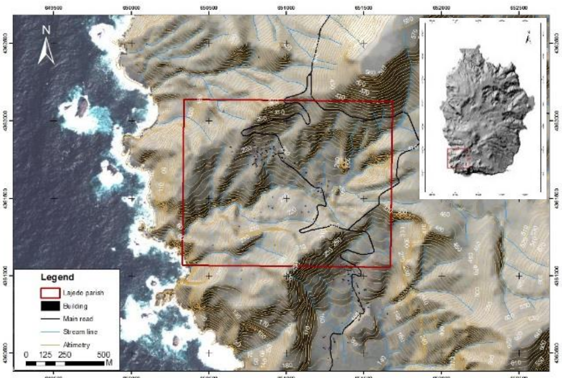

Figure 1. Location of Lajedo parish.

Thus, conditions are created for the recharge of the underground aquifers and also the maintenance of the gound water level near the surface throughout the year. Landslide activity occurs when the water level reaches a favorable threshold of the geological and morphological settings (Malheiro, 1997 and Marques et al., 2011).

In December of 2010, after a rainy winter, several geomorphological instability situations occurred in the south-west zone of Flores Island, particularly affecting terrains localized at Lajedo parish. Figure 2 presents the mapping of landslides observed in Lajedo and the monitoring zones implemented.

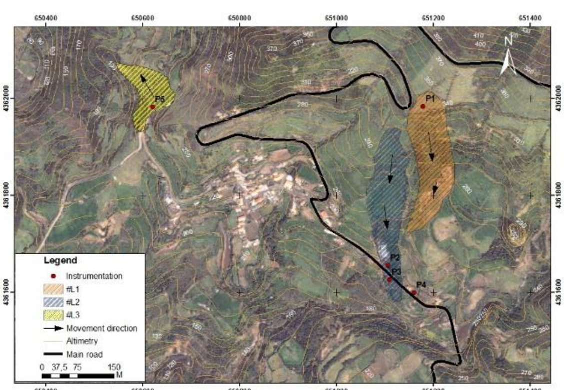

Figure 2. Landslides inventory observed in Lajedo and the monitoring zones implemented.

The rainfall records in 2010 indicated an amount of 81 mm during the day of the event, and for the second and third days an accumulated rainfall amount of 151 and 198 mm, respectively, recorded in the meteorological station of Santa Cruz aerodrome (Marques et al., 2011). Those values are surely lower than the ones that were observed in Lajedo, due to the orographic and altitude characteristics of the zone.

The most worrying situation occurs in test site #L2, due to the fact that only this site presents reatiavation, proven with displacements measured by inclinometer data.

This site is located in the proximity of #L1. Taking into account the direction of the dislocated mass and the morphological aspects of the topography, the #L2 situation does not share the surface plane with the #L1. It corresponds to a complex movement, of deep-seated earthflow type, resulting from the occurrence of a sucessive deep translational landslide. The topography surface presents a gradient of 18º. Punctually, a gradient variation occurs, coincident with minor scarps of the dislocated mass. Based on geomorphological aspects, it is considered that this movement suffered a reactivation of the system.

The local geomorphology allows to identify two movement zones: (1) the initiation zone, which develops between the 300 and 240 m a.s.l, and presents the largest width of dislocated mass (80 m); (2) the lower zone, which corresponds to the downstream end of the movement, between the 230 and 200 m a.s.l, confined by the terrain morphology. This sector presents a maximum width of 50 m. In the lower zone, the indicators of kinematics instability activity are more visible: wall ruptures, deformation and cracks in masonry elements in an agricultural building, and in the road and rupture and separation of about 0.6 m in the walking curb.

3 HYDROLOGICAL AND GEOTECHNICAL MONITORING NETWORK

In general, the implemented hydrological monitoring network is composed by vibrating wire piezometers modules, with continuous measurements of water pressure, and of Casagrande piezometers with punctual measurements of water level. Regarding to geotechnical monitoring network, several inclinometers casing were installed, distributed in the mentioned test sites, for displacement measurements and for the detection of failure surfaces. Furthermore, tiltmeters were installed to measure the tilt component of slope deformation, and a rainfall station to measure the amount of rainfall and barometric pressure, to do the corrections in water pressure records.

The monitoring network is distributed by the three geomorphological instability situations identified in Lajedo parish (#L1, #L2 and #L3) (Figure 2). In #L1, two biaxial tiltmeters of the Geosense brand, IPTM-2-420 model and the vibrating wire piezometer (VWP) were installed. In this place, a rainfall station was also installed, because it is the highest and more representative site of the zone. In #L2 the equipment installed was: three inclinometers casing, two Casagrande piezometers and two vibrating wire piezometers, distributed by three places (P2, P3 and P4). One of these locations is outside of the unstable mass (P4). In #L3 only a Casagrande piezometer and an inclinometer system were installed. Given the absence of coverage for telecommunication transmission in this local, it was not possible to install a vibration wire piezometer.

4 INTERPRETATION OF MONITORING DATA

4.1 *Poro-water pressure*

Figure 3 shows the water level fluctuation obtained from the pressure registered by the vibrating wire piezometer P2p1 installed in #L2 in function of accumulated daily rainfall. Since November 2016 until September 2018, the measured water level is near the ground surface, between 1.04 m and 1.62 m.

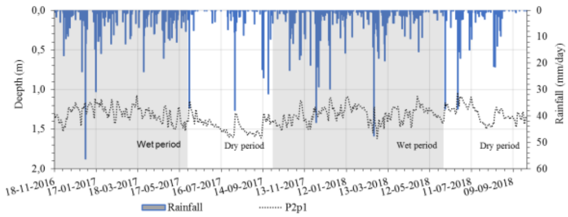

Figure 3. Ground water level fluctuation (P2p1) and accumulated daily rainfall (November 2016 to September 2018).

The ground water level is very close to the ground surface and is subject to extremely rapid variation in response to rainfall (Figure 3).

This suggests that materials, in this place, present a high to moderated permeability or there are cracks in the soils that allow a quick recharge of water level on the subsoil.

A groundwater flow patern parallel to the ground surface was assumed to be the cause in the subsequent modelling and it is compatible with what is observed.

4.2 *Displacement*

From the inclinometers measurements obtained until September 2018 at Lajedo, the one that presents a relevant displacement is P2i, situated downstream of the #L2 geomorphological instability situation (Figure 2). Figure 4 shows the more relevant observations performed by P2i inclinometer, during the monitoring period.

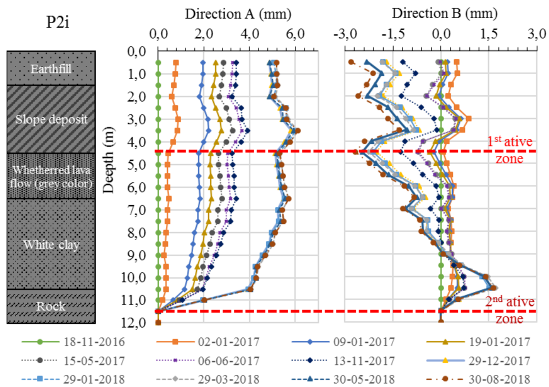

Figure 4. Manual inclinometer readings on P2i (November 2016 to September 2018).

Inclinometer data reveals alternating phases of start-stop motion.The results obtained until now show two actives zones in deep, with different displacement rates. The more superficial zone is situated at approximately 4.5 m. This occurs in the interface between the slope deposit and the weathered lava flow with grey color layer. The second active zone is located at 10.5 m, in the transition of a white clay to a basaltic rock, where is located the base of the inclinometer. The maximum displacement was detected in slope deposit with a quantitative of 6.0 mm, with a mean velocity of 4.8 mm/year.

Figure 5 presents a projection of the velocity of the movement and the accumulated daily rainfall. From this figure it is possible to verify that the test site #L2 consists of an instability with reactivation periods in rainy months (October to May), and deceleration periods in dry months (June to September). This aspect can also be seen in Figure 4, where a continuous displacement exists during wet months (18-11-2016 to 06-06-2017) in response to rainfall events, ceasing the displacement until 13-11-2017 measurement, occurring a new reactivation from this day. The three reactivations periods occurred with values of rain between 40 to 60 mm/day. The subsequent 10 days did not show significant increase in the accumulative rainfall, with values between 76 to 121 mm, revealing a rapid response of the landslide system to rainfall infiltration.

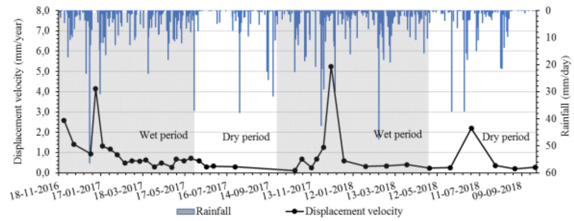

Figure 5. Relationship between displacement velocity and accumulated daily rainfall of the P2i.

5 HYDROLOGICAL AND GEOTECHNICAL MODELING

In this work, pore water pressure was computed, both in saturated and unsaturated conditions, through a 2D transient groundwater analysis, using Slide V6.0, of Rocscience.

For the modeling of water distribution in the soil, a temporal calibration period was used, from November 30, 2017 to January 29, 2018, in which a reactivation of the slope movement occurred, as evidenced by the incliniometric measurements. The soil water distribution simulated by the software was used to evaluate the stability conditions for that period of time.

The stability analysis was performed using the Morgenstern-Price method of slices, through the critical slip surface determination.

The geological and geotechnical profile (Figure 6) was obtained during the geotechnical prospecting campaign carried out to install the equipment. The existing water level at the site was considered, which is being monitored since then.

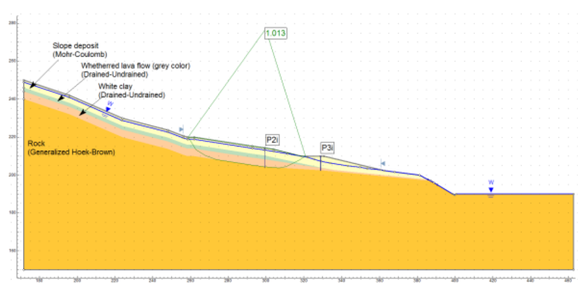

Figure 6. Geotechnical model of #L2. Safety factor of calibration model.

The defined hydrological model takes into consideration the input and output of the system (water balance). The input was materialized by daily cumulative precipitation, while the output corresponds to discharge points and to evapotranspiration.

Water exsurgencies were identified throughout the topographic surface of this site. These points were identified and introduced in the hydrological model, considering a constant flow of 10 l/day. A reference value of 2 mm/day was considered for evapotranspiration.

Taking into account that the slope deposit has an unsaturated fraction, it was considered the Van Genuchten (1980) adjustment parameters obtained from a SWCC (Soil Water Characteristic Curve) determined for materials with identical textural nature (Amaral, 2010).

The hydraulic conductivity of the volcanic deposits was obtained by the constant load method, with values of 5.1E^{06} m/s for the slope deposit, from 3.7E^{07} m/s for the gray clay deposit and 2.8E^{08} m/s for the white clay level.

Two months (61 days) were analyzed for the calibration of the model. Figure 7 shows the response of the observed water level and the simulated water level for the precipitation recorded in that period of time.

Although the modeling was not able to include all the characteristics of the site, because it was a two-dimensional analysis, a good approximation was achieved between the variations of the measured water level and the one of the model.

Based on the obtained information, the stability analysis was performed. The mechanical parameters used in the modeling were obtained by triaxial compression tests. However, in order to calibrate the geotechnical model, the parameters were adjusted, namely the cohesive component of the white clay so that the critical slip surface reached a safety factor equal to one (SF = 1.0) at the more conditioning position of the water level during the calibration period (Figure 6).

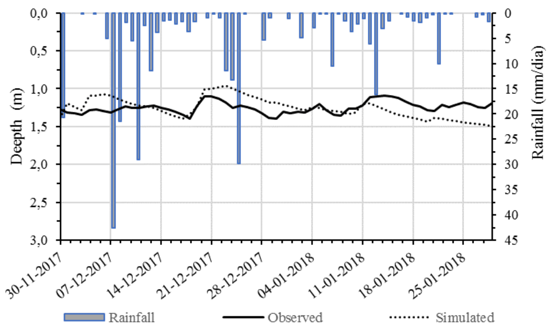

Figure 7. Water level variations monitored vs modulated, between 30-11-2017 and 29-01-2018.

It should be noted that despite measurements taken in this case has detected a surface break at 3 m, the critical slip surface does not reach the position where the P3i inclinometer is installed. This can be justified by the topographic survey used in the model, and also because most likely the movement detected by P3i is independent of the one of P2i, since site # L2 consists of a set of slides with successive rupture planes.

After the definition and calibration of the models, it was intended to evaluate the influence of an amount of precipitation of 20, 40, 60, 80, 100, 120, 140 and 180 mm/day in the water level variation. This analysis was carried out from three initial depth positions of the water level (WL): maximum depth (1.63 m), minimum (1.04 m) and mean (1.33 m) registered until 09-30-2018. The higher amounts of precipitation, depending on the level at which the water level is located, may cause the saturation of the terrain. In addition, these are plausible values, since they have already been registered in metrological stations near the area that is now being monitorized.

This analysis allows to estimate the variation of the water level for a certain quantity of precipitation, being known the position of the water level that precedes a precipitation event. Furthermore, it is possible to see that for the mean and minimum depth of the water level position, the influence of a given precipitation on the water level fluctuation is the same (Figure 8).

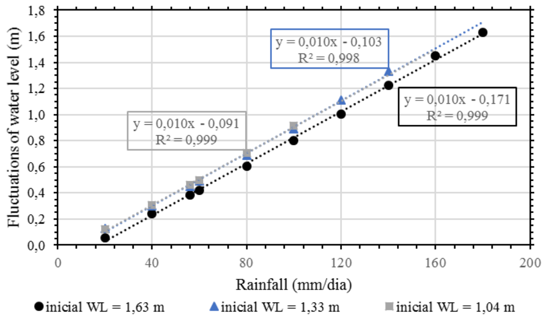

Figure 8. Fluctuations of the water level in function of accumulated daily rainfall.

For the three WL positions mentioned above, from this analysis it was still possible to estimate the SF for a given accumulated daily precipitation scenario and for a known position of the water level (Figure 9).

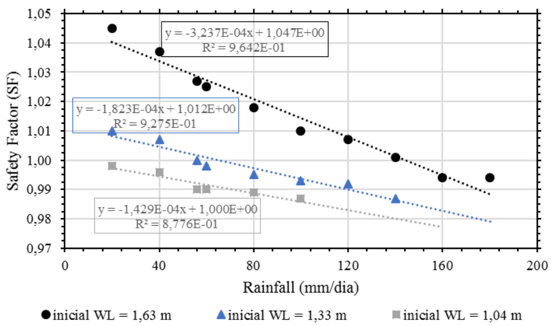

Figure 9. SF decreasing in function of accumulated daily rainfall.

Thus, when the SF is lower than the unit, this indicates that the scenario in question can reactivate the system, causing its instability.

6 CONCLUSIONS

The movement of landslides is a complex process that depends on many factors. In landslides prone zones, the hazard management have been mostly oriented to avoid dangerous sites and stabilizing of unstable slopes. However, in some situations, as in the present case, the type and dimension of landslide phenomenon does not allow the execution of stabilization techniques, due to their high cost and / or the high environment impact.

Therefore, it is important to use monitoring techniques, that when complemented with hydrological and geotechnical modelling, allows to understand the landslide phenomenon behaviour. The work done at Lajedo parish is yet at an early stage, in what concerns the acquisition of the monitoring data, once the equipment was only installed at the end of 2016. However, with the continuous geotechnical and hydrological results obtained until now it is almost possible to identify the instantaneous response of monitored water level with rainfall. This situation was verified in the modelling carried out. Furthermore, an occurrence of slow movements, at local teste #L2 was also detect.

Considering the displacements measured by the inclinometers until now and the hydrological modelling, it is possible to conclude that a reactivation of the movement existed in periods when rainfall achieved values between 40 to 60 mm/day, for a water level position equal or higher than 1 m. So, it is possible to conclude that the main monitored landslide, #L2, presents an active and intermittent behaviour.

From the hydrological and geotechnical modelling carried out for situation # L2, it was possible to obtain equations that estimate the variation of the water level and the decrease of the safety factor due to a certain amount of precipitation, taking into account the position of the water level that precedes this precipitation. With these data, it is possible to conclude about the stabilization of the site # L2, in a dynamic and practically instantaneous way.

7 ACKNOWLEDGEMENTS

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