

Distributed transient response modelling of rainfall-triggered shallow landslide for susceptibility assessment in Ribeira Quente valley (S. Miguel Island, Azores)

P. Amaral, R. Marques & G. Queiroz

Centro de Vulcanologia e Avaliação de Riscos Geológicos, Universidade dos Açores, Ponta Delgada, Açores, Portugal

J.L. Zêzere

Centro de Estudos Geográficos, Universidade de Lisboa, Portugal

F. Marques

Centro e Departamento de Geologia, Faculdade de Ciências da Universidade de Lisboa, Portugal

ABSTRACT: In the last 15 years, several heavy rainstorms have occurred in Povoação County (S. Miguel Island, Azores), namely in Ribeira Quente Valley. These rainfall events have triggered hundreds of shallow landslides that killed tens of people and have been responsible for direct and indirect damages amounting to tens of millions of Euros. On the 6th March 2005 an intense rainfall episode, up to 160 mm of rain in less than 24 h, triggered several shallow landslides and caused 3 victims and damaged/blocked roads. The Ribeira Quente Valley has an area of 9.5 km² and is mainly constituted of pyroclastic materials (pumice ash and lapilli), that were mostly produced by the Furnas Volcano explosive eruptions. To provide an assessment of slope-failure conditions for the 6th of March 2005 rainfall event, it was applied a distributed transient response model for slope stability analysis. The adopted methodology is a modified version of Iverson's (2000) transient response model, which couple an infinite slope stability analysis with an analytic solution of the Richard's equation for vertical water infiltration in quasi-saturated soil. The validation was made on two different scales: (1) at a slope scale, using two distinct test sites where landslides were triggered; and (2) at the basin scale, using the entire landslide database and generalizing the modelling input parameters for the regional spatialization of results. At the slope scale, the obtained results are very accurate, and it was possible to predict the time of the slope failures. At the basin scale, the obtained results are very conservative, even though the model predicts all the observed landslide locations. The used methodology revealed to be a reasonable tool for landslide forecast for both temporal and spatial distributions. In the future, the model components will be integrated into a GIS based system that will publish the FS values to a WebGIS platform, based on near real time ground rainfall monitoring. This application will allow the evaluation of scenarios considering the variation of the pressure head response, related to transient rainfall regime. The resultant computational platform combined with regional empirical rainfall triggered landslides threshold can be incorporated in a common server with the Regional Civil Protection for emergency planning purposes.

1 INTRODUCTION

In volcanic areas, landslides are one of the main causes of destruction and fatalities (Costa 1984), namely where steep slopes cut pyroclastic materials. The high recurrence rate of extreme rainfall events in some of these regions makes them authentic "clock bombs" concerning slope instability.

In Europe, important rainfall-triggered landslides events occur in volcanic areas like in Campania Region, Southern Italy (Cascini et al. 2000, Frattini et al. 2004, Calcaterra et al. 2007), and in S. Miguel island, namely in Povoação County (Valadão et al. 2002, Marques et al. 2008).

The trigger mechanism of a landslide and the landslide subsequent behavior are conditioned by the

rheological material proprieties as well as by the, hydrologic system inherent to the slope. The decisive precipitation amount needed to determine slope failure depends on the morphology, on the mechanical and hydrological properties of the soil and on the vegetation that cover of the slope (Crosta 1998, van Asch et al. 1999).

In recent years, research has been focused on combining hydrological models with slope stability analyses for understanding the mechanism of rainfall-triggered landslides, based upon the different responses of the terrain according to the geological, physical, hydrogeological and soil mechanical characteristics (e.g., Montgomery & Dietrich 1994, Terlien et al. 1995, Iverson 2000).

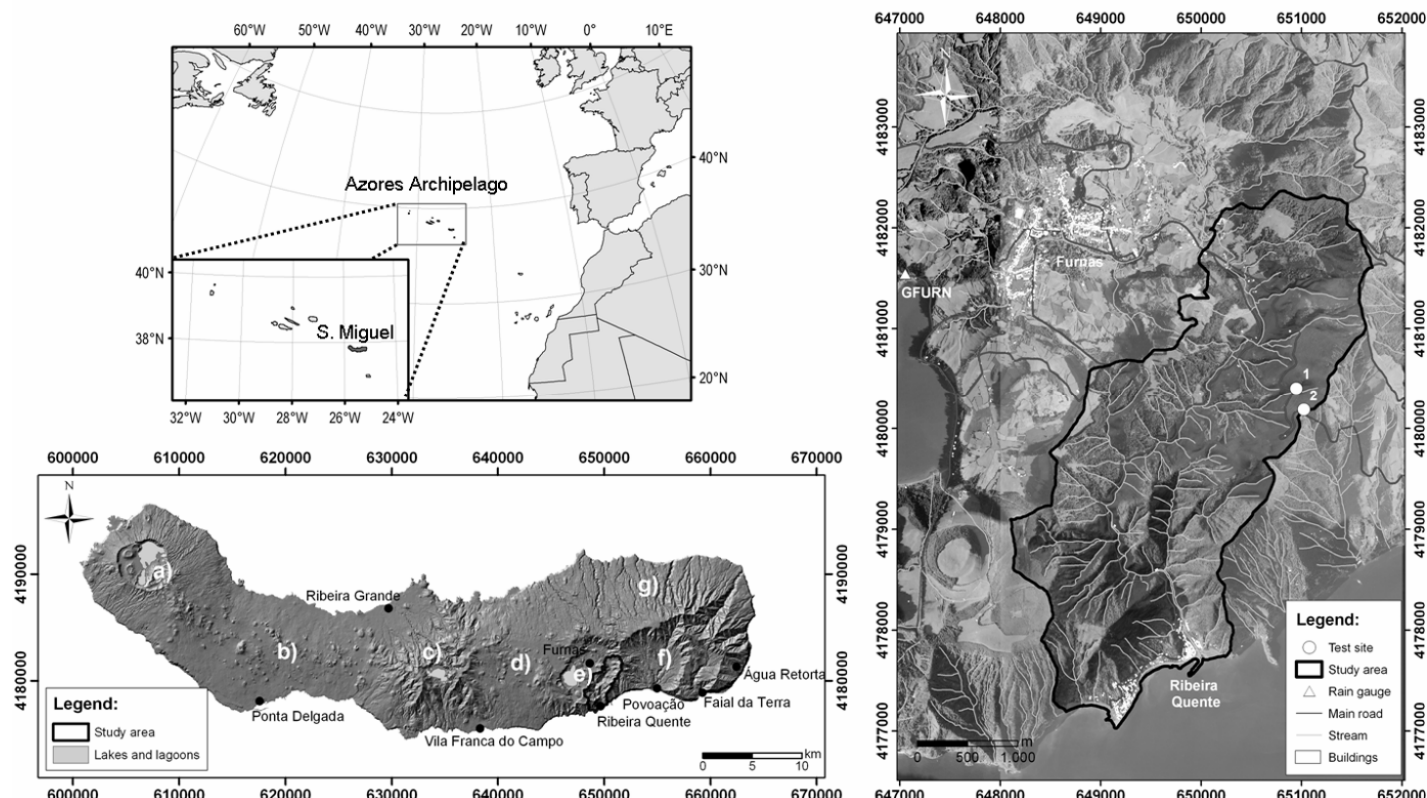


Figure 1. Ribeira Quente Valley in Azores archipelago context. Legend: a) Sete Cidades Volcano; b) Picos Region; c) Fogo Volcano; d) Achada das Furnas; e) Furnas Volcano; f) Povoação Volcano; and g) Nordeste volcanic complex.

Mass movements recognized in the Povoação County are mainly soils slips and debris flows (according to Cruden & Varnes (1996) landslide classification). Typically, these failures occur at less than 2 m deep, so the initial stress state is very low, and tends to develop parallel to the original slope. These landslides are usually triggered by short period but very intense rainfall events, and have been responsible for direct and indirect damages amounting to tens of millions Euros and loss of tens of human lives in the last 15 years (e.g., on the 31 October 1997 and the 6 March 2005). For this region, the temporal frequency and spatial distribution of shallow landslide is of extreme importance for landslide hazard assessment and risk mitigation.

The present work aims to provide a preliminary assessment of slope-failure conditions in the Ribeira Quente valley. We applied a hydrological model coupled with the infinite slope analysis to evaluate the time of occurrence of shallow slope movements. The adopted methodology is a modified version of Iverson's (2000) transient response model for vertical water infiltration in quasi-saturated soil conditions, which was applied at the basin-scale and for two specific sites, to assess areal slope stability for the 6th of March 2005 landslide events.

2 STUDY AREA CHARACTERIZATION

The Ribeira Quente Valley is located in the Povoação County, (S. Miguel, Azores) (Fig. 1). The study

area has an extension of about 9.5 km² and its altimetry ranges between 0 and 700 m a.s.l.

The valley is characterized by very deep fluvial channels and very steep slopes (38.9 % of the area have slope gradient higher than 35°, reaching a maximum of 87.5°).

One single road exists along the valley that connects R. Quente Village (780 inhabitants), located near the sea, to Furnas village. In the bottom of the valley, basaltic lava flows (s.l.) are present, mantled by a sequence of loose pyroclastic deposits. In some locations, the thickness of pyroclastic deposits reach more than 300 m. Locally, some of these deposits have been affected by pedogenetic processes originating weathered pumices levels and buried soils.

The valley is frequently affected by landslides that disrupt the single road connecting to R. Quente village, isolating the population, as it happened on the 6th of March 2005.

From the climatic point of view, the area has a mean annual temperature of 18°, a mean annual precipitation (MAP) of 1992 mm and a mean annual humidity of 85% (Marques et al. 2008).

The precipitation regime is dominated by high variability at both inter-annual and inter-seasonal scales. The monthly rainfall distribution shows an evident seasonal pattern, with a significant difference between the 'rainy season' that extends between October and March, and the 'dry season' with a minimum of rainfall in July.

3 THE 6TH MARCH 2005 LANDSLIDE EVENTS

On the 6th March 2005, an intense rainfall episode, up to 160 mm in less than 24 h (Fig. 2), was recorded at a rain gauge located close to Furnas Lake, 285 m a.s.l. (GFURN, Fig. 1).

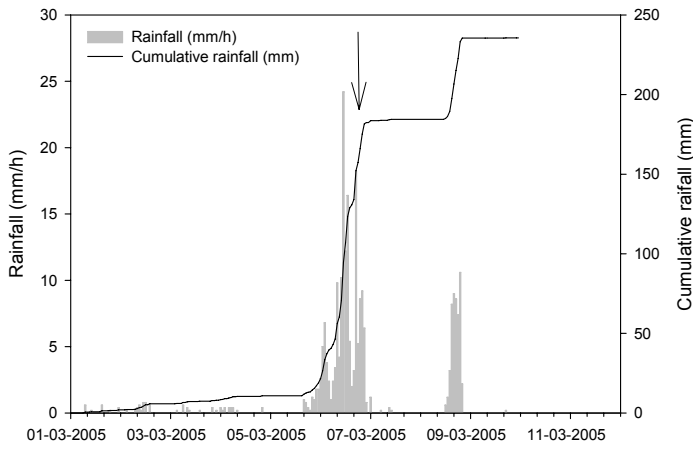


Figure 2. Hourly and cumulative rainfall record in the reference rain gauge (GFURN) from 1 to 11 March 2005.

The highest intensity rainfall period was observed between 06:00h and 20:00h. The rainfall data show two distinct rainfall intensity peaks, the first occurred at 13:00h and the second occurred at 17:00h. During the second peak several shallow landslides were triggered (22 inside the study area), which have caused 3 fatal victims and damaged/blocked roads in several places. The failure surfaces geometries were essentially planar, parallel to the original topography. The spatial distribution of the landslides in the area suggests a non uniform rainfall pattern due to the orographic effect and also to the progress of the cold front that was responsible for the precipitation.

4 HYDROLOGICAL AND GEOTECHNICAL MODELLING

In the present work a pressure head diffusive model and a stability slope model were coupled in order to predict shallow slope movements in time and space.

The pressure head diffusive model involves the mathematical approach developed by Iverson (2000), based on the Richards equation for unsaturated shallow groundwater flow. The model assesses the effects of transient rainfall infiltration by approximating the pore pressure response to non-steady rainfall in different spatial and temporal scales.

Iverson (2000), using appropriate initial and boundary conditions, obtain a response function R that depends on time, slope angle, failure depth and diffusivity values. An important assumption of the model is that the soil pressure head is initially near zero, and so the hydraulic conductivity and diffusivity

can be represented by a single value. This assumption is supported by the fact that landslide activity occurs when the soil is extremely wet.

The relationship between pore pressure and unsteady rain rates then becomes (Iverson, 2000):

$$\frac{\psi}{Z}(Z, t \leq T) = \zeta \left(1 - \frac{d_z}{Z}\right) + \frac{i_z}{K_{sat}} [R(t^*)] \quad (1)$$

$$\frac{\psi}{Z}(Z, t > T) = \zeta \left(1 - \frac{d_z}{Z}\right) + \frac{i_z}{K_{sat}} [R(t^*) - R(t^* - T^*)] \quad (2)$$

with:

$$R(t^*) = \sqrt{\frac{t^*}{\pi}} \exp\left(-\frac{1}{t^*}\right) - \operatorname{erfc}\left(\frac{1}{\sqrt{t^*}}\right) \quad (3)$$

$$t^* = \frac{t}{Z^2} (4D_0 \cos^2 \beta) \quad (4)$$

$$T^* = \frac{T}{Z^2} (4D_0 \cos^2 \beta) \quad (5)$$

where t is the time (s); d_z is the depth to the steady-state water table (m) (in vertical direction, Z); T is the duration of a pulse of constant intensity rainfall (s); ζ is a constant that expresses the initial steady state pressure head distribution, being $\zeta = \cos^2(\beta) - (i_z/K_{sat})$; $R(t^*)$ and $R(t^* - T^*)$ are the pore pressure response functions; erfc is the complementary error function; t^* and T^* are normalized time and rainfall duration, respectively; and i_z/K_{sat} is the normalized rainfall intensity, with i_z and K_{sat} as the rainfall intensity (m/s) and the saturated hydraulic conductivity (m/s), respectively. The existing hydraulic head $\zeta(1 - d_z/Z)$ is static and acts before the beginning of the rainfall, while the transient hydraulic head proceeds during the transient rain infiltration and it is represented by two complementary and fundamental factors, $R(t^*)$ and (i_z/K_{sat}) . In this case, the failure mechanism is due to the rise of the water table during the infiltration process.

However, field evidences in the study area confirm that a water table does not exist near the ground surface, in most landslide locations. This evidence enables considering that the rapid variation and evolution of pore pressures into the upper portion of the slope is not directly connected to the evolution and rise of groundwater level. Therefore, the infiltration process and the development of a percolation front are considered as the triggering mechanism of soil slips in the study area. In this case, the first member of equation 1 and 2 $[\zeta(1 - d_z/Z)]$ become zero, and the $i_z/K_{sat}[R(t^*)]$ and $i_z/K_{sat}[R(t^*) - R(t^* - T^*)]$ were calculated. Due to the additive nature of the solution, the pressure head at a certain time t is simply expressed as the sum of the contributions of single rainfall pulses. Each pulse contribution follows a function in

time that is expressed by the response function $R(t)$. The time-varying pore pressure was computed on the above-mentioned assumptions, and it was integrated to calculate slope stability using the infinite slope model equation in the form presented by Iverson (2000):

$$FS = \frac{\tan \phi}{\tan \beta} + \frac{-\psi(Z,t)\gamma_w \tan \phi + c}{\gamma_s Z \sin \beta \cos \beta} \quad (6)$$

where FS is the factor of safety; β is the slope angle ($^\circ$); ϕ is the internal friction angle ($^\circ$); c is cohesion (kPa); γ_s is the material unit weight (kN/m^3); and γ_w is the water unit weight (kN/m^3). During a rain-storm, the factor of safety will vary dynamically as a function of depth and time reflecting the pore pressure response.

5 SOIL PROPERTIES

The geotechnical characterization of pyroclastic deposits that constitute the slopes of the study area was based on standard soils analyses, including: (i) assessment of the physical parameters of materials (grain size distribution, bulk and dry densities and Atterberg limits); (ii) standard geotechnical tests (direct shear tests (DST) and oedometric tests); (iii) analysis of the hydrological behavior of the material (saturated and unsaturated hydraulic conductivity and retention capacity).

Specific gravity ranges between 2.26 and 2.90 g.cm^{-3} , and dry density ranges from 0.51 to 1.28 g.cm^{-3} . Porosity ranges between 50.5 and 79.5%, and void ratio ranges from 1.02 to 3.87.

Shear strength results for the analyzed materials shown two distinctive families of internal friction angle: $30\text{--}34^\circ$ for silty soils and $34\text{--}43^\circ$ for sandy soils. Effective cohesion ranges from 0 to 8 kPa. The majority of the analyzed samples are non plastic or slightly plastic soils and generally, have low clay content ($<15\%$). According to USCS classification, the analyzed material can be classified as sandy-silt non-plastic soil.

From the hydrological point of view, the saturated hydraulic conductivity was measured, using both in situ and laboratory tests, with double ring infiltrometer and constant head permeameter, and the obtained values range between 10^{-4} m.s^{-1} and 10^{-6} m.s^{-1} .

The maximum hydraulic diffusivity was acquired by the ratio between K_{sat} and the minimum slope of the Soil Water Characteristic Curve close to the saturation (Iverson, 2000). The values obtained ranged from 10^{-2} to $10^{-4} \text{ m}^2.\text{s}^{-1}$.

6 APPLICATION AND RESULTS

In this section it is present an example of slope stability modelling, within the previous assumptions from the 6th of March 2005 landslide event occurred in R. Quente Valley. In order to model the slope stability conditions we used two different scale approaches: (i) a slope scale, using two discrete test sites (see Fig. 1) where the modelling of triggered landslides is supported by accurate input data; and (ii) a basin scale, using the whole landslide database and generalizing the modelling input parameters for the entire area.

The test sites slopes are characterized by medium-high gradient ($33^\circ\text{--}45^\circ$) and are composed by weathered lava flow (test site 1) and by pyroclastic deposits (pumice lapilli and ash), slope deposits and buried soils (test site 2). Table 1 summarizes the soil parameters used to model the hillslope pore water pressure and to perform the stability analyses during the transient rainfall, for both the slope scale and the basin scale.

Table 1. Values of the parameters used in this study.

Properties	Slope Scale		Basin Scale
Symbol and Units	Site 1	Site 2	All
Slope angle, β ($^\circ$)	33	45	MDT
Land. depth, Z (m)	0.8	0.6	0.5
Sat. H. Cond., K_{sat} (m.s^{-1})	$1.7\text{E-}05$	$2.7\text{E-}05$	$1.0\text{E-}05$
Hyd. diff., D_θ ($\text{m}^2.\text{s}^{-1}$)	$9.2\text{E-}04$	$1.0\text{E-}03$	$1\text{E-}04$
Soil friction angle, ϕ ($^\circ$)	41	33	38
Soil cohesion, c' (kPa)	5	5	5
U. w. of water, γ_w (kN.m^{-3})	9.8	9.8	9.8
U. w. of soil, γ_s (kN.m^{-3})	16.5	16	16
R. intensity, vertical, i_z (m.s^{-1})	Variable		
Rainfall duration, T (s)	3600		
Norm. infiltration rate, vertical, i_z/K_z	Variable		
Norm. rainfall duration, T^*	11.25	19.91	7.73

For each test site, a detailed stratigraphic profile was constructed to support the definition of geotechnical and hydrological input parameters.

At the basin scale, it was implemented the diffusive model coupled with the infinite slope model in a GIS, using a 5 m pixel size grid. It was assumed that pyroclastic deposits mantle the valley.

Additionally, the geotechnical and hydrological parameters of pyroclastic deposits were assumed as the average values obtained in test sites 1 and 2, together with parameters obtained, for similar materials, by Amaral et al. (2008) for Povoação County.

Figure 3 shows the variation of the factor of safety against precipitation for test sites 1 and 2. On both cases, it is possible to observe the FS decreasing during the precipitation pulses as well as the FS increasing with the reduction of rainfall intensity. At 13:00 (elapsed time 85, Fig. 3), the FS value was very close to 1, and decreased below 1 at 17:30 (elapsed time 89.5, Fig. 3), very near to the precise time of the landslide occurrence in both test sites.

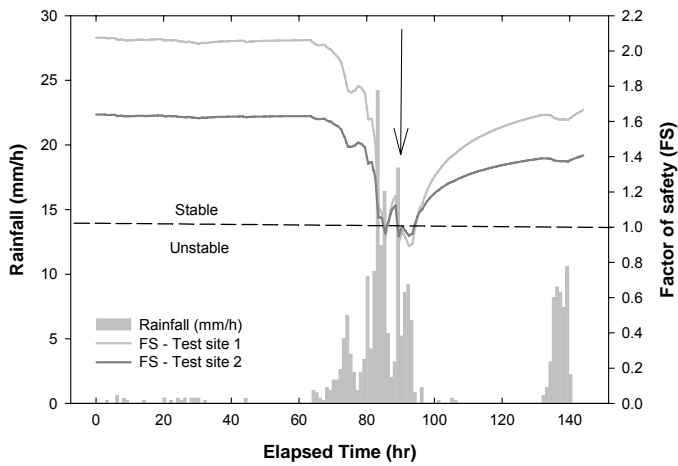


Figure 3. Safety Factor and hourly precipitation versus elapsed time for the 6th of March 2005 event in test sites 1 and 2 (simulation from 03-03-05 3:00 to 08-03-05 20:00).

The FS computed at the basin scale is shown in Figure 4. In general, FS decreases in time, with the increase of rainfall intensity and accumulation.

It is possible to observe the FS decrease at 13:00 (Fig. 4b) and its smooth recover at 16:00 (Fig. 4c).

At 18:00 (Fig.4d) there was a significant decrease of the FS and 23.7% of the area was considered as unstable, predicting the total set of landslides in the area, triggered by the 6th of March 2005 heavy rainfall episode.

7 DISCUSSION AND CONCLUSIONS

Figures 3-4 show the obtained results by the diffusive model coupled to an infinite slope model to simulate the slope instability occurrences on the 6th of March 2005 both at the slope scale and the basin scale.

Comparing the obtained results from the simulations with the real time of landslide triggering and the landslide spatial incidence, it can be concluded that the model was able to predict very satisfactory the landslide activity in time and space at both scales.

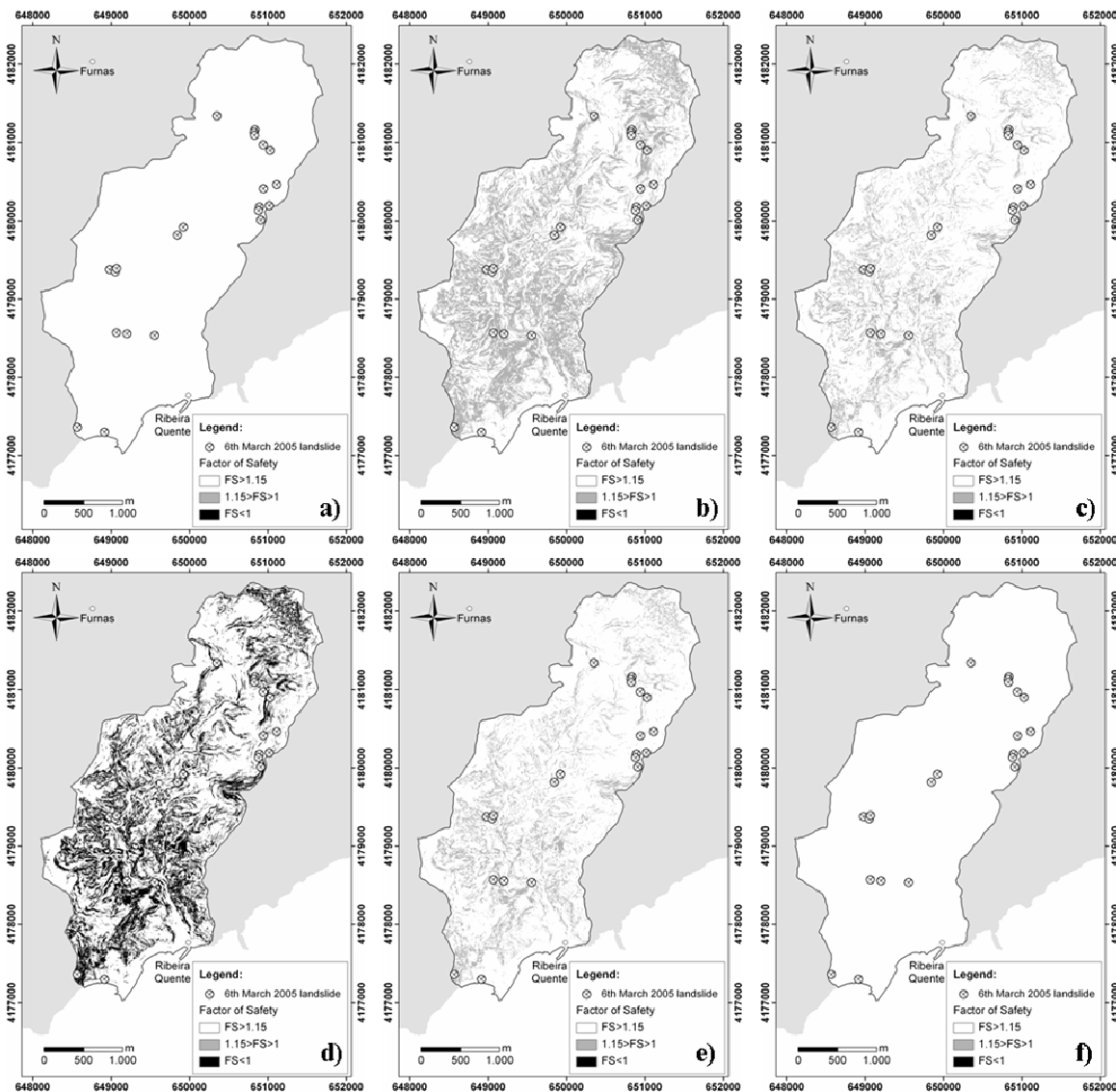


Figure 4. Basin scale Factor of Safety computation for different time steps. a) 6th of March 2005 - 10:00; b) 6th of March 2005 - 13:00; c) 6th of March 2005 - 16:00; d) 6th of March 2005 - 18:00; e) 6th of March 2005 - 22:00; f) 6th of March 2005 - 24:00.

At the site scale (Fig. 3), the obtained results were very precise, and it was possible to accurately predict the time of slope failures.

At the basin scale (Fig. 4), the obtained results were very conservative (23.7% of the area with $FS < 1$), even though the model predicts 100% of the identified landslides. This conservative result is frequent to occur at the basin scale, due to the generalization of geotechnical, hydrological and rainfall data, and to the assumption that the changes in the hydrological systems have a similar behavior in the whole area.

This model has some limitations as it happens in all numerical and analytical models of ground water flow and slope stability. Model limitations are imposed by simplifying assumptions, approximations, and other shortcomings in the underlying theories.

In future works, different hydrological models coupled with the infinite slope model will be analyzed in order to compare their performance in this study area.

The present approach allowed the physical explanation of the role of heavy rainfall episodes on landslide activity in the study area. The coupled hydrological and stability analysis presented in this work has provided the reconstruction of the landslide triggering mechanisms, during the storm occurred on 6th of March 2005 in Povoação County. Despite the necessary simplifications and assumptions, the results support the hypothesis that vertical fluxes were responsible for landslide triggering. The prediction of landslide occurrence in time and space was possible by modelling the vertical flux in quasi-saturated conditions, with the diffusive model. This type of approach, due to its dynamism, has revealed to be an excellent tool for the landslide prediction, and could be used as a useful tool for land-use management and emergency planning.

ACKNOWLEDGMENTS

This work is part of the project VOLCSOILRISK (Volcanic Soils Geotechnical Characterization for Landslide Risk Mitigation), supported by Direção Regional da Ciência e Tecnologia do Governo Regional dos Açores. The authors are thankful to Thomas Glade for his helpful comments and suggestions that improved the quality of this paper.

REFERENCES

Amaral, P., Marques, R., Zêzere, J.L., Marques, F., Queiroz, G. 2008. Geotechnical and hydrological characterization of pyroclastic soils in Povoação County (S. Miguel island, Azores) for modelling rainfall-triggered shallow landslides. *Geophysical Research Abstracts*, Vol. 10, EGU2008-A-07312, 2008, SRef-ID: 1607-7962/gra/EGU2008-A-07312.
Calcaterra, D., Coppin, D., de Vita, S., Di Vito, M.A., Orsi, G., Palma, B., Parise, M. 2007. Slope processes in weathered

volcaniclastic deposits within the city of Naples: The Camaldoli Hill case. *Geomorphology* 87: 132–157.
Cascini, L., Guida, D., Nocera, N., Romanzi, G., Sorbino, G. 2000. A preliminary model for the landslides of May 1998 in Campania Region. *Proc 2nd Int. Symposium on Geotechnics of Hard Soil-Soft Rock*, vol. 3. Balkema, Napoli:1623–1649.
Costa, J. E. 1984. Physical geomorphology of debris flows, in: *Developments and applications of geomorphology*, (Eds) Costa, J. E. and Fleisher, P. J., Springer-Verlag, Berlin, Heidelberg:268–317.
Crosta, G.B. 1998. Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. *Environmental Geology* 35(2-3): 131–145.
Cruden, D.M. & Varnes, D.J. 1996. Landslide Types and Processes. In: Turner, A.K., Schuster, R.L. (Eds.), *Landslide Investigation and Mitigation. Special Report 247*, vol. 3. Transportation Research Board, US National Research Council, Washington, DC: 36–75.
Fratini, P., Crosta, G.B., Fusi, N., Dal Negro, P. 2004. Shallow landslides in pyroclastic soils: a distributed modelling approach for hazard assessment. *Eng. Geology* 73, 277–295.
Iverson, R. M. 2000. Landslide triggering by rain infiltration, *Water Resources Research*, 36:1897–1910.
Marques, R., Zêzere, J.L., Trigo, R., Gaspar, J.L., Trigo, I., 2008. Rainfall patterns and critical values associated with landslides in Povoação County (São Miguel Island, Azores): relationships with the North Atlantic Oscillation. *Hydrol. Process.* 22: 478-494.
Montgomery, D. R. & Dietrich, W. E. 1994. A Physically based model for the topographic control on shallow landslide, *Water Resources Research*, 30:83–92.
Terlien, M.T.J., van Westen, C.J., van Asch, T.W.J. 1995 Deterministic modelling in GIS-based landslide hazard assessment. In: Carrara A, Guzzetti F (eds) *Geographical Information Systems in Assessing natural hazards*. Kluwer Academic Publishers:57–77.
Valadão, P., Gaspar J.L., Queiroz G, Ferreira T. 2002. Landslides density map of S. Miguel Island (Azores archipelago). *Natural Hazards* 2: 51–56.
van Asch, Th.W.J., Buma J., VanBeek L. 1999. A view on some hydrological triggering systems in landslides. *Geomorphology* 30(1–2): 25–32.