# Mega rockslides in Canary Islands: the role of the geomechanical properties of the submarine rocks in the stability of the flanks of Tenerife

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ABSTRACT: The failure mechanisms that could originate the mega paleo-rockslides of Güímar and La Orotava in Tenerife (Canary Islands) are analyzed, based on the geomechanical site investigations carried out on the pre-failure volcanic materials of Tenerife island flanks. Geological and geomorphological modelling and geomechanical characterization of the materials are presented. Hyaloclastites rocks are forming the submarine substratum of the island edifice presenting a highly deformable behaviour. Preliminary stability analyses have suggested potential failure surfaces in the hyloclastites rocks.

## 1 INTRODUCTION

More than 20 mega rockslides have been described in Canary Islands (Acosta *et al*., 2005). The resulting slided masses, deposited on the ocean floor, cover areas of thousands of square kilometers (350-2600 km$^2$) and volumes of hundreds of cubic kilometers (80-650 km$^3$). These paleo-landslides have been considered as one of the largest known in the world by their volume.

Güímar and La Orotava valleys in Tenerife were originated by mega rockslides. Both constitute exceptional examples due to their geomorphological features and the fact that the slided deposits have been identified in the ocean floor and inside the galleries excavated in the island (Navarro & Coello, 1989). In spite of their importance, only few investigations have been carried out to analyze these processes under a geomechanical point of view. The authors are carrying out detailed studies on the geomechanical properties of the materials involved, including in situ testing and geophysical surveys, to evaluate the instability processes of the volcanic islands flanks (Ferrer *et al*., 2007, 2008).

This paper presents the preliminary results of the site investigation carried out on the submarine materials formed by hyaloclastites and the role of these rocks on the stability of the volcanic edifice of Tenerife.

## 2 GÜÍMAR AND LA OROTAVA ROCKSLIDES

Güímar and La Orotava valleys are 9-12 km wide. They present opposite orientations, ESE and NNW respectively. Their heads are located in the *Cordillera Dorsal*, main rift zone in the island with NE direction and maximum heights between 1700 and 2200 m (Fig. 1).

The morphological characteristics of the valleys are singular, outstanding the symmetry and the important height of the lateral scarps (500 m), formed by pre-landslide volcanic materials with slope angles higher than 35º. The depressions formed were filled by post-landslide volcanic materials with slope angles lower than 15º.

The estimated volume of these rockslides is in the order of 30-50 km$^3$.

The age of Güímar rockslide has been estimated approximately 1 Ma (Ferrer *et al*., 2008). The age of La Orotava rockslide has been estimated between 0.54 to 0.69 Ma (Cantagrel *et al*., 1999).

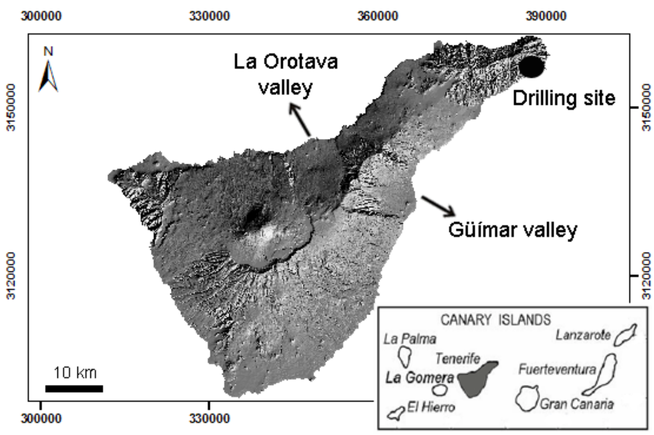


Figure 1. Güímar and La Orotava valleys (Tenerife) and drilling site location.

## 3 GEOLOGICAL AND GEOMECHANICAL CONDITIONS OF THE PRE-FAILURE VOLCANIC EDIFICE

In order to analyze the mechanical behavior of the flanks of the volcanic edifice, the geological, geomorphological and geomechanical representative modeling of the pre-landslide edifice have been prepared.

The different factors influencing volcanic landslide processes have been considered: morphology, lithology, geological structure, hydrogeological conditions, geomechanical properties, weathering and alteration and state of stress. Also the triggering factors on stability have been studied: volcanic and hydrothermal activity, dike intrusion and seismic activity.

The geometrical model before the occurrence of Güímar and La Orotava rockslides has been assessed considering paleomorphological data obtained from the slopes and lateral scarps of the volcanic edifice not affected by landsliding processes. The morphological features of the submarine slopes have been obtained from bathymetric data analysis.

It has been assumed that the ground water conditions for the pre-failure edifice could be similar to those encountered before intensive ground water exploitation of the island aquifers had taken place. A water table at 600-700 m below surface was estimated according with ground water records, with exception of the coastal areas. In the central part of the edifice due to the presence of a large number of dykes the ground water levels should be higher.

Geological and geotechnical data were recorded from field survey and from the extensive network of small diameter tunnels, with a total length over of 4000 km, excavated in the inland flanks for ground water supply purposes. Geotechnical properties of the volcanic materials of the emerged edifice have been also obtained from engineering geological surveys (González de Vallejo *et al*., 2008).

With respect to the geological and geomechanical data of the submarine edifice, only morphological and tectonic data are available from oceanographic surveys. In the Easter corner of the island site investigations have been carried out where submarine rocks are outcropping (Fig. 1). Three boreholes have been drilled in hyaloclastites reaching one of them 200 m depth.

Hyaloclastites and basaltic lavas have been the rock materials core drilled in the three boreholes, although hyaloclastite has been the predominant lithology. Hyaloclastites are composed of clastic particles of irregular shape and sizes ranging from 0.5 to 3 cm, forming a green, grey or brown coloured breccia. This material is poorly consolidated and weakly cemented. Voids and vacuoles are occasionally present with sizes ranging from 1 to 3 cm. Secondary minerals are observed inside them. Fracture zones and slikenside surfaces have been identified.

Pressuremeter tests, borehole geophysics (sonic, acoustic, televiewer camera, calliper) and laboratory tests have been carried out. Laboratory and geophysical results are not yet available at time of writing this paper (2009, December).

The deformational properties of the hyaloclastites were obtained from 16 pressuremeter tests carried out at different depths in one of the boreholes (Table 1). The values for pressuremeter moduli ranged from 10 MPa to 3212 MPa. Most frequently intervals range from 50 to 80 MPa and from 125 to 135 MPa. A representative value of 129 MPa has been considered for modelling purposes.

Table 1. Hyaloclastites pressuremeter moduli ($E_p$).

| Depth m | $E_p$ MPa | Depth m | $E_p$ MPa |
|---|---|---|---|
| 23.5 | 159 | 95 | 1833 |
| 35 | 48 | 96 | 235 |
| 38.5 | 169 | 102 | 262 |
| 47.5 | 60 | 103 | 10 |
| 60 | 58 | 107 | 903 |
| 62 | 81 | 107.5 | 123 |
| 74 | 145 | 118 | 335 |
| 89 | 824 | 118.5 | 3212 |

The simplified geological model for the pre-failure edifice is shown in Figure 2. The materials were grouped in those corresponding to the emerged edifice (above sea level) and the submarine edifice (below sea level). The following lithological units have been distinguished as representative of the simplified geological model of Tenerife island flanks for geomechanical purposes:

Forming the flanks of the island:

1 Lava flows (60%) and autoclastic breccias (40%).
2 Lava flows (70%) and autoclastic breccias (30%).
3a Altered lava flows (90%) and pyroclastic deposits (10%), below the water level.
3b Altered lava flows (80%), pyroclastic deposits (10%) and dykes (10%), below the water level.

Forming the structural axis of the island:

4 Lava flows (30%), autoclastic breccias (20%), pyroclastic deposits (40%) and dykes (10%).
5 Altered lava flows (40%), pyroclastic deposits (30%) and dykes (30%), below the water level.

Forming the submarine edifice:

6a Hyaloclastites (70%) and pillow lavas (30%).
6b Hyaloclastites (65%), pillow lavas (25%) and dykes (10%).
7a Pillow lavas (90%) and hyaloclastites (10%).
7b Pillow lavas (85%), hyaloclastites (5%) and dykes (10%).
8 Fragmentary submarine deposits.
9 Dykes (90%) and pillow lavas (5%).

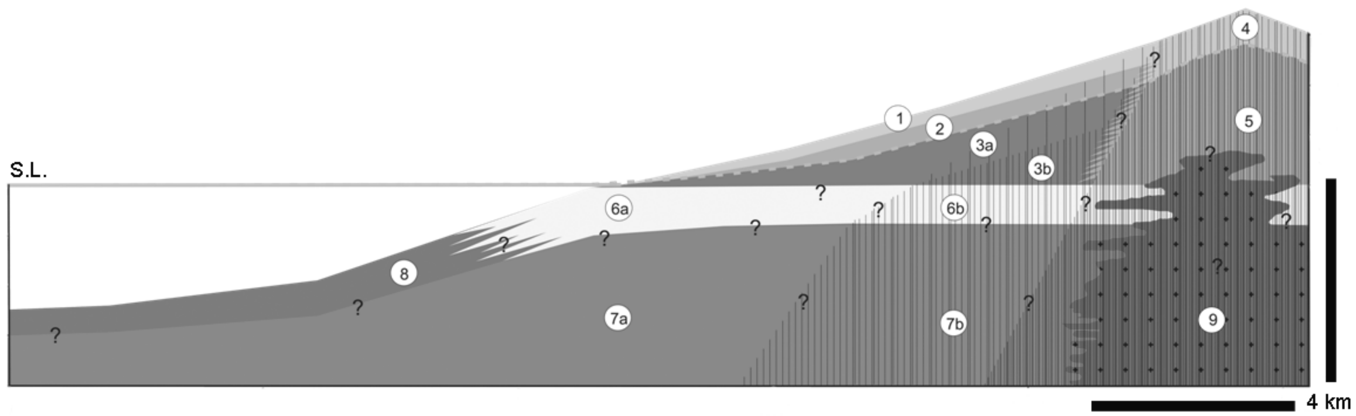


Figure 2. Simplified representative geological model of the flank of the volcanic edifice of Tenerife. Numbers represents the different lithological units considered. 1, 2, 3a, 3b, units forming the flanks: lava layers predominant; 4, 5, units forming the structural axis: pyroclastic deposits predominant; 6a, 6b, submarine rocks: hyaloclastites predominant; 7a, 7b, submarine rocks: pillow lavas predominant; 8, Fragmentary submarine deposits; 9, Plutonic complex: dykes predominant. S.L.: Sea level. Dashed line: water level. ?: uncertainties. The same scales horizontal and vertical.

## 4 STABILITY CONDITIONS OF GÜÍMAR AND LA OROTAVA PRE-FAILURE EDIFICES

Stability analysis has been carried out in the pre-failure edifices of Güímar and La Orotava applying stress-strain methods. A first analysis has been carried out using rock mass parameters obtained from the Hoek-Brown criterion (Table 2). Figure 3 shows the results of this analysis showing a large deformation surface affecting the whole edifice. In this case a factor of safety of 1.34 was obtained applying c-ϕ reduction procedure.

A second stability analysis has been carried out using deformability values for the hyaloclastites. Figure 4 shows the results obtained. In this case, the distribution of the maximum deformations shows larger deformations affecting the hyaloclastites and a new failure surface.

In this second analysis values of 0.1 MPa for cohesion and 16º for angle of internal friction are needed to reach limit equilibrium.

Limit equilibrium methods have been also applied showing similar results, Figure 5 (Seisdedos, 2008).

Although these results are still preliminary they present significant potential failure surfaces that are in accordance with the geomorphological and geological features observed in Güímar and La Orotava valleys, as well as with the geomechanical properties of the materials.

The importance of the hyaloclastites rocks has been also pointed out on the stability of the Hawaiian volcano flanks (Schiffman *et al.*, 2006).

Table 2. Geomechanical properties (c, ϕ, E) obtained for the pre-failure edifice using Hoek-Brown criterion.

| Unit | $\gamma_d$ | c | ϕ | E | ν |
|---|---|---|---|---|---|
| | kN/m$^3$ | MPa | º | MPa | - |
| 1 | 20.7 | 0.9 | 51 | 6756 | 0.30 |
| 2 | 21.7 | 1.7 | 47 | 8921 | 0.30 |
| 3a | 20.2 | 2.3 | 34 | 4204 | 0.29 |
| 3b | 18.0 | 3.1 | 25 | 2779 | 0.29 |
| 4 | 18.0 | 0.9 | 33 | 2299 | 0.26 |
| 5 | 18.9 | 2.8 | 22 | 2056 | 0.26 |
| 6a | 22.6 | 1.0 | 23 | 1012 | 0.33 |
| 6b | 23.0 | 2.5 | 17 | 1176 | 0.32 |
| 7a | 26.8 | 8.0 | 36 | 12023 | 0.28 |
| 7b | 27.2 | 11.4 | 34 | 13183 | 0.28 |
| 8 | 19.0 | 1.0 | 20 | 1000 | 0.30 |
| 9 | 27.6 | 13.2 | 33 | 10233 | 0.28 |

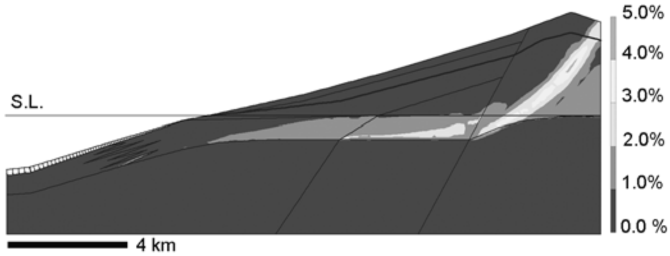


Figure 3. Shear strains using Table 2 properties (maximum shear strain 4.3%). Same scale horizontal and vertical.

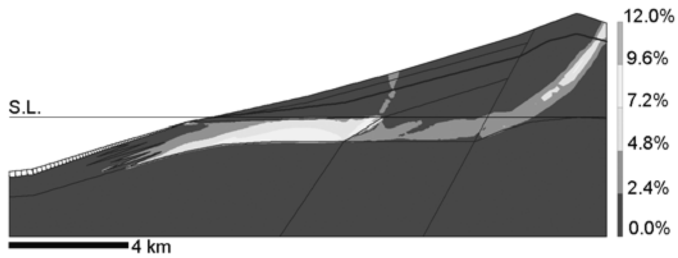


Figure 4. Shear strains using pressuremeter moduli for hyaloclastites (maximum shear strain 11.24%). Same scale horizontal and vertical.

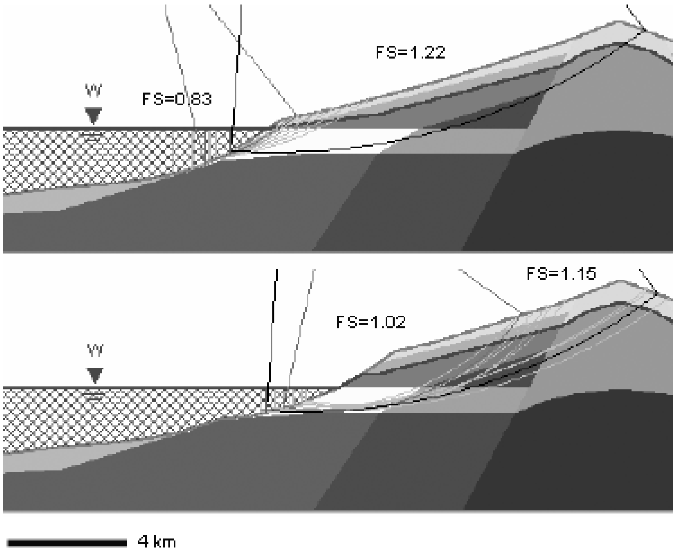


Figure 5. Limit equilibrium analysis results showing potential failure surfaces for the properties included in Table 1 and considering c = 0.1 MPa and $\phi$ = 14º for hyaloclastites. Same scale horizontal and vertical.

## 5 CONCLUSIONS

The highly deformable hyaloclastite rocks can play a primary factor in the destabilization process of the flanks of Tenerife. The preliminary results obtained have shown the geometry of the potential failure surfaces of Güímar and La Orotava rockslides. These results are in accordance with the geomechanical properties of the rocks, the surface and submarine geomorphological data and the geological processes involved. The results suggest that the large instability processes common of the volcanic islands flanks depend on the high deformability properties of hyaloclastites, as well as the morphological conditions of the emerged volcanic edifice, mainly the height and the slope angle of their flanks. Other influencing or triggering factors such as dyke intrusion pressures and volcanic seismicity activity should be also considered.

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