Stability and failure mechanisms of large landslides in the volcanic island flanks of the Canary Islands

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The stability conditions and failure mechanisms of volcanic flanks in the Canary Islands, considering both, first generation collapses and potential future giant landslides on the islands affected by ancient collapses, as is the case of La Palma and Tenerife, have been analysed by means of numerical methods. Geometrical, geological and geomechanical models have been developed for Cumbre Vieja and El Teide volcanic edifices, on La Palma and Tenerife islands respectively. The mayor difficulties and uncertainties are associated to the large scale of the landslides, both in regard to their geological-geomechanical characterization and the preparation of the models. One of the main aspects investigated was the geomechanical characteristics of the volcanic materials, specially the submarine rock masses forming the substratum underlying the subaerial volcanic buildings. The low strength and high deformability properties of these rocks play a fundamental role on the stability of the island flanks, and they constitute the main key factors to assess the current stability conditions. Results of the stability analysis in terms of safety factor are presented for Cumbre Vieja and El Teide volcanic edifices.

Keywords: Volcanic landslides, flank collapses, stability analysis, Canary Islands

1. Geological setting

The Canary Islands are an outstanding example of the growth of large oceanic volcanic islands, reaching maximum heights of 3,718 m on the island of Tenerife and 2,423 on the island of La Palma. These values must be added the height of the submerged part of the islands, which can reach 4,000 m. These dimensions make the island of Tenerife the third highest volcano on the planet.

As other volcanic islands of great height, throughout their geologic history the Canary Islands have been affected by large flank collapses. At least 10 mega-

landslides have been described in the last 1 Ma. Some of the younger islands - Tenerife, La Palma, El Hierro- present outstanding morphological features evidencing the occurrence of these large landslides, with volume of tens of cubic km.
The Icod landslide stands out in Tenerife, around 170 ka ago, on whose sub-aerial emptying has subsequently grown the Teide volcanic building, covering the remains of the Icod landslide. The same happens on the island of La Palma, where a large collapse occurred about 500 ka ago, the Cumbre Nueva landslide, whose remains were later covered and buried by successive lava flows, forming the current Cumbre Vieja building.

2. Geological modelling

For the numerical analysis of the volcanic edifices of Tenerife and La Palma, the geometric, geological and geomechanical models representative of current conditions are necessary. For these, field work, in-situ investigations and tests and laboratory tests were carried out, as well as an exhaustive compilation of available literature on these aspects. The data are not included here due to lack of space, but the models are summarized below.
For analyses of Cumbre Vieja edifice, two sections E-W have been chosen representing different geological and topographical characteristics, the presence of buried ancient landslide deposits levels, and the maximum heights of the edifices (Figure 2.1). Section CV-1 has a maximum height of 1,560 m and a width of 16.3 km a.s.l.; under the lava flows that form the current morphology are the deposits

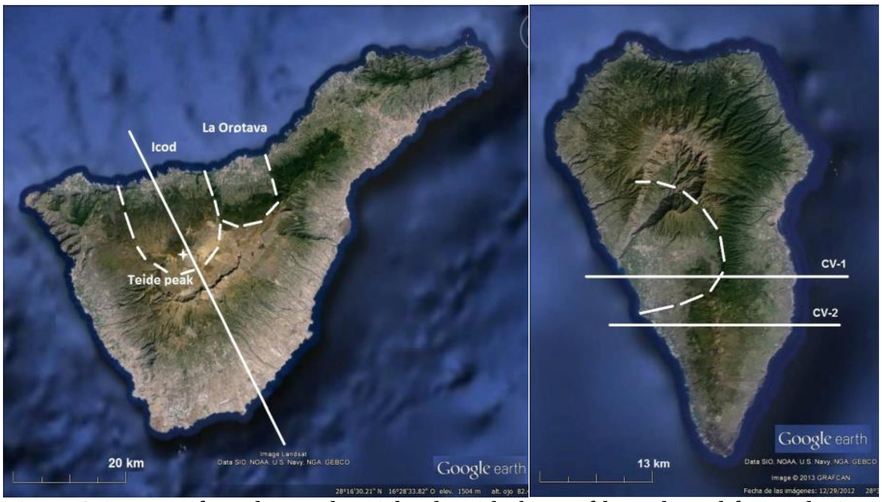

Figure 2.1. Tenerife and La Palma islands with the profiles selected for analysis. The onshore limits of the main more recent (< 500 ky) mega-landslides occurred are indicated: Icod and La Orotava in Tenerife, and Cumbre Nueva in La Palma.

and scars of a large ancient pre-historic mega-landslide. Section CV-2, further south, passing through the highest point of the edifice, 1,940 m, with a width of about 13.4 km a.s.l.; this model has been analysed without including the presence of landslide deposits, as is located south of the limits of the ancient Cumbre Nueva mega-landslide.

For El Teide edifice, a NW-SE section was selected with an elevation of 3,660 m, and a width of 40.6 km a.s.l.; under the lava flows that form the current morphology are the deposits and scars of the Icod landslide.

The emerged geometrical profiles have been extended under the sea level with the corresponding submarines profiles, obtained from the bathymetric data provided by the Instituto Español de Oceanografía and the Instituto Hidrográfico de la Marina.

The geological models are based on previous studies in similar volcanic edifices of the island of Tenerife, specifically the Dorsal edifice (Ferrer et al. 2007 and 2011; Seisdedos et al, 2012) where extensive and detailed investigations were conducted on the characteristics of the different geological units that form the subaerial edifices (Figure 2.2). The model has been adapted to the geometric conditions of the volcanic buildings of Cumbre Vieja and El Teide.

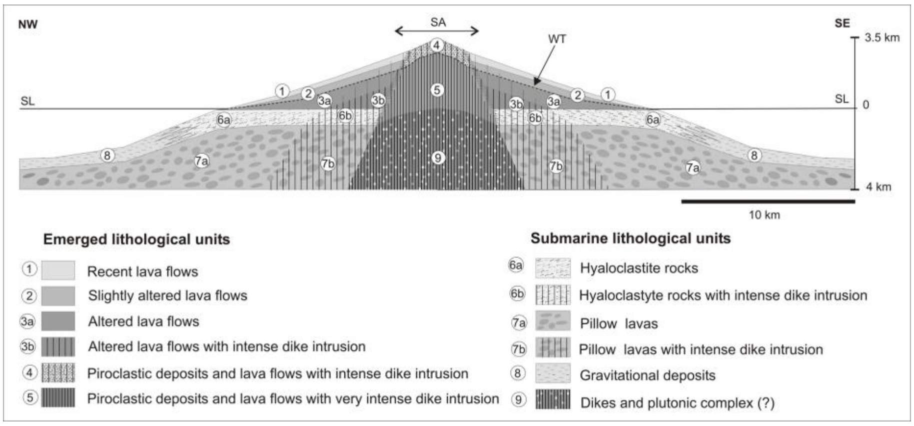

Figure 2.2. Schematic geological model of La Dorsal edifice, Tenerife (Seisdedos et al. 2012). WT = water table. SL = sea level. SA = structural axis.

The lithological units, or lithological groups, that form the island flanks and the structural axis of edifices are shown in Figure 2.2. The materials of the submerged part of the edifice represent the submarine growth phases of the islands. Most of the information about shallow submarine materials (hyaloclastites, unit 6) has been obtained from boreholes drilled in the area and relevant literature (DePaolo et al, 2001; García and Davis, 2001; Schiffman et al., 2006).

The ancient landslide deposits buried under hundreds of meters of basaltic lava flows in the cases of CV-1 and El Teide, have been reflected in the geological models (locally so-called *mortalón*). This poorly known aspect of the geology of the Islands could be resolved thanks to information provided by the geologist D. José Manuel Navarro.

3. Geomechanical modelling

The geomechanical characteristics assigned to the geological units are shown in Table 3.1. The onshore rock masses parameters were obtained by applying the Hoek-Brown criterion, based on data from field surveys and laboratory tests. To assign mechanical properties to the lithological units it was considered both the degree of weathering/alteration of volcanic rock masses (according to their age and depth) and the degree of saturation, according to the position and evolution of the "island scale" water table. The low values obtained for E and the relatively high values obtained for c, are according to the special mechanical characteristics of the volcanic rock masses.

The characterization of the hyaloclastites was carried out from field tests in a deep borehole carried out for the characterization of these specific submarine rocks in Tenerife, and from strength and deformability laboratory tests (Seisdedos et al. 2012; Ferrer et al. 2011).

The properties of the deposits of ancient landslides buried in the volcanic edifices were also obtained the from field survey, adits and small tunnels excavated in the island flanks, and laboratory tests. Figure 3.1 shows the schematic geological-geomechanical model prepared for the analysis of Cumbre Vieja.

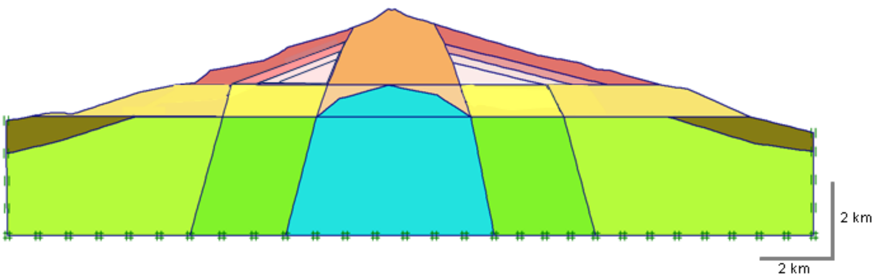

Figure 3.1. Simplified geomechanical model of Cumbre Vieja edifice, section CV-2

Table 3.1. Geomechanical properties assigned to the geological units using Hoek-Brown criterion

Units	c (MPa)	ϕ	E (MPa)
1	0.9	51	6,7
2	1.7	47	8,9
3a	2.3	34	4,2
3b	3.1	25	2,8
4	0.9	33	2,3
5	2.8	22	2,0
6	1.5-2,5	30-35	1,2
7	10.0	35	12,5
8	1.0	20	1,0
9	13.2	33	10,2
Mortalón	0.1 - 0.5	20 - 25	1,1

4. Stability analysis results

The stability analyses were carried out using the PLAXIS code and the shear-strength-reduction method. The main difficulty lay in the dimensions of the modelled volcanic edifices (with several km in length and height) and the representativeness and interpretation of the results. In this regard it must be pointed out the lack of data in the literature on analysis of geological dimension models, with very few available studies (Schiffman et al. 2006; Thomson et al. 2008; Van Berlo 2007; Okubo 2004; Apuani et al. 2005).

The acting forces considered in the analysis include the gravity forces according the specific weight of the materials and the water pressure according the “island scale” actual water table. Also forces simulating magma intrusions and volcanic earthquakes has been applied in order to know their influence in the stability conditions; these have not been included here as they don’t play a definitively role in the triggering of flank failure.

The results show that all the models analysed are stable for the parameters of Table 3.1, giving values of safety factor SF > 1.8 for the model CV-1 of La Palma and SF > 1.5 for the model CV-2 and El Teide, for large flank collapses and failure through submarine materials (hyaloclastites).

The back-analysis carried out adequately reproduced the typical flank instabilities of these volcanic edifices, with the same patterns and features than the pre-historical collapses occurred in the islands. The results show that for a flank collapse of the volcanic edifice, the hyaloclastites strength parameters must be considerably reduced: cohesion c<0.1 MPa and friction ϕ<16º for the CV-1 model; c<0.5 MPa and ϕ<14º for the CV-2 model, and c<0.5 MPa and ϕ<13º for El Teide model. Figure 4.1 shows some examples of the most representative graphical re-

sults. These results show the stability conditions at present for the islands analysed, showing their stable conditions against large flank failures.
The interpretation of results and the obtained values of the strength parameters clearly depend on the data, criteria and methods used to obtain them. In this case, as described above, all the steps adequate to the specific geological and geomechanical characteristics and properties of the rock masses forming the volcanic edifices, affected by the corresponding geological and volcanic processes.

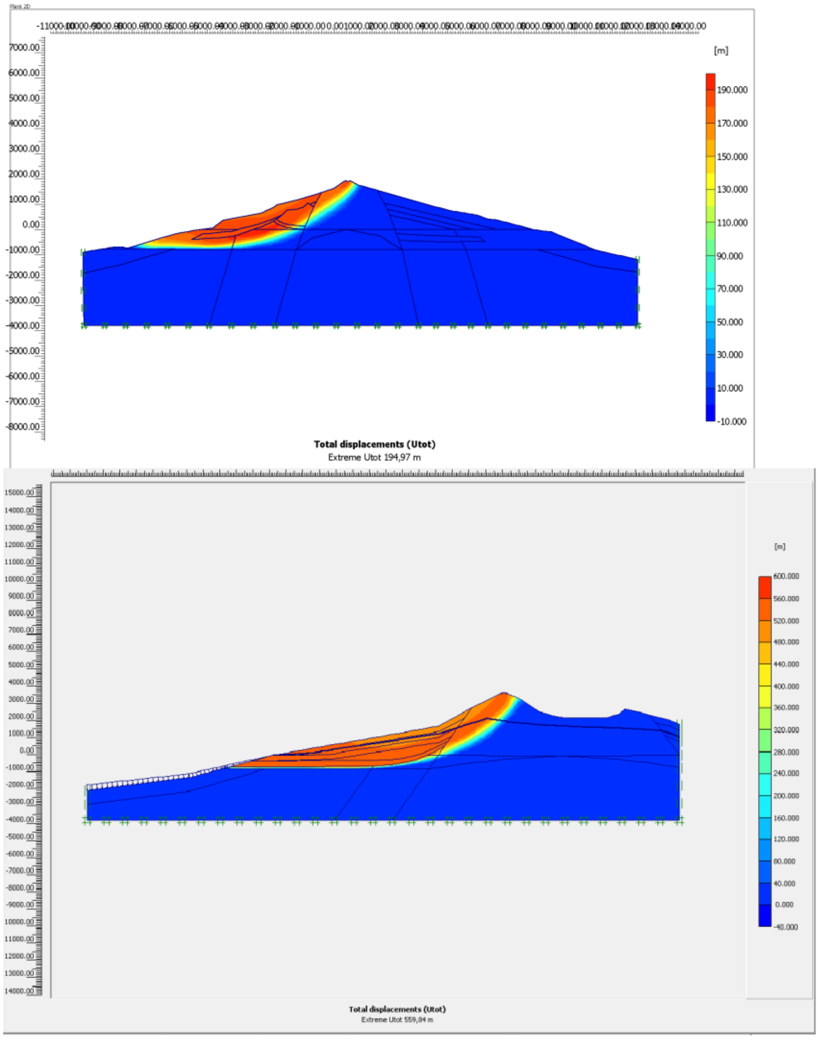

Figure 4.1. Graphic results obtained for 2 of the analyzed models, CV-2 in La Palma and El Teide in Tenerife, showing the deformation pattern at failure (displacements).

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