Simulation of a volcano in Plaxis

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Introduction

Modelling of slope stability is a common practice in Plaxis. Modelling of a volcanic edifice of 16 km wide and 2 km high however, required some pioneering in the familiar finite element package. For geological processes such as magma intrusion and water expansion, Plaxis offers no ready made features. Nevertheless this article will show that with creative use of the program one can accomplish more than might be expected on first sight.
The island of San Miguel de la Palma is the most north-western island of the Canary Islands archipelago, situated about 400 km from the coast of central Morocco.
The South-western part of the island, which is formed by the Cumbre Vieja volcano has been considered to be more or less unstable by various authors (Ancochea et all, 1994; Carracedo et al, 1999; Day et al, 1999). (Figure 1) Ward and Day (2001) even forecast that an effective collapse of the Island may cause a tsunami in the Altantic ocean.

This research emcompassed quantifying the likelyness that the supposed La Palma landslide will actually take place. The (boundary) conditions under which the West flank of the Cumbre Vieja volcano could start sliding have been investigated. Moreover the time lapse from the present day to the day such mass movement would occur was assessed.
The purpose of this article is to inform the reader about the specific problems encountered during the modelling of a volcano and the applied solutions. At the same time the results of the research objectives will be discussed briefly.

Figure 1 Satellite view of La Palma with indication of modelled area

The geometry of the mountain

In order to construct a full cross-section through the mountain, at least 16 km of modelling space was required. On the other hand, the drawing space is limited to 10 km. But with the origin in the centre, both positive and negative coordinates up to 10 km can be used. Because modelling was carried out in 2D, a least stable cross section through the edifice was chosen. Figure 2 shows the layout of the cross section. The asymmetry of the cross section stands out: A significant part of the Eastern flank has not been modelled. This is because the Eastern flank contains a relatively weak layer of sediments that were deposited there after a previous giant collapse of the island about 560 thousand years ago. This layer is called 'Post Collapse Sequence' or 'Post Collapse Sediment' (PCS) and is depicted in yellow in Figure 2. It is to be expected that this layer governs the failure mechanism. Earlier modelling in a fully symmetric cross section confirmed this prospect.

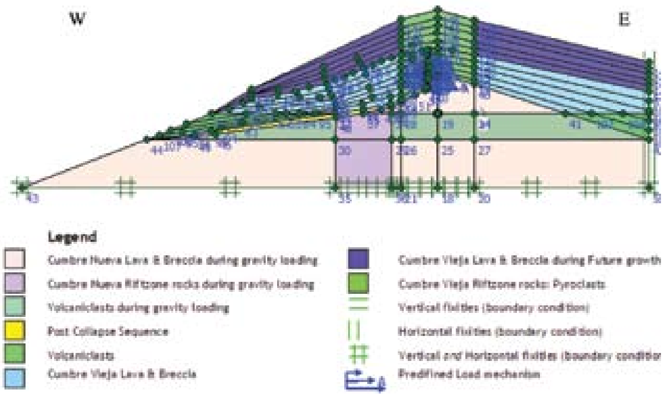

Figure 2 The layout of the model

Geotechnical properties of the rocks

Due to its volcanic character La Palma almost entirely consists of rocks. But the one major soil unit present at the island (the PCS, indicated in yellow in figure 2) indeed governs the stability situation. The rocks on the island are often characterized by a mixed character on scales too small for modelling. Examples are found on the volcano flanks in the geotechnical unit 'Cumbre Vieja Lava & Breccia' and in the riftzone rocks (figure 2). The parameters representing these zones have been chosen to be averaged values of the rocks present there. Modelling has been carried out with the use of two datasets. The first one representing an average or 'standard' state of rock mass properties, the second one representing a 'worst case' of rock mass properties. From these data appropriate parameters for the Mohr-Coulomb model were selected. Table 1 depicts a summary of the 'worst case' rock mass parameters.

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Table 1. Summary of worst case parameter data set

Parameter	Unit	Lava & Breccia	PCS	Pyroclasts	Dykes	Volcaniclasts (submarine)
d	MN/m^3	0.0177	0.016	0.012	0.025	0.0133
w	MN/m	0.0180	0.017	0.016	0.026	0.0136
n	-	0.25	0.35	0.25	0.25	0.25
E_{50}	MPa	-	125	1495	29867	-
	°	30	25	25	37	26
c	MPa	5.8	0.01	2.1	9	3.9
σ_{tm}	MPa	-0.072	-0.006	-0.016	-0.134	-0.039
E_m	MPa	7913	-	-	13335	4519

σ_{tm} and E_m are parameters according to the Hoek-Brown formulation
σ_{tm} = tensile strength
E_m = deformation modulus

Modelling of geological and volcanological processes

The program has been made fit to address volcano growth, varying ground water levels, extreme pore pressure or explosions and dike-shaped magma intrusions. The next paragraphs will briefly describe the way these processes and structures have been incorporated.

Volcano Growth

The historical growth of the Cumbre Vieja volcano has been simulated in stages. In each stage, about 100m of magmatic rocks are put on top of the edifice. The growth has been simulated this way, because the influence of the loading path on the final stress distribution in the edifice was not known. Thus the volcano has been slowly built up, up to the height that it currently has. From this point on the model was extended with possible future processes and future growth. The height of the water table is updated along with every stage of growth.

Pore pressures and explosions due to heating of pore water around intrusion in the riftzone

A volcanic dyke is a tabular intrusion of magma that cuts across the bedding of the country rock. An intruding dyke can heat up surrounding water which is trapped between vertical impermeable dykes. Subsequently the water may expand and when experiencing little counter pressure, cause explosions. Although it is plausible that some of the produced forces are deviated in horizontal direction, experience shows that great amounts of heated pore water escape in vertical direction through the riftzone. After all, the vertically zoned pyroclastic rocks in the riftzone will expose less resistance to pressure than the dykes and lavas that are governing the horizontal direction.

In reality pressurized pore water will move, escape vertically and not be bounded inside a specific area. When expanding and migrating water cannot dissipate and when counter pressure is small, explosions occur. Plaxis cannot simulate the migration of water. Instead the pressures are imposed on the model by means of insertion of manually defined pore pressures on top of the normal hydrostatic pore pressures. The increased pore pressures have been placed in a limited space in the subsurface. The material data sets in the pressurized areas have been temporarily replaced by material sets with a very low Elastic modulus. Thus pressures can be transmitted to surrounding rocks through occurring deformations. Hence, a worst case approach has been adapted (as if it were that the water is blocked in vertical direction e.g. by a sill). Two of these limited areas have been investigated; one simulating a heat source above sea level and another simulating a heat source below sea level. A range of these pressures have been modelled in Plaxis until failure of the model occurred.

Dyke intrusion

A strong dyke intrusion could fill a fissure from the sea bottom to about 100 m below the crest of the riftzone. In lateral sense, it is known that during an eruprion of the Cumbre Vieja volcano in 1949, a fissure of at least 800 m, but more likely 2000m existed (Day et al, 1999). When a dyke intrudes into the riftzone, two mechanisms contribute to a weakening of the volcanic edifice. Firstly the weight of the magma exerts a magmastatic pressure on its surroundings (figure 3). Secondly, the magma cannot resist shear stress and will therefore immediately be the weakest material unit in the model, thus introducing a potential zone of failure.

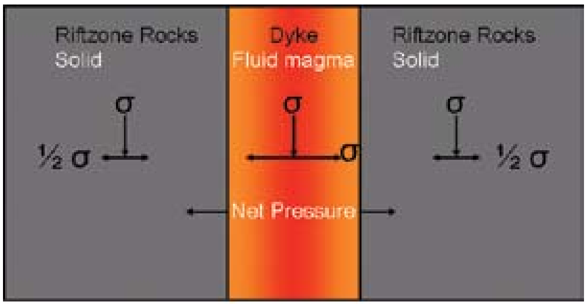

Figure 3 Illustration of the stress difference in a fluid and in a rock mass

In a Modelled representation of an intrusion the dyke would ideally be introduced as a "fluid cluster" instead of a soil cluster. This "fluid cluster" would contain the proper features to both simulate the equi-directional pressure forces of the magma fluid and the specific weight of the magma. However the only fluid available in the Plaxis software is water, so a real magma material cannot be introduced in the program. Therefore the area of the dyke has been assigned an infill of water only. At the same time, a horizontal prescribed load of 0.017 $MN/m^2/m$ has been imposed on the sides of the dyke in order to make up for the density difference between water and magma (γ_{magma} is approximately 0.027 MN/m^3.

Check: $P_{water} + _{magmastatic} = \gamma_{magma}$; 0.010 + 0.017 = 0.027 MPa). See figure 4.

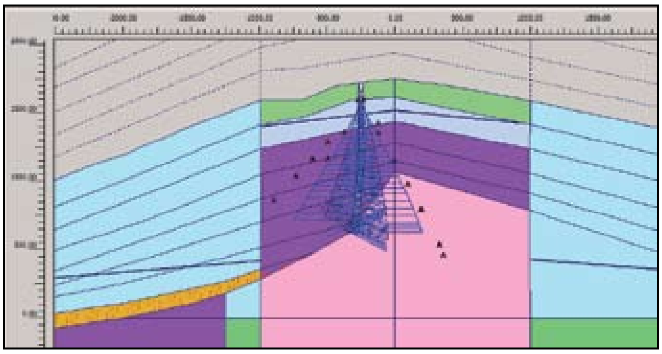

Figure 4. Layout of the prescribed load system that simulates a magmastatic dyke pressure

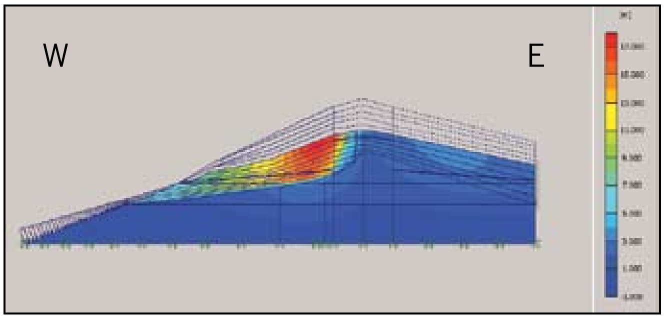

Figure 5. Total displacements due to historical growth only. The plane of weakness is formed by a sequence of Post Collapse Sediments.

Future volcano growth

Apart from eruption mechanisms that may destabilize the western flank of the volcano any further, a process of different nature would be a more steady and certain destabilizer. This mechanism is further accumulation of lavas at the top part of the volcano. Former landslides at La Palma have been estimated to occur at greater heights and slopes than the Cumbre Vieja has currently reached. heights of 2000-3000 m, with flanks consistently exceeding 20° and frequently even 30-35°. For comparison: The Cumbre Vieja volcano is now 1900 m high at its peak, but on average 1700 m. The dips of its slopes vary from 16° to 20°. The possible future growth has simply been added in the model by a continuation of lava streams on top of the topography of the current Cumbre Vieja volcano.

Results

In a situation where gravity only acts on the volcano body in its current configuration, the Factor of Safety is 1.70 under a standard parameter set and decreases to 1.44 under a worst case parameter set. Similar results were also obtained earlier using a conventional limit equilibrium method. Hence under its own weight the edifice is not prone to collapse. The failure mechanism along the weak sediments under the western volcano flank, however, is already clearly visible (figure 5). Even in this situation of relative stability, about 9 m of displacement has taken place along the volcano crest. A mayor fissure which formed in 1949 at the crest of the volcano, may be the result of such accomodative displacement. Formerly scientists have postulated that this 1949 fissure was an indication of instability. From the results of this work however, one may conclude differently. The presence of the fissures has been confirmed by the calculations, but they are more likely the result of deformation only than of a collapse situation. Future growth of the Cumbre Vieja is the most effective agent to trigger the potential landslide. On average, the Factor of Safety is decreased with 0.1 with every 200 m of growth. According to this model, due to growth only it would take in the order of magnitude of tens of thousands of years to trigger a massive flank collapse.

The pore water heating mechanism is an effective agent to disrupt the volcano. Nevertheless it does not cause the landslide as feared by many. Instead, as may be expected, this mechanism causes a collapse of the top of the volcano that is blown upward, in the same way as often observed during volcanic eruptions that involve water. Figure 6 shows how Mohr-Coulomb and Tensions cut-off points are concentrated in the riftzone. Under the extreme pressures that have been modelled here, the flank also develops an almost interconnected chain of Mohr-Coulomb points. Yet, the preferential path of rupture develops in the central zone.

The magmastatic pressure of an intruding dyke can have a significant influence on the Factor of Safety (FS) of the potential landslide body, with a reduction of the FS up to 0.4.

Conclusion on modelling and research goals

Plaxis has proven to be suitable to simulate a volcano of significant size and complex rock structure. In particular, two volcanic processes have been simulated: Thermal pore pressure development due to heat radiation of an intruding magma body and magmastatic pressure of a dyke. The former can be simulated by a combination of the manual pore pressure feature working on a fully elastic infill material. The density of the latter has been simulated by a prescribed load acting on a body of water.

An eruption during the next several human generations is not expected to cause a landslide hazard at the Cumbre Vieja volcano. The eruption forces cannot generate enough momentum to trigger failure in a 3D situation. However, after further volcano growth in the far future, when significant extra gravity forces act on the edifice, the eruption forces may be able to trigger a landslide. This will, however, take place in a time span of not less than 10.000 years.

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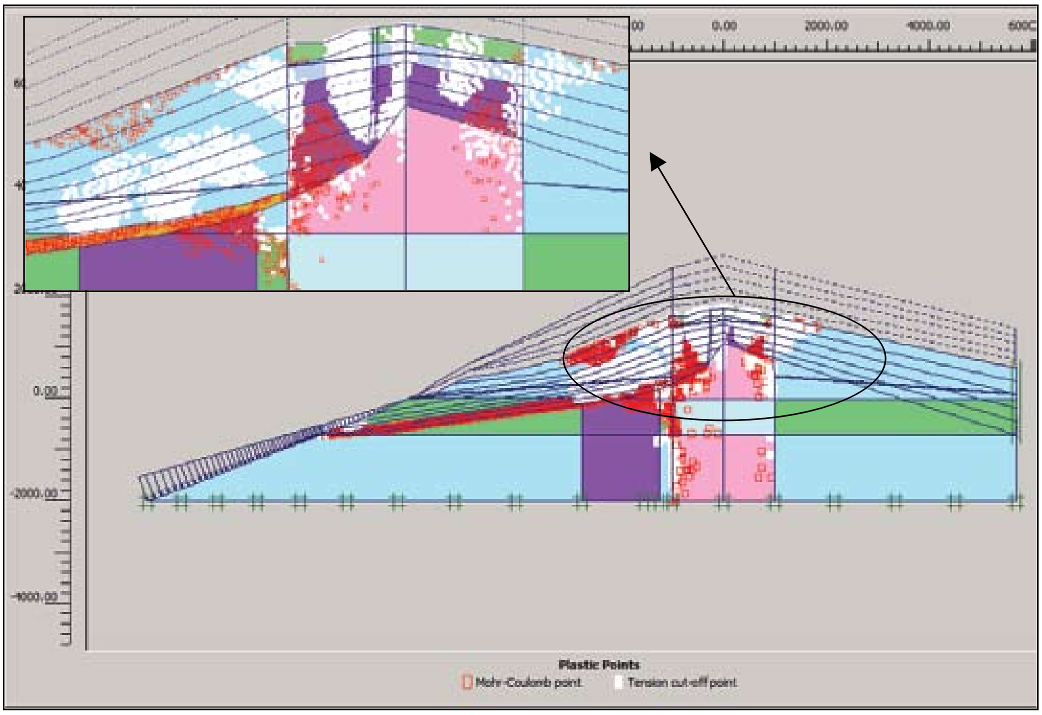

Figure 6 Failure points in the riftzone as a result of thermal pore pressures. The thermal pore pressures form due to heat radiation of deep seated magma intrusions.

References

Ancochea E et all. (1994) Constructive and destructive episodes in the building of a young Oceanic Island, La Palma, Canary Islands, and genesis of the Caldera de Taburiente, Journal of Volcanology and Geothermal Research, 60, 243-262

Carracedo JC et all. (1999) Later stages of volcanic evolution of La Palma, Canary Islands: Rift evolution, giant landslides, and the genesis of the Caldera de Taburiente, Geological Society of America Bulletin, 111 (No. 5), 755-768

Day SJ et all. (1999) Recent structural evolution of the Cumbre Vieja volcano, La Palma, Canary Islands: volcanic rift zone reconfiguration as a precursor to volcano flank instability?, Journal of volcanology and geothermal research, 94 (issues 1-4), 135-167

Masson DG et al (2002) Slope failures on the flanks of the western Canary Islands, Earth-Scx. Reviews, 57, 1-35

Ward SN, Day S (2001) Cumbre Vieja Volcano -- Potential collapse and tsunami at La Palma, Canary Islands, Geophysical Research Letters, 28 (17), 3397-3400

White JDL; Schmincke HU (1999) Phreatomagmatic eruptive and depositional processes during the 1949 eruption on La Palma (Canary Islands), Journal of volcanology and geothermal research, 94, 283-304