

Preliminary evaluation of volcanic flank stability using finite difference modeling: Citlaltépetl volcano, Mexico

Evaluación preliminar de estabilidad de flancos volcánicos con modelación en diferencia finita: volcán Citlaltépetl, México

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Abstract

Catastrophic volcanic collapses (avalanches) behave mechanically as large-scale landslides. We present a geomechanical study evaluating potential failures of volcanic edifices, by creating two-dimensional numerical models for Citlaltépetl volcano, Mexico. The numerical models were constrained by using the distribution and strength of the involved materials, and the inferred preferential dyke strikes. Through finite difference analysis we model two different geological aspects that, according to geological studies at Citlaltépetl, could trigger the most recent collapse: water percolation from snowmelt and strength reduction by hydrothermal alteration.

Geological reconstructions and characteristics of previous constructive volcanic stages were used to assess which of the two input parameters dominates the failure process. We modeled the volcano stability while the changing rock mass strength and the extension of the hydrothermally altered zone, in presence and absence of a pore water pressure distribution. We examined the resulting strain conditions and concluded that, at Citlaltépetl, the hydrothermal alteration by itself is the dominant process that defines the unstable zones. The presence of water reduces the general stability for the same dry critical zones.

Resumen

Los colapsos volcánicos (avalanchas) se comportan mecánicamente como deslizamientos gigantes. Aquí presentamos un estudio geomecánico con modelos numéricos en dos dimensiones, en el volcán Citlaltépetl, México, que evalúa fallas potenciales en edificios volcánicos. Los modelos numéricos se basaron en la distribución y resistencia de los materiales involucrados, los principales conjuntos de discontinuidades (dirección preferenciales inferidas para los diques). A través de un análisis de diferencia finita modelamos dos diferentes aspectos que, de acuerdo a los estudios geológicos en Citlaltépetl, originaron el colapso: percolación de nieve fundida y la reducción de la resistencia de los materiales debido a la alteración hidrotermal.

Reconstrucciones geológicas y características de previos estadios volcánicos fueron usados en determinar cuál de los dos parámetros mencionados domina el modo de falla. Modelamos la estabilidad volcánica modificando la resistencia de los materiales y extensión de la zona alterada hidrotermalmente, en presencia o ausencia de presión de poro. Examinando la deformación resultante, concluimos que en Citlaltépetl la alteración hidrotermal por sí sola es el proceso dominante que define las zonas de inestabilidad. La presencia de agua no es determinante pues solo reduce ligeramente la estabilidad de las mismas zonas críticas en estado seco

1 VOLCANIC AVALANCHES

Since the occurrence of the volcanic avalanche of Mount St. Helens in 1980, the structural instability of volcanic edifices became be recognised as a common phenomenon in the evolution of volcanoes world wide. The volume of rock mass removed by these volcanic avalanches commonly is larger than 0.1 km³. Velocities

exceed 100 m/s, and the momentum is large enough to trespass topographic barriers, human and infrastructure loses can be catastrophic, McGuire, et al. (1996). Few volcano collapses have occurred in historical times (e.g. Mount St. Helens, Bandai and Shiveluch), the size and extension of identified deposits at different volcanoes show how catastrophic a volcanic collapse could be to present day surrounding urban areas. To understand and quantify the

mechanisms that trigger volcanic collapse, this paper presents a geomechanical evaluation of present day edifice at Citlaltépetl (Pico de Orizaba) volcano, Mexico.

Geomechanical approaches are a practical tool for two reasons. Firstly, the volcanic collapse potential can be identified and better understood at any volcanic edifice by identifying the type of materials and volcano structure. Secondly, these types of studies would permit, in a relatively inexpensive way, comparison of the present day conditions of the edifice with those that triggered previous collapses. The results can improve overall volcanic hazard evaluations and/or point at the necessity of different or more detailed monitoring when it does not exist.

1.1 Citlaltépetl avalanches

Citlaltépetl, or Pico de Orizaba, is located at the eastern end of the Transversal Mexican Volcanic Belt (Figure 1). It has been historically active and represents a geological hazard for the surrounding population of Puebla and Veracruz. The evolution of this volcano can be summarised by three constructional stages, Carrasco-Núñez (2000): 1) the construction of an initial stratovolcano (Torrecillas stage) and subsequent collapse approximately 210 Ka ago; 2) the extrusion of peripheral silicic domes, construction of a superimposed cone (Espolón de Oro cone) and a second collapse occurring 20 Ka ago; 3) the last stage represents the construction of the present cone (Citlaltépetl cone).

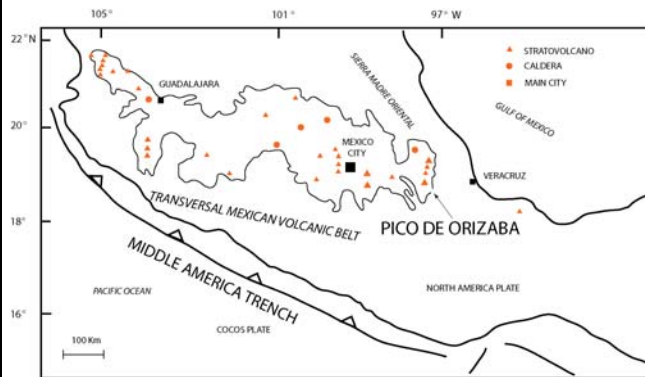


Figure 1. Location of Pico de Orizaba at the Transversal Mexican Volcanic Belt

The second and most recent collapse, Espolón de Oro, is well described. The deposits, known as Tetelzingo avalanche-lahar, are characterised by clasts with a high degree of hydrothermal alteration supported by a clayey matrix that suggests high water contents during deposition. Carrasco-Núñez et.al. (1993) suggested that the high water content of the deposit could be due to

the melting of a large glacier during late Pleistocene. They also reported no volcanic activity related to the Espolón de Oro collapse. This suggests that only two factors generated edifice instability: water and hydrothermal alteration.

The present cone has many similarities to the Espolón de Oro stage prior to its collapse. For instance, the same type of hydrothermal alteration identified at Tetelzingo deposits, has been recognised at Citlaltépetl stage, Hubbard (2001), and fumarolic activity exists at the summit. The research by Carrasco-Núñez et.al. and Hubbard raises interesting questions: Can Citlaltépetl cone collapse in the same way as Espolón de Oro stage, that is, solely under the influence of hydrothermal alteration, water, and gravity? How stable is the present cone with the existing hydrothermal alteration? What if alteration was more extensive at the interior of the cone? Is it necessary to add the water saturation effects (by snow-melt percolation) for triggering the collapse? Through a sensitivity analysis of distributions of water-saturated and strength-reduced zones, we analysed the effects of these two geological processes in the stability of Citlaltépetl cone.

2 GEOTECHNICAL INVESTIGATIONS

Slope stability of the cone is dependent on the strength of volcanic materials, topography and the influence of forces at the interior of the volcano (e.g. pressure of fluids and seismic loads). For a geomechanical edifice stability assessment, the edifice rock mass strength and its spatial distribution are key for defining the depth and volume of the failing mass, Reid, et al.(2000), Voight (2000). This approach involved sample collection, rock strength testing, and numerical modelling. For the study at Pico de Orizaba, the edifice strength was obtained with a two-part field mapping program following procedures detailed in Watters et al. (2000). The first part consisted of obtaining rock structure information bedding and joint orientations, fracture spacing, and location of major shear or fault zones. The second part included the collection of representative rocks exposed on the Citlaltépetl cone.

2.1 Intact rock and rock mass strength evaluations

The geotechnical study concentrated on obtaining intact rock properties (UCS, m_i , s) samples with different degrees of hydrothermal alteration exposed on the Citlaltépetl cone. The

alteration classification is based on visual observation of alteration, as described in Watters and Delahaut (1995), and varies from a grade of zero (no alteration) to a grade of four (complete replacement of phenocrysts and matrix). In general hydrothermal alteration, when not silicic, produces lower density rocks with a corresponding reduction of strength (Table 1). In Citlaltépetl the unconfining compressive strengths (UCS) ranged from 50 MPa, altered andesite grade 1, to 1.0 MPa on altered andesites grade 4 and pyroclastic deposits. Triaxial tests on altered andesite permitted to better evaluate the confined strength of the intact rock and calculation of the Hoek and Brown parameters, m_i and s .

We performed calculations for cohesion, friction, and Young modulus (c', ϕ', E_m) of the rock mass through the procedures shown in Hoek(1990), Hoek and Brown (1998). In these calculations, we considered a blocky disturbed fair-poor (GSI=35) rock mass as characteristic of the worst conditions at the volcanic cone and the obtained range of UCS values for intact rock with different degrees of alteration (Table 1).

Table 1. Experimental intact rock properties and calculated rock mass strength values

Sample	s1	s2	s3	s4	s5
Intact Rock Properties					
UCS (MPa)	50	40	30	10	1
ρ (kg/m ³)	2.7	2.6	2.55	2.4	2.3
Alteration degree	1	1	3	4	4
Rock Mass Properties					
GSI	35	35	35	35	35
c' (MPa)	3.57	3.24	2.87	1.75	0.58
ϕ' (°)	19.5	18.2	16.6	11.4	4.7
E_m (MPa)	2982	2667	2309	1133	421

3 NUMERICAL MODEL

Volcanic edifice collapse is a phenomenon that can be well characterised in two dimensions as a result of the size of the landslide and preferential directions of collapse of the volcanic edifice. Many volcanoes collapse along preferential directions. The preferential strike is perpendicular

to the elongation of the cone, the strike of dykes and the aligned volcanic vents, which are parallel to a maximum horizontal compressive stress direction, σ_{Hmax} Nakamura (1977); Siebert (1984), Voight and Elsworth (1997). At Citlaltépetl volcano the σ_{Hmax} strikes at a NE 40°SW direction, related to volcanic vents and fault, see Figure 2.

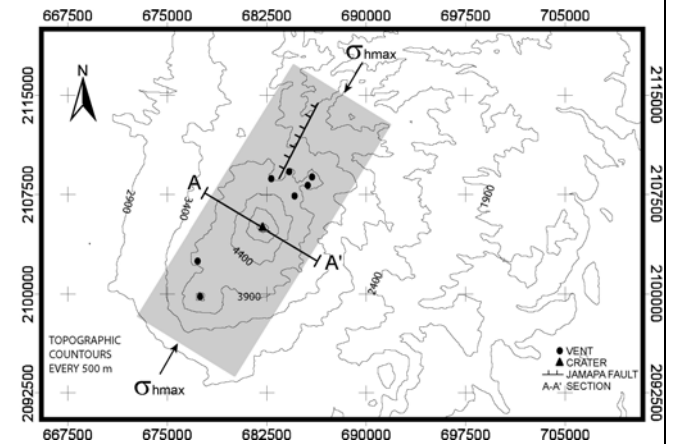


Figure 2. Pico de Orizaba topographic map showing volcanic vent lineation, fault and cross section A-A' used for the construction of the model

The construction of the 2-D model is in a plane perpendicular to σ_{Hmax} , SE60°NW. The value of σ_{Hmax} is defined by equation (1) acting out of the A-A' (xy) plane of the model.

$$\sigma_{Hmax} = k\sigma_z = k\gamma h \quad (1)$$

The lateral earth coefficient is $k=0.5$. The model is 3500 m high by 6500 m long, with elements of 100x100m (Figure 3). Two types of isotropic and linearly elastic materials constitute the model: one representing the hydrothermal altered material and the second representing almost fresh microcrystalline lavas. The values of rock mass strength used for each materials are those obtained respectively for the cases of lower and highest hydrothermal alteration, column s1 and column s5 of Table 1.

The hydrothermally altered zone extension is defined for two cases, see Figure 3. The first region, shallower and smaller, is the present day distribution. The second, and more extended, is the one representing the extreme case reported for Espolón de Oro stage, Hubbard (2001), covering about 90% of the cone. Both cases were modelled in presence and absence of the static pore-water pressure distribution shown in Figure 4.

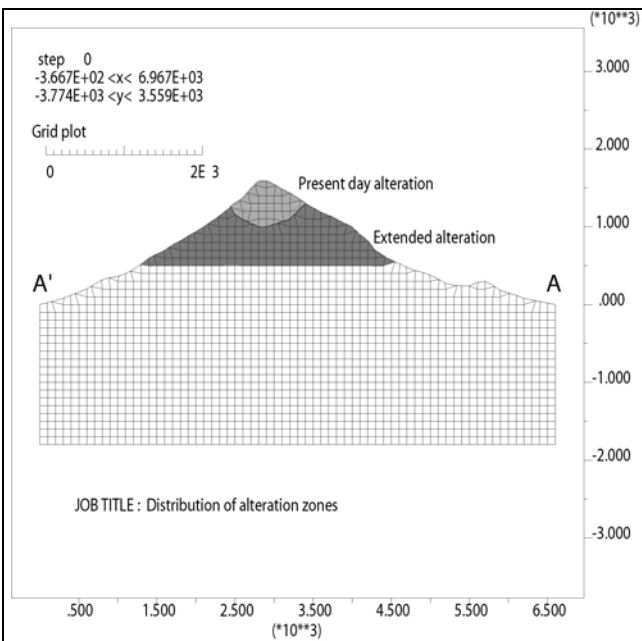


Figure 3. Finite difference grid and zones defining the two extensions of hydrothermal distribution

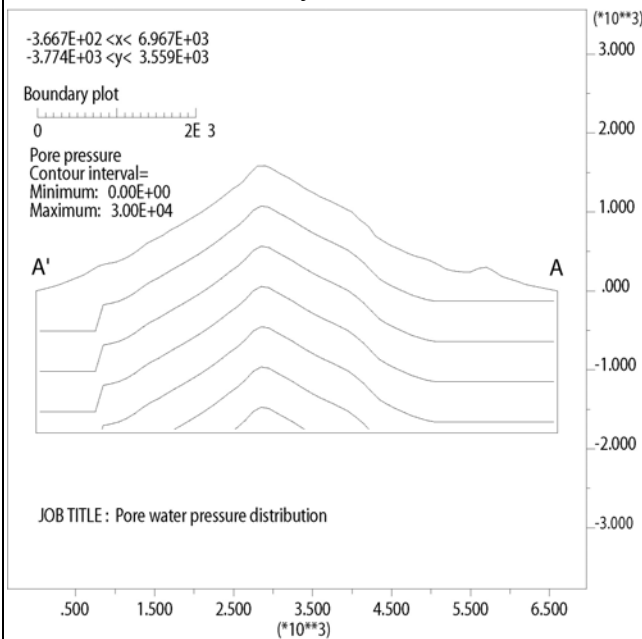


Figure 4. Pore water pressure distribution due to a static water table

4 RESULTS

We modelled hydrothermally-altered zones with two different distributions: one shallow and one extended. In both cases failure zones are delimited by plotting velocity contours and displacement vectors. The failure zones have the shape of the alteration zones. The size and failure mode are different for each case.

4.1 Hydrothermal alteration

The first part of the analysis that we performed was based on the distribution of the hydrothermal

altered zones. The shallow altered zone, at the top of the cone, shown in Figure 5a), has a circular failure surface shallower at the NE ("A" end) of the section. The absolute maximum horizontal velocity value was 12.5 m/s.

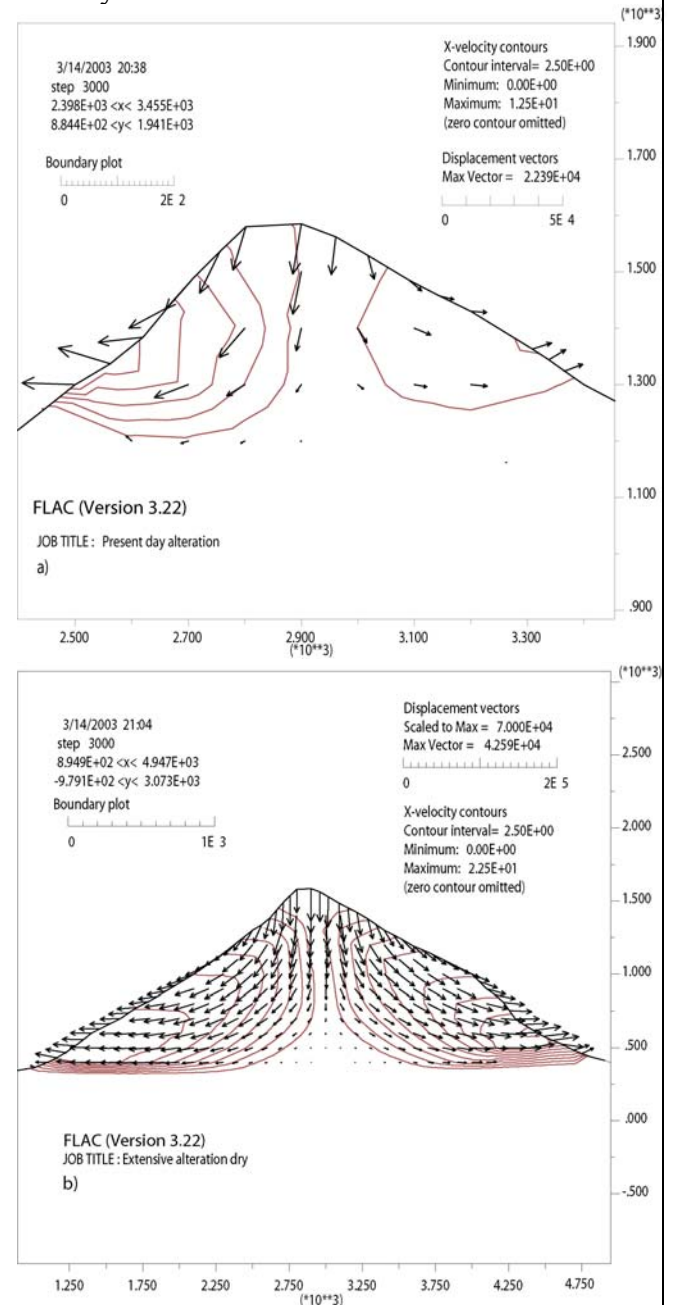


Figure 5. Failure zones for: a) Shallow dry alteration; b) Extended dry alteration

The hypothetical extended altered zone, Figure 5b), fails as a wedge. The basal plane is approximately 1500 m wide and the head plane is 1250 m below the summit. Absolute horizontal maximum velocity contour at the surface is 22.5 m/s.

4.2 Saturated zone and hydrothermal alteration

In the second part of the analysis we introduced a static water table at the surface of the central part of the volcanic cone, similar the one generated by snowmelt percolation. The resulting geometry of the failing surface did not change. The velocity magnitudes, though, did change. For the shallower case maximum horizontal velocity is 40% larger (17.5 m/s), see Figure 6a). For the extended zone, maximum horizontal velocity is almost 10% larger (25 m/s), see Figure 6b).

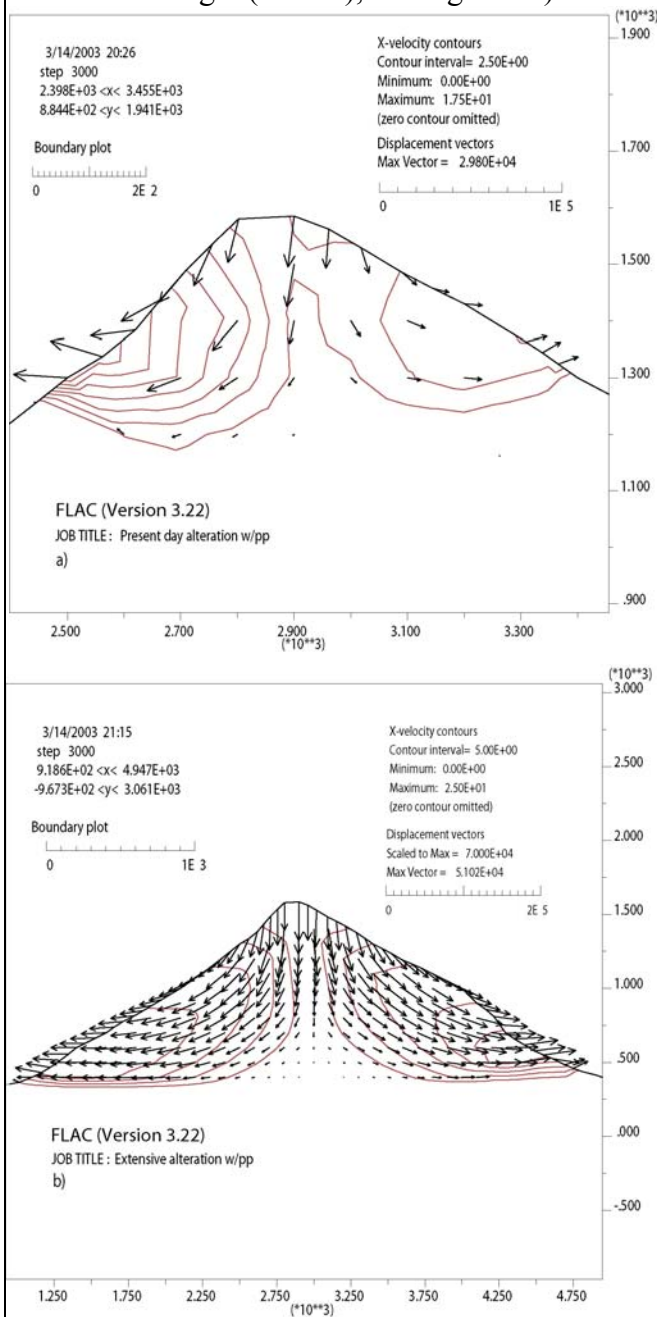


Figure 6. Failure surface with introduction of pore water for: a) Shallow alteration; b) Extended alteration

5 CONCLUSIONS

Hydrothermal alteration greatly affects the stability of Citlaltépetl volcano. The investigation suggests that hydrothermal alteration plays an important role in reducing the intact rock strength and subsequently the rock mass strength.

- 1) The present day distribution of hydrothermal alteration can trigger the collapse of the volcanic cone. Since hydrothermal alteration is present and acting, it can reduce enough the strength of the volcanic edifice for failure.
- 2) The inclusion of pore fluid pressure into the model did not change the geometry of failure, but did increase the resultant initial velocity of the avalanche
- 3) The Espolón de Oro stage might have not need of elevated pore-fluid pressure to collapse; hydrothermal alteration was sufficient.

The results of this work can assist for avalanche hazard evaluations and subsequent modelling. The initial velocities of the particles can be introduced in run-out mass movement evaluations. The failure surface geometry can be used for discrete element modelling in which incorporation of discontinuities and generation of blocks can better characterize the resulting moving mass.

6 ACKNOWLEDGEMENTS

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