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GEOTECHNICAL PROPERTIES AND SEISMIC SLOPE STABILITY OF VOLCANIC SOILS

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ABSTRACT
Volcanic soils are widely encountered around the world and they underlay several cities, making an understanding of their geotechnical properties of great importance, particularly since the same geological processes responsible for their deposition also generate earthquakes. Landslides in volcanic soils, often of catastrophic proportions, are frequently triggered both by seismic ground shaking and by heavy rainfall. Despite the wide occurrence of these soils and the hazards associated with their tendency to become highly unstable during earthquakes and heavy precipitation, there are relatively few published studies on their geotechnical characterisation, much less attempts to identify common properties and formulate a generic model for their behaviour. Studies of volcanic soils in a few locations around the world are briefly reviewed, prior to the presentation of some results of testing programmes on volcanic soil samples from Central America and exploratory slope stability analyses.

Keywords: Volcanic soils; Seismic slope stability; Partial saturation; Cementation

INTRODUCTION

Volcanic soils are encountered in many countries around the world and dominate the surface geology in several areas of high population density. By virtue of the same tectonic processes that give rise to the volcanism responsible for the formation of these soils, the deposits tend to occur in areas of high seismic hazard. Furthermore, many of the areas where volcanic soils predominate are within tropical regions with high annual rainfalls and frequently intense precipitation. Volcanic soils are often able to support near-vertical slopes, advantage of which is often taken for road cuts and to create plots for housing. These steep slopes, often totally denuded of vegetation, are susceptible to sudden and catastrophic failure. The isthmus of Central America is one region where young volcanic soils are abundant and where rainfall- and earthquake-induced landslides constitute significant natural hazards. Recent examples include the landslides triggered by Hurricane Mitch in 1998 [1] and by the earthquakes of 13 January and 13 February 2001 in El Salvador [2, 3].

Mitigation of landslide hazard in regions such as Central America first requires a thorough understanding of the behaviour of these volcanic soils, under static and dynamic conditions, and when subjected to infiltration due to rainfall. Researchers from around the world have exchanged results and insights from work on different types of soils at international conferences dedicated to specific groups of deposits, such as partially saturated soils, residual soils and sensitive clays. Despite the importance of volcanic soils, to the knowledge of the authors there has never been an international conference, or even a special session at a conference, dedicated to the study of these deposits. This particularly study is mainly focused on a specific volcanic soil from Central America but it also forms part of a broader project to develop an engineering characterisation of volcanic soils for general application.

VOLCANIC SOILS

Volcanic soils are one of the most widely distributed group of soils in the world, occurring in such areas as Central and South America, the Pacific and Caribbean islands, Africa and Indonesia. Most of the volcanic soils described in the literature are composed of fragments produced in volcanic vents, fragments formed from the break-up of moving lava or fragments of dust, ash or pumice which fall around the vent of the volcano or are carried to a distance by wind. They also include deposits that weather and erode from solidified lava flows or consolidated pyroclastic debris [4, 5]. What can be observed in general is that in relation to the plasticity, particle size and mineral composition, volcanic soils have a relatively high shear strength and permeability, while their compressibility is quite low under relatively low stress increments [6].

O'Rourke and Crespo [7] performed a study on the geotechnical properties of a volcanoclastic formation that is found in the Andes of Ecuador and Colombia, known as Cangahua. It covers an area of about 20,000 km^2, having a thickness of 100-120m. Cangahua can be characterised as a silty sand, as it is composed of about 60-65% sand, 30-35% silt and the remaining fraction of clay. The dry unit weight of the material was found to range between 11 and 14kN/m^3, the moisture content between 15 and 20% and the porosity varied from 43 to 56%. The high porosity is typical of a volcanic ash and loess-like deposits.

At low stresses the material exhibits a brittle response and becomes continuously more ductile as the confining pressures increase. The angle of shearing resistance was found to be around 39^o but the cohesive intercept reduces from peak to residual by 90kPa. At low saturations the peak strength is relatively constant. As the degree of saturation becomes larger there is a clear drop in strength and the maximum stresses seem to migrate from the peak strength envelope to the residual strength envelope.

This loss of shear strength after saturation might explain why slope failures occur in Cangahua during or after periods of intense rainfall. Also other material properties like the tensile strength or the uniaxial compressive strength reduce significantly as the moisture content increases [7]. All these features imply that rainfall and water infiltration should be taken into consideration when stability evaluations for slopes in Cangahua are performed.

Gonzalez de Vallejo *et al.* [6] presented a study of a volcanic soil located in the north-eastern part of Tenerife, Spain. The soil shows the general tendency to form aggregations of clay particles, usually showing different fabrics and levels of cementation. The void ratios in the natural state lie between 0.9 and 1.2. The undrained shear strength of these soils was found to be highly dependent on the clay minerals and structure, with values ranging between 60 and 125 kPa. The material showed a predominantly ductile response, but large drops in strength were observed upon remoulding.

Yamanouchi and Murata [8] argue that among the conceivable factors that contribute to the strength of a volcanic soil in Japan is the cementation or welding as well as the interlocking between particles The so-called "Shirasu" is a structurally unstable soil that originates from volcanic eruptions in the Pleistocene age and is widely distributed in the southern Kyushu region of Japan. The moisture content of this soil was found to be in the range between 2% and 25%, with dry densities going from about 10 kN/m^3 to 15 kN/m^3.

Yamanouchi and Murata [8] carried out a series of uniaxial compression, triaxial and Brazilian splitting tests on undisturbed Shirasu specimens in order to investigate the behaviour of slopes composed of that soil during earthquakes or heavy rains. It was found that the tensile strength showed a rapid increase with density from about 0.01 kPa at γ_d=13 kN/m^3 to about 0.2 kPa at γ_d=15 kN/m^3. The compressive strength showed the same trend, increasing from about 0.1 kPa to 9 kPa for the same density range. At densities lower than these ones the strength did not show significant changes.

Belloni and Morris [9] performed a study in order to investigate how the behaviour of volcanic debris soils affects the stability of the slopes on the north east side of Ecuador in South America. The area affected by the landslides is situated in the transition zone between the Andes (Cordillera Real) and the Amazon Basin. The soils in the area are the partially weathered products of various volcanic eruptions and comprise a series of clays, pyroclasts, quartz sands, lahars and agglomerates with cinders and lapillites. The last two represent the final phases of the explosive activity of the volcanoes and have a high capacity for alteration [9]. The thickness of the deposits varies from 2m to more than 7m having an average of 3.5m. Some index properties of the soil are presented in Table 1. This material seems to be composed of about 55% silt, 35% clay and 10% of coarser material, so it has been described as a clayey silt.

TABLE 1
INDEX PROPERTIES FOR A VOLCANIC SOIL FROM ECUADOR [9]

	Maximum	Minimum	Mean
Moisture content (%)	215	58	122
Specific gravity	2.79	2.32	2.49
Bulk density (kN/m^3)	17.4	11.6	13.8
Dry density (kN/m^3)	9.1	3.7	6.9
Liquid limit (%)	293	34	111
Plastic limit (%)	165	25	65
Plasticity index	139	7	46

In terms of structure the material can be described as a granular agglomerate rather than a true clayey soil. Some researchers, including Wesley [10], De & Furdas [11] and Belloni *et al.* [12], have argued that the strength of the soil originated in a structure comprising an open skeleton of rock-forming minerals surrounded by clay particles and a cementing agent in the form of a viscous gel. These viscous gels have been recognised by several researchers as an important cementation or bonding agent between the soils particles, which contribute significantly to the shear strength of the material [13, 14]. Furthermore, an additional component to the shear strength is offered by the suctions, which are generally high in residual soils. However, in the case of this volcanic debris soil the moisture content was determined to be significantly high and hence the negative pore water pressures must be relatively small. In any case, the combination of suction and inter-particle bonding might explain the existence of steep slopes formed from this material.

Belloni and Morris [9] concluded that the areas under study failed after a prolonged period of heavy rainfall followed by earthquake loading. Neither the saturation of the slopes due to rain nor earthquake shaking alone would have caused extensive damage, but it was the combination of both that resulted in widespread landsliding.

It has been observed that volcanic deposits are characterised as having a meta-stable, open structure and relatively low moisture contents, which lead to negative pore water pressures within the soils. Additionally, rather weak cementation seems to be present in most volcanic deposits reviewed herein. Most authors agree that these two factors play an important role in the stability of slopes formed by these soils.

TIERRA BLANCA

Tierra Blanca is a dalacitic pumice ash composed of acidic pyroclastic and epiclastic deposits, which covers most of the upper part of the area of San Salvador [15]. These young, poorly consolidated deposits originated from multiple volcanic eruptions (as recent as 260 AD) that can reach thicknesses of up to 50 m. Due to its geological origin and the local climatic conditions, the *Tierra Blanca* presents variable degrees of cementation and negative pore water pressures, which seem to explain the presence of nearly vertical slopes in the city of San Salvador.

Based on several studies (e.g. [16, 17, 18]) *Tierra Blanca* can be classified as a sandy silt or silty sand, with moisture contents that vary from 7.5% to 30% and degrees of saturation of the order of 23%, that can increase to around 80% during the rainy season. The specific gravity, Gs, usually lies between 2.25 and 2.5, with bulk unit weights, γ, ranging from 13 to 15 kN/m^3 and void ratios, e, typically in the range between 0.8 – 1.14, corresponding to average porosities of 51 %.

The negative pore water pressures present within the soil, as measured with the filter paper technique [19] and the Imperial College suction probe [20], range from 300 kPa to 500 kPa. It is important to note that these suctions were measured in high-quality block samples with moisture contents between 7.5 and 9.5%.

Shear strength parameters of the soil have been determined from direct shear and UU triaxial compression tests [17, 18, 21]. In the case of undisturbed samples at low degrees of saturation, the soil has been found to have a cohesion c=25-30kPa and an angle of shearing resistance ϕ= 35-40^o. It should be noted that the soil is extremely heterogeneous and its physical and mechanical properties vary widely from location to location and with moisture content.

The shear strength of *Tierra Blanca* is particularly influenced by the negative pore water pressures and the presence of weak cementation. The favourable effects of these two parameters are clearly demonstrated in Figures 1 and 2 which show the failure envelopes obtained from direct shear tests on undisturbed and reconstituted samples, at natural moisture content and saturated. When the undisturbed samples become saturated the angle of shearing resistance reduces from 39^o to about 34^o, and the cohesion of 30 kPa in the undisturbed, unsaturated sample, is completely lost.

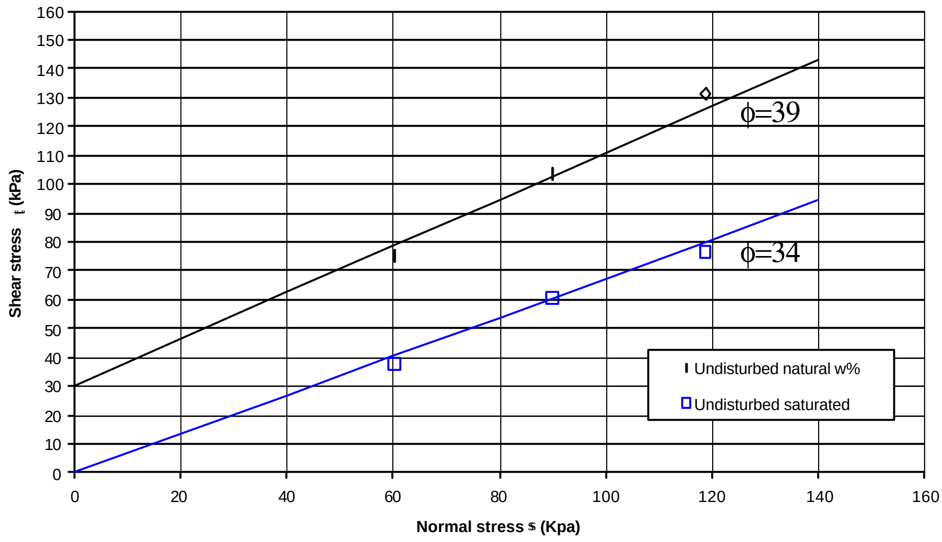

Figure 1. Failure envelopes obtained from shear box tests on undisturbed samples of Tierra Blanca at natural moisture content and after saturation [18]

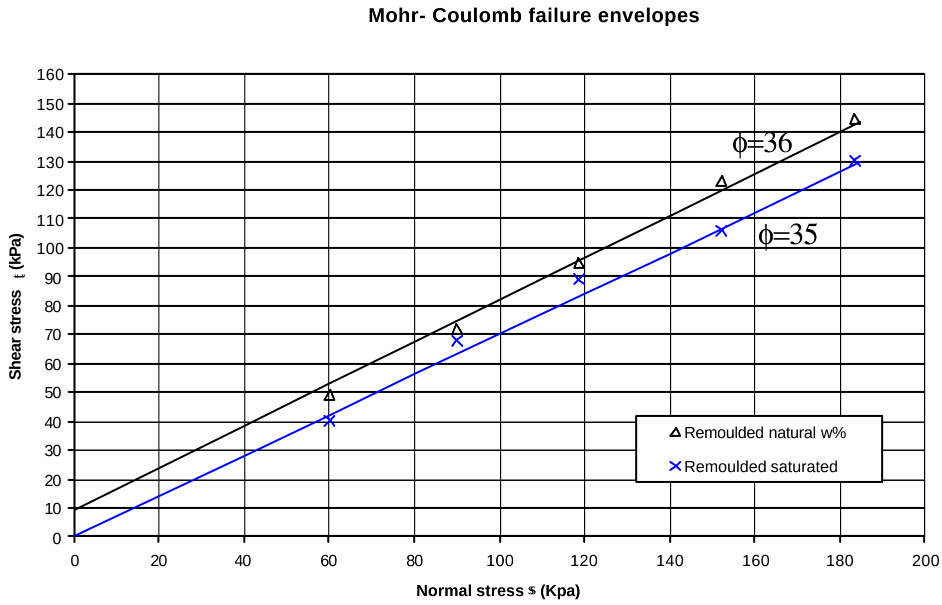

Figure 2. Failure envelopes obtained from shear box tests on remoulded samples of Tierra Blanca at natural moisture content and after saturation [18]

The fact that the cohesion is lost upon wetting is a strong indication not only of the loss of suction but also of the weak nature of the cementation present in the *Tierra Blanca*.

Comparison of the failure envelopes from undisturbed reconstituted and samples (Figures 1 and 2) at the same natural moisture content and density as the natural specimens so as to obtain similar suctions, show the effects that cementation has on the strength of *Tierra Blanca* [17]. It can be observed that for the reconstituted soil the failure envelope lies considerably below that of the undisturbed sample, having an angle of shearing resistance 3^{o} lower than the unsaturated specimen and a significantly lower cohesion of only 9 kPa. As the process of remoulding has rid the soil of the cementation, negative pore water pressures are solely responsible for the small cohesive intercept present on the failure envelope. This implies that the loss of cementation due to the remoulding has reduced the angle of shearing resistance but has not completely removed the cohesion intercept.

These findings have very significant practical implications since it has been shown that the *Tierra Blanca*, in agreement with other volcanic soils, possesses a shear strength that is very prone to drastic reductions when subjected to remoulding and/or wetting. This creates a great potential for the soil to fail or collapse under the effect of disturbances such as those generated by seismic activity or heavy rainfall [17, 22, 23].

SEISMIC SLOPE STABILITY

As with other cemented soils in different parts of the world, Tierra Blanca is able to stand in deep, near-vertical slopes, as often exist in ravines incised due to erosion during heavy rainfall. Advantage is taken of this to produce very steep road cuts [24]; the high population density in El Salvador results in settlements adjacent to these steep, unprotected slopes, which frequently become unstable during heavy rains and earthquakes. The soil falls and slumps that result are generally of rather small volume, with the scarp extending only a few metres, at most, from the free face, but they can nonetheless cause serious damage [25].

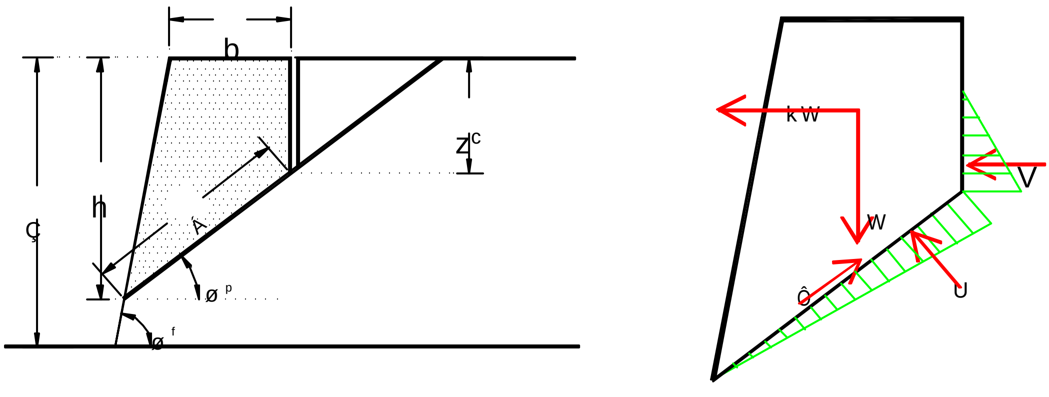

Figure 3. (a) Slope failure model used for analysis, and (b) forces considered in the analysis.

In order to investigate the seismic stability of such slopes, simple stability calculations were performed for typical slopes with an inclination of 80°, as shown in Figure 3a. It is assumed that for failure to occur a tension crack must first be formed in the slope to a depth z_c. Slope heights of 10 m and 20 m were considered, assuming the following dimensions: *h*=0.8H and *b*=0.2H, based on field observations of slope failures triggered by earthquakes in El Salvador in 1982, 1986 and 2001. The analysis is similar to that performed by Cecconi and Viggiani

[26] for steep slopes on pyroclastic deposits southeast of Rome, except that the effect of earthquake loading is included, represented as a horizontal force kW (Figure 3b), and instead of the static factor safety, the critical acceleration was calculated [27]. The vertical component of the ground motion is not considered. Since the soil is known to be partially saturated, and since the interest here is in landslides triggered by earthquakes rather than rainfall, it is assumed that the soil is dry, hence U and V are zero. The matrix suction in the soil is assumed to contribute to the apparent cohesion and furthermore to be unaffected by the ground vibration.

Figure 4 shows the results for a 10 m high slope with two depths of tension crack (2.8 m and 5.6 m); the strength parameters of the soil are c=30 kPa and angles of shearing resistance ranging from 20° to 45°.

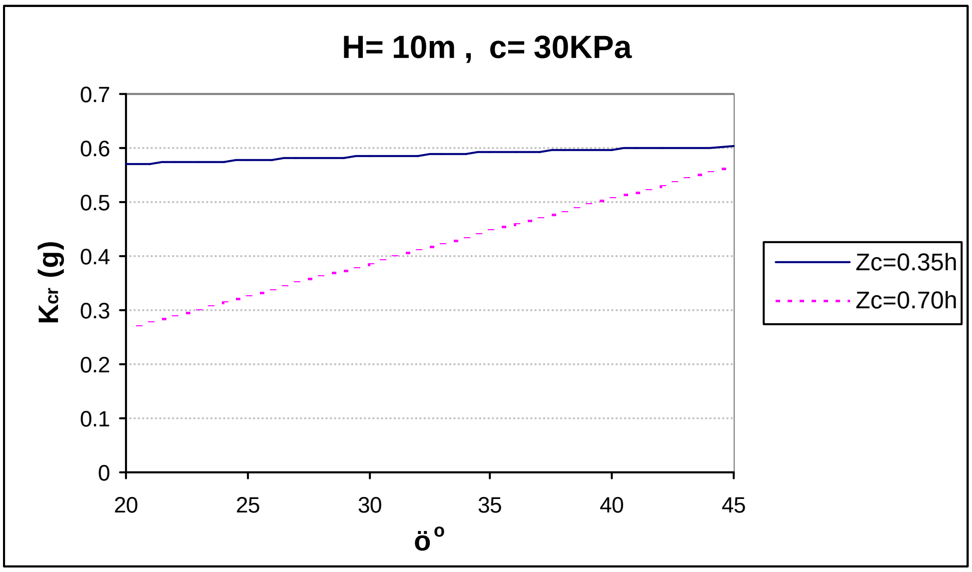

Figure 4. Results of seismic slope stability analysis for 10 m slope in *Tierra Blanca*.

A number of observations can be made from these results, the first being that a deeper tension crack creates greater instability, as indicated by the lower value of K_{cr}; for the case of a 20 m slope this is reversed, implying that instability can be induced with shallower tension crack. For a typical angle of shearing resistance of about 37, the critical acceleration is 0.45*g*. Although this value appears rather high, greater levels of accelerations were recorded in both the 10 October 1986 [28] and 13 January 2001 [29] earthquakes, and the *Tierra Blanca* has been shown to strongly amplify earthquake shaking [25, 30]. Even with angles of shearing resistance near the lower end of the range, accelerations of about 0.3*g* are required to induce failure in the slope. The results indicate that the slope instability increases significantly with slope height: for a 20 m slope and a value of 37° for f, the critical acceleration is found to be close to 0.1*g*.

Figure 5 shows the results obtained assuming that the cementation in the soil is lost, reducing the apparent cohesion to 8kPa, which is attributed to the soil suction. The results show a dramatic reduction in stability and with even a shallow tension crack of 0.22*h* the slope fails under static conditions for f<37°. *Tierra Blanca* loses its structure under small strains and hence as soon as slope failure begins the material tends to undergo almost complete degradation and under certain topographical configurations can become a debris flow.

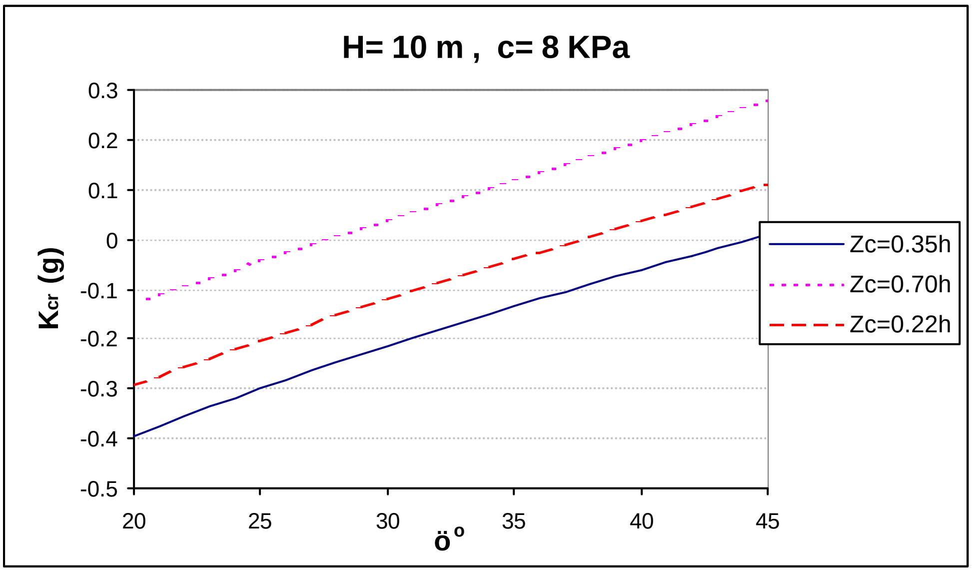

Figure 5. Results of seismic slope stability analysis for 10 m slope in *Tierra Blanca* without cementation.

The critical feature in determining whether or not a slope fails appears to be the formation of a tension crack. Using the FE program Diana-Swandyne II a number of dynamic analyses were performed for a 15 m high slope of Tierra Blanca, with a 70° inclination, overlying lava deposits. Figure 6 indicates the stresses induced in a slope with c of 30 kPa and f' of 39°, subjected to an accelerogram recorded at Santa Tecla during the 13 January 2001 earthquake [29]. The slope fails under the conditions; it is clear from Figure 6 that the ground motion induces tension in the upper part of the slope, which permits the failure to occur.

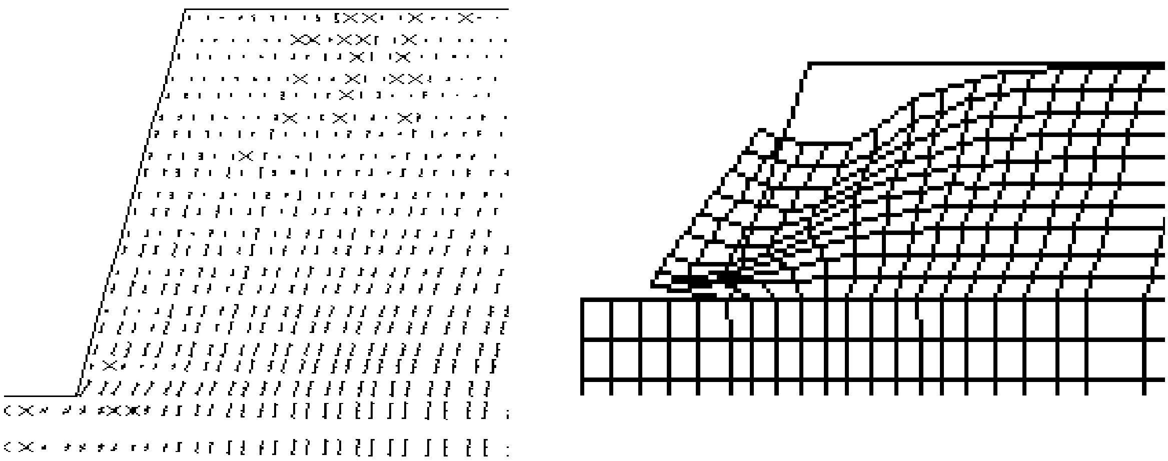

Figure 6. Stresses (left) and deformation (right) induced in a 15 m slope subjected to accelerogram from the 13 January 2001 earthquake in El Salvador; crosses indicate tension.

CONCLUSIONS

Volcanic soils are a special group of deposits that create particular engineering problems, particularly with regard to slope stability. This study of the Tierra Blanca soil from Central America has demonstrated that one of the most important factors in terms of slope stability is the relatively weak cementation, probably provided by silica gels, that is broken when the soil is subjected to even small strains. Although high matrix suctions of the order of 300 kPa and above have been measured in this soil, it appears to contribute relatively little to the stability of slopes. The drastic reduction of strength experienced in this soil as a result of disturbance precludes the use of many slope stabilisation techniques used in cohesive soils. There is a need to encourage the exchange of data, experience and insight amongst those engaged in the characterization and engineering of volcanic soils worldwide, to overcome the present gaps in our knowledge and create appropriate engineering solutions for these difficult deposits.

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