

NUMERICAL INVESTIGATION OF A CATASTROPHIC LANDSLIDE DURING THE EL SALVADOR JANUARY 2001 EARTHQUAKE

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ABSTRACT

The aim of this contribution is to investigate the mechanisms of the “Las Colinas” landslide, which was triggered by the 13th January 2001 earthquake in El Salvador, with the *Finite-Element-Method* (FEM). A two-dimensional plain strain slope is considered in the numerical simulations. An acceleration record from the earthquake at a station near to the “Las Colinas” hill was used as base excitation. The non-linear behaviour of the soil layers was simulated with a hypoplastic constitutive model which can simulate drained and undrained soil behaviour (including soil liquefaction) under alternating shearing. Based on the results of the numerical study and assuming that ground water existed at the toe, it can be concluded that two mechanisms must have been responsible for the Las Colinas landslide: The achievement of a limit condition in a shallow shear zone parallel to the slope and the liquefaction of the soil at the toe. According to our numerical results, the failure of the slope and the toe occurred almost simultaneously and were independent events.

Keywords: dynamic soil modelling, numerical methods, strong motion, soil liquefaction, landslides

INTRODUCTION

The west coast of the American continent is one of the regions with the highest occurrence of strong earthquakes worldwide. Especially the Central-American region is highly affected by strong earthquakes, which repeatedly cause a lot of damage. The plate tectonics in this region is dominated by the interaction of the Caribbean-plate and the Cocos-plate. At the Middle American trench the Cocos-plate slips from the south-west to the north-east under the Caribbean-plate, with a relatively high subduction rate of 92 mm/year. Due to this subduction process El Salvador is crossed by chains of volcanoes. Two types of earthquakes result from this particular tectonic configuration. The first types are earthquakes with volcanic origin resulting from faults at the volcanic mountain range. These earthquakes reach magnitudes up to 6.5 (after Richter). The second type are earthquakes with origin along the subduction zone and also inside the plates, which have already reached magnitudes of eight and higher. A tragic example for this type of earthquakes was the January 13th 2001 earthquake ($M_w=7.6$) in El Salvador (cf. Figure 1).

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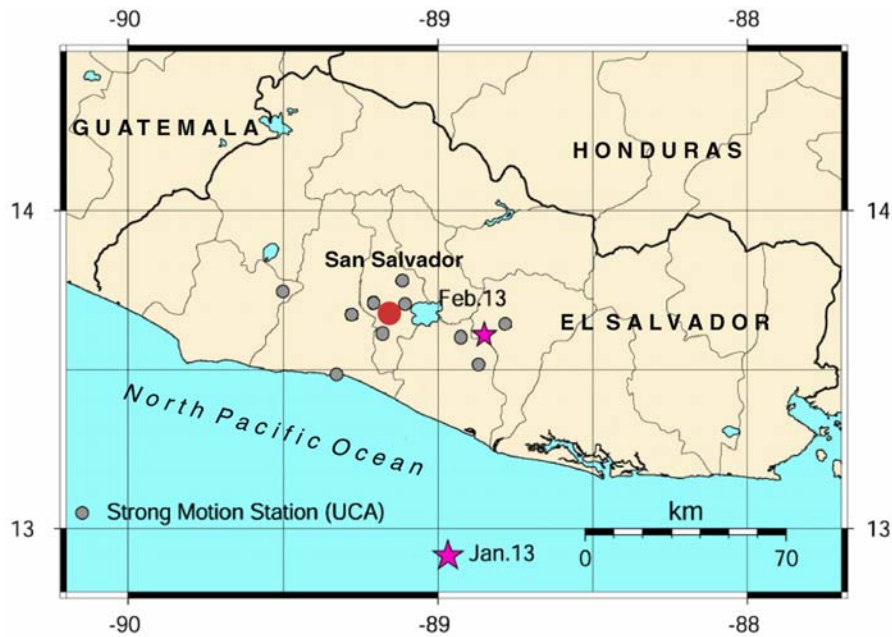


Figure 1. El Salvador – geography, epicenters and strong motion stations (Konagai, 2001)

THE JANUARY 13TH 2001 EARTHQUAKE

The main shock occurred on the 13th of January 2001. It was followed by another earthquake of lower intensity one month later on February 13th. The epicentre of the main shock was located more than 100 km from the city of San Salvador (cf. Figure 1). In the area of San Salvador peak accelerations of 0.3 to 0.6 g were recorded by the strong motion network of the Universidad Centro Americana (UCA). The acceleration time history records and the peak acceleration, velocity and displacement values for a station near the city (hospital San Rafael in Santa Tecla HSRF) are shown in Figure 2.

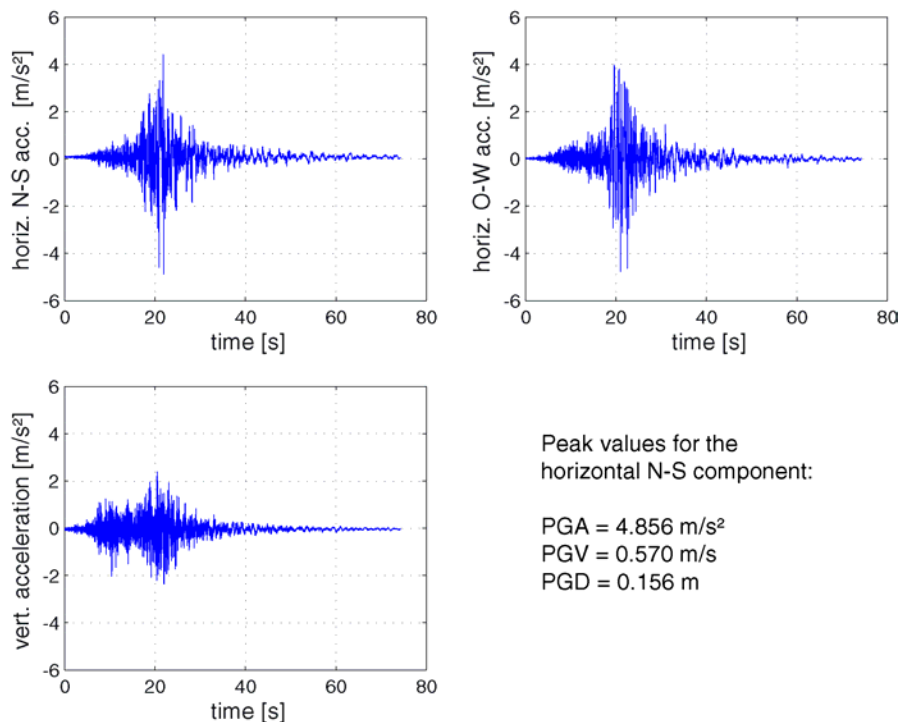


Figure 2. Original strong motion record from the January 13th 2001 earthquake (UCA, 2001).

The “Las Colinas de Santa Tecla” landslide

One of the most spectacular aspects of the January 13th Earthquake was the damage inflicted by 445 landslides. They caused over 900 fatalities, injured more than 5500 persons and damaged or destroyed 270000 buildings and infrastructure facilities. More than half of the earthquake’s victims were caused by a landslide in “Las Colinas” of Santa Tecla (the Santa Tecla hills), a middle class district of the great San Salvador (Fig. 1).

During the strong motion, the hillside flowed down and destroyed many houses in its path killing about 500 people. Eyewitnesses reported that the landslide occurred during the earthquake. The landslide took the form of a debris flow in spite of the fact that ground water was not found in depths lower than 50 m underneath the toe of the slope. Figure 3 shows a cross section of the slope before and after the earthquake and a top view with the area covered by the debris.

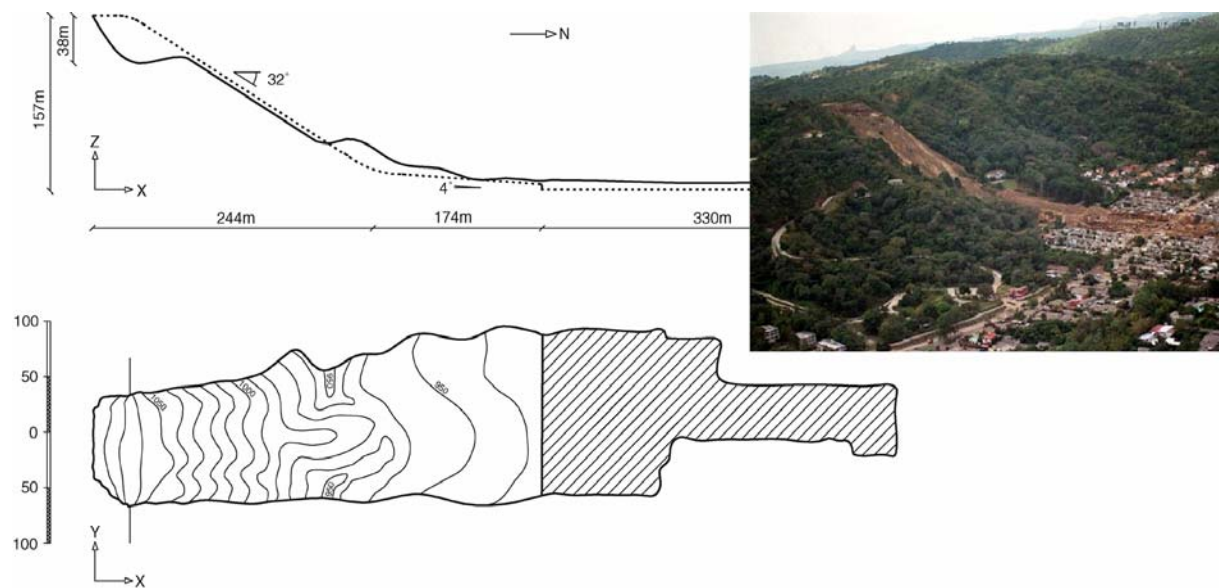


Figure 3. Profile of the slope before and after the slide (Mendoza et al., 2001) and aerial view of the “Las Colinas” landslide.

Geologically, the slope - as most of El Salvador - consists of volcanic deposits. Two large calderas, Ilopango and Coatepeque, are the main sources of tephra covering more than 50 % of the country. According to the available geological maps (Lomnitz & Rodríguez, 2001) the city of El Salvador is built on unconsolidated and poorly welded tuffs from the Ilopango caldera. The geology of the area features Tertiary to Holocene volcanics, mostly andesitic and basaltic lavas, brownish tuffs of intermediate age, and young silicic pyroclastics and epiclastics. The Las Colinas slide occurred in pyroclastics of the Cordillera del Bálsamo. In the upper layers, the slope consists mainly of a white and silicic tuff called *Tierra Blanca* (Figure 4). The grain size of this tuff varies from lapilli (gravel size) to silt and the grains are much softer and more breakable than quartz grains.



Figure 4. Soil profile (Jibson & Crone, 2001) and picture of the slip zone (Konagai, 2001) at the head of the slope

Failure mechanisms of the slope

There are three different hypotheses about the possible failure mechanism of the slope. Orense et al. (2003) suggest that the failure was induced by an amplification of seismic motion from the bottom to the top of the slope. As evidence for their hypothesis they indicate the rotational failure of the uppermost scarp, the cracks behind the shoulder of the slope and the damage of reinforced-concrete houses at the top terrace. Lomnitz & Rodríguez (2001) suggest that confined aquifers might be present at different levels in Las Colinas. Large pore pressure pulses of up to one bar caused by the earthquake could have helped to destabilize the steeper hillsides and triggered the landslide. Based on accounts of residents of Santa Tecla, Mendoza et al. (2001) found out that the ground water table might have been at the ground surface at the toe of the slope. Most probably, the accumulation of water was caused by the obstruction of drainage through an existing gravity wall. They allege that the failure began with a liquefaction of the soil at the toe of the slope, propagated as a chain reaction uphill and finished with a rotational failure at the uppermost scarp. The main goal of our numerical modelling is to clarify the causes and mechanisms of the landslide.

NUMERICAL ANALYSES

Finite-Element-Model

For the investigation of the landslide mechanisms the *Finite-Element-Method* (FEM) was used. The idealized profile of the slope and the plain strain FE-Model used in the computations are shown in Figure 5. The geometry of the model is based on the data given by Mendoza et al. (2001) (cf. Figure 3 and 5). For the retaining wall it was supposed that it makes no or minor mechanical contribution to the behaviour of the slope, so the wall and the region in front of it was substituted with soil. In the model the slope consists of an upper layer of Tierra Blanca lying on a much stiffer volcanic rock layer. The behavior of the Tierra Blanca and rock layers are modelled as hypoplastic and linear elastic materials, respectively. The soil density of the Tierra Blanca was assumed to vary from medium dense at the surface to dense at the rock horizon. Two situations of the slope are considered in the calculations: 1) no water in the slope, 2) saturation of the slope toe.

The earthquake was simulated by prescribing the velocity of the lower boundary of the model. The velocity history was obtained by integrating the north-south component of the acceleration history recorded at the HSRF station in Santa Tecla (Figure 2). In order to limit the computation time only the strong motion duration between 15.9 and 29.8 s is considered (Figure 6). Input signals for two weaker earthquakes are generated by scaling the velocities of the original signal with scaling factors of 0.7 and 0.5, respectively.

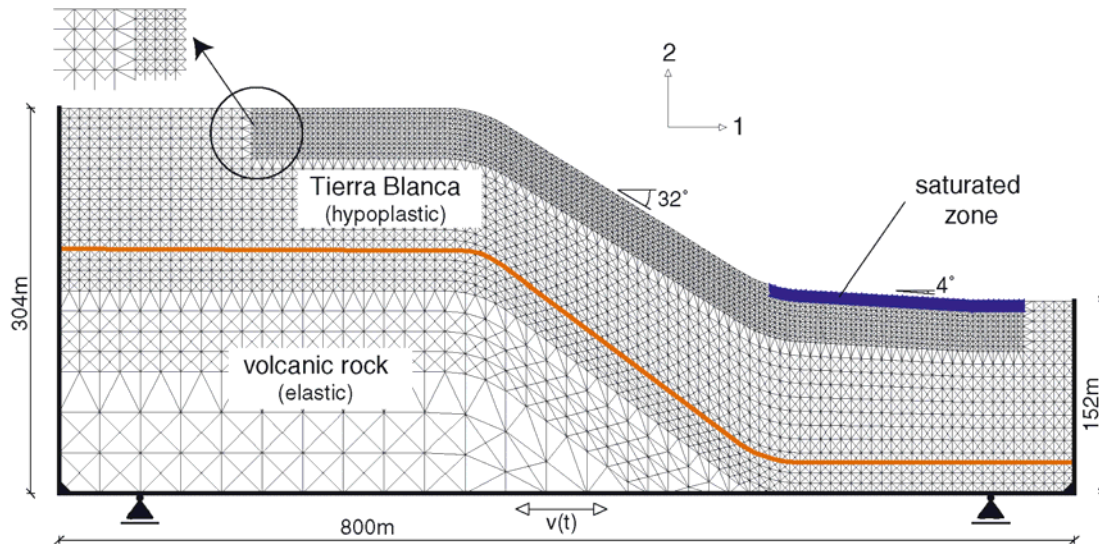


Figure 5. Finite Element Model – geometry, boundary conditions and soil layers

At the lateral boundaries of the model the same motion is prescribed as at the lower boundary. This “rigid wall” condition is acceptable if the displacements of the slope at failure are more than one order of magnitude bigger than the soil displacements on the lateral boundaries of the model. This condition is fulfilled in our case since the lateral model boundaries are far enough from the slope, and therefore the expected soil displacements there which would be induced almost under plane conditions are much smaller than the slope displacements occurring at failure. .

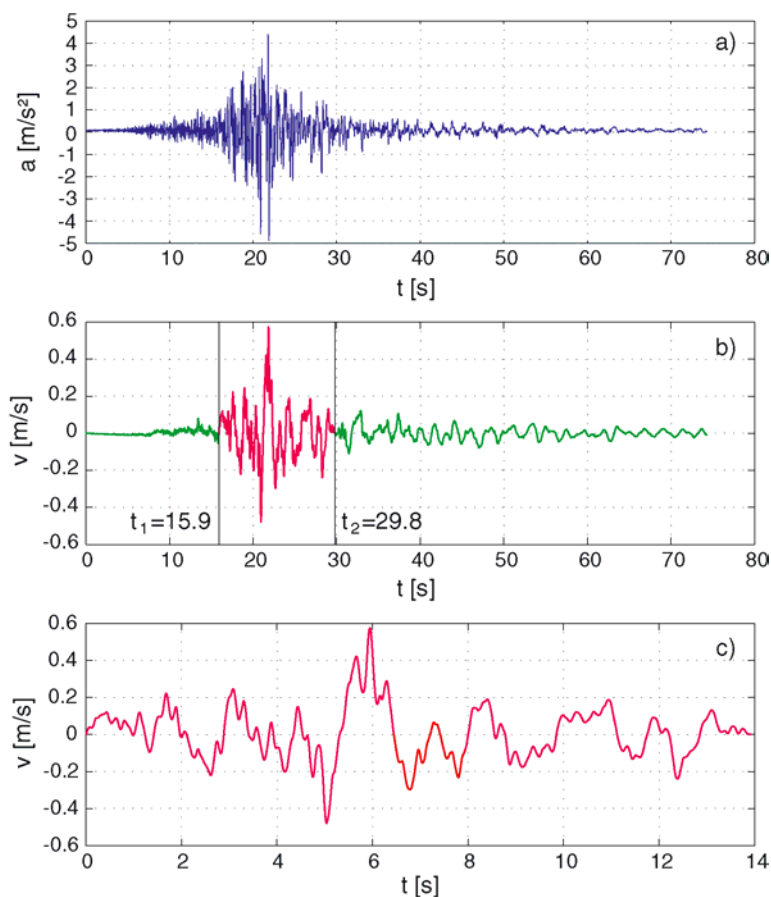


Figure 6. Acceleration time history (a), velocity time history (b) and velocity signal used as input (c)

Hypoplastic Constitutive Law

The mechanical behaviour of the soil in the slope was modelled by a hypoplastic constitutive equation with intergranular strain (Niemunis 2003). This is an incremental non-linear constitutive law incorporating the critical state concept of soil mechanics. Strength, stiffness and plastic deformations of the grain skeleton depend on the current state of the soil, which is defined by the stress state, the density (void ratio) and the previous deformation history. In opposite to elastoplastic models, the parameters of the hypoplastic model are independent on the soil state and can be determined from laboratory tests on disturbed soil samples. Since our study was concentrated on the failure mechanisms and not in a precise calculation of ground movements, the different tuff layers in Figure 4 were simplified to a single *Tierra Blanca* material. Based on results of various index and laboratory tests (Mendoza et al. 2001, Konagai 2001, Cuchilla 1999), the hypoplastic parameter of this *Tierra Blanca* were estimated (Table 1). Figure 7 shows a good agreement of the results of cyclic torsion tests performed by Mendoza et al. (2001) with the results of cyclic element test simulated with the hypoplastic model, using the constitutive parameters for this soil.

Table 1. Hypoplastic parameters for the Tierra Blanca

φ_c	h_s	n	e_{d0}	e_{c0}	e_{i0}	α	β	m_R	m_T	R	β_R	χ
36°	100 MPa	0.10	0.90	1.40	1.60	0.08	1.0	14.5	14.5	$2 \cdot 10^{-5}$	0.2	1.0

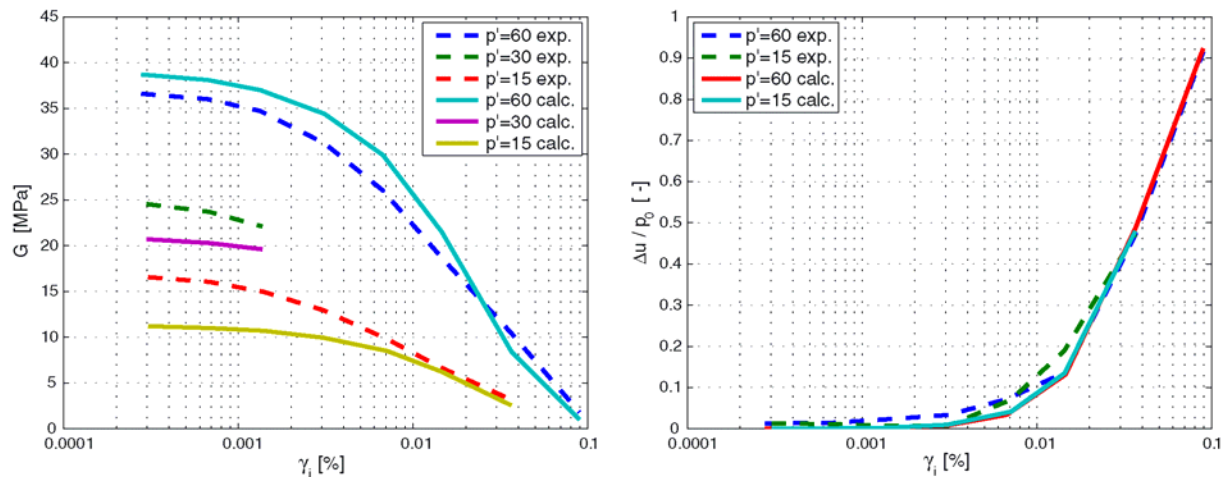


Figure 7. Experimental and simulated results of undrained cyclic torsion tests

Results and Discussion

Fig. 8 and 9 show the contour plots of the shape change \bar{e} ($\bar{e} = \sqrt{e_1^2 + e_2^2 + e_3^2}$, $e_1 = \varepsilon_1 - \varepsilon_v/3$, $\varepsilon_v = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$) at the end of the earthquake for the three considered maximum velocities (0.3, 0.42 and 0.6 m/s) for the two analyzed slope situations (LC-1: dry slope; LC-2: slope toe saturated). \bar{e} is a measure of the intensity of accumulated shear deformation and is appropriated to identify zones of shear localization. In both models a shear zone develops near the surface of the slope during the strong earthquake.

The shear zone begins at the toe, is almost parallel to the slope and emerges vertically to the surface in the uppermost part of the slope. The order of magnitude of shear deformation of 10 % (red color) indicates that the soil reaches a limit state in the shear zone. On the contrary, the order of magnitude of deformation of 0.1 % and 1 % for small and medium earthquakes indicates a stable behavior of the slope in both cases. The most remarkable difference between the response of the models LC-1 and LC-2 is observed at the toe of the slope. With the model LC-1 (without ground water), the predicted soil deformations at the toe are at least three orders of magnitude lower than in the shear zone of the slope,

whereas the deformations predicted with the model LC-2 in the assumed water saturated zone have the same order of magnitude as in the shear zone. This can be understood with the help of Figure 10 showing the evolution of effective pressure and shear stresses over the time at different depths of the saturated layer. As it can be seen, the mean effective stresses (and also the shear stresses) decay to almost zero, i.e. the soil liquefies, during the earthquake.

Figure 11 shows the evolution of vertical and horizontal displacements at the scarp (P1) and the toe of the slope (P2). Figure 12 shows the displacement paths at the same points. At the scarp, the direction of sliding is parallel to the slope. The magnitude of accumulated displacements depends on the intensity of shaking and it is practically not influenced by the presence of ground water at the toe. The accumulated horizontal displacement at the toe of about 0.15 m predicted without ground water (model LC-1) is considerably lower than the value 4.5 m obtained when ground water is taken into account (model LC-2). The vertical displacements predicted by model LC-1 at the toe are due to soil compaction.

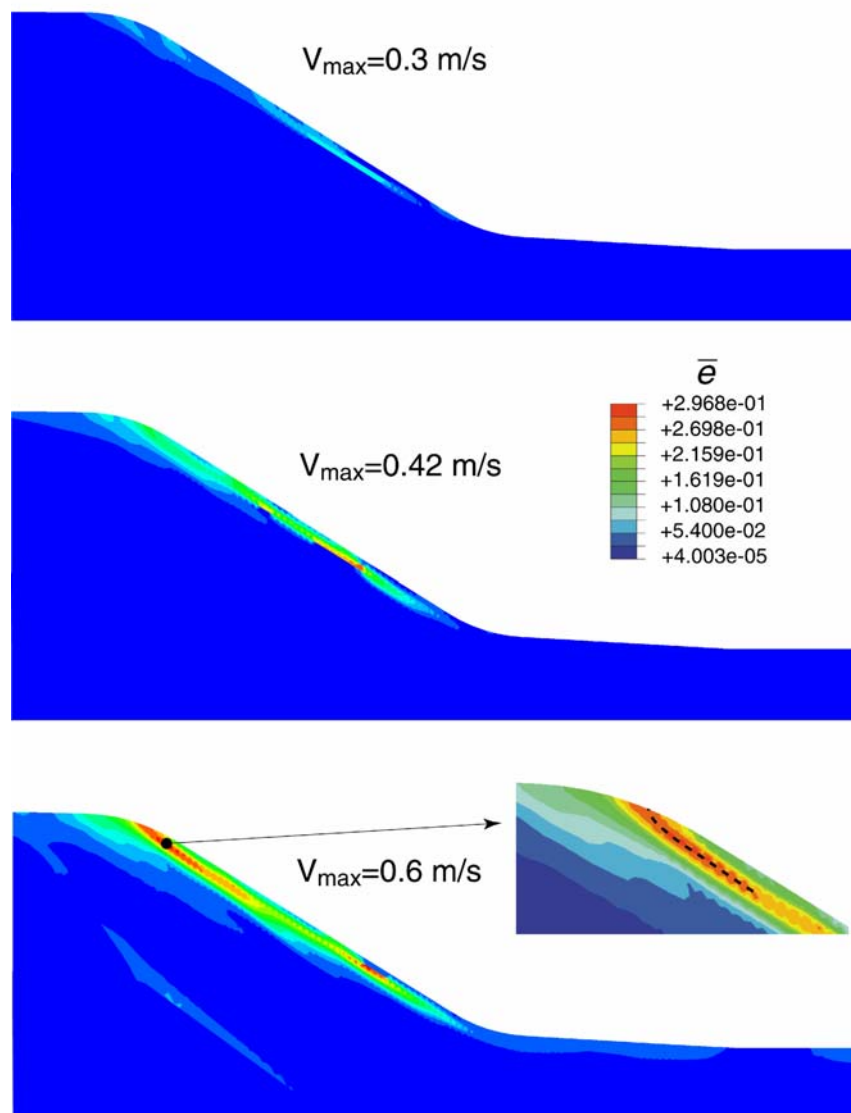


Figure 8. Calculations with the FE-model LC-1: Contour plots of the shape change \bar{e} at the end of the input signal for base shaking with $v_{\max}=0.3, 0.42$ and 0.6 m/s

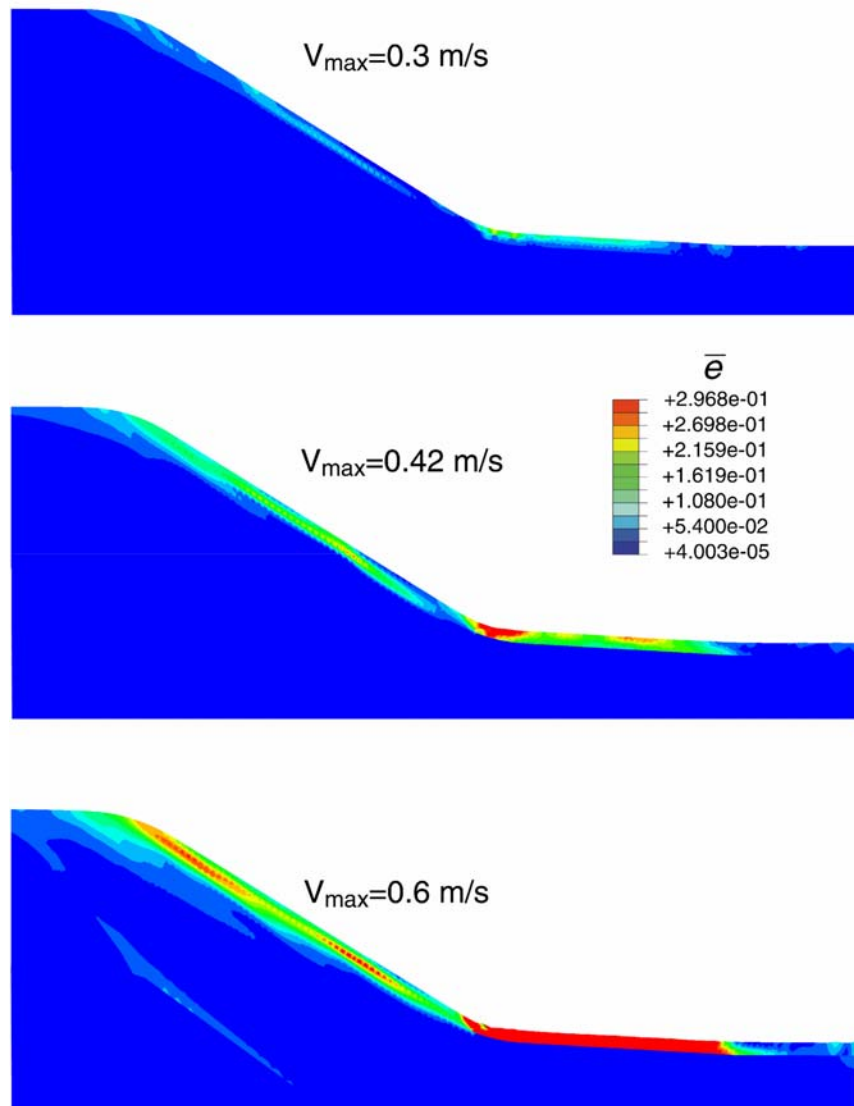


Figure 9. Calculations with the FE-model LC-2: Contour plots of the shape change \bar{e} at the end of the input signal for base shaking with $v_{\max}=0.3, 0.42$ and 0.6 m/s

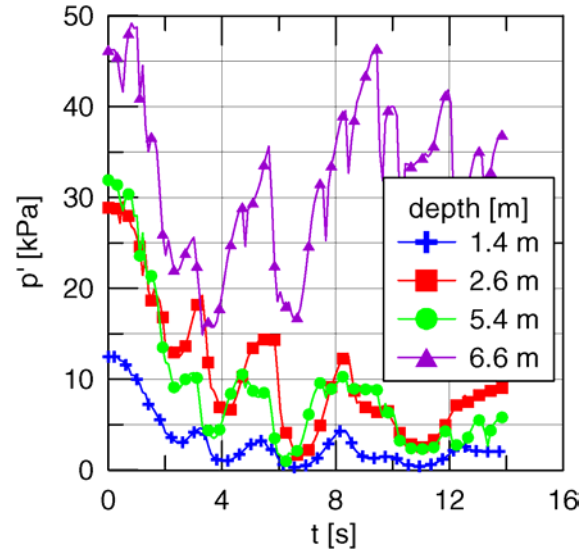


Figure 10. Evolution of effective pressure p' over time at different depths in the saturated layer at the toe of the slope for $v_{\max} = 0.6$ m/s

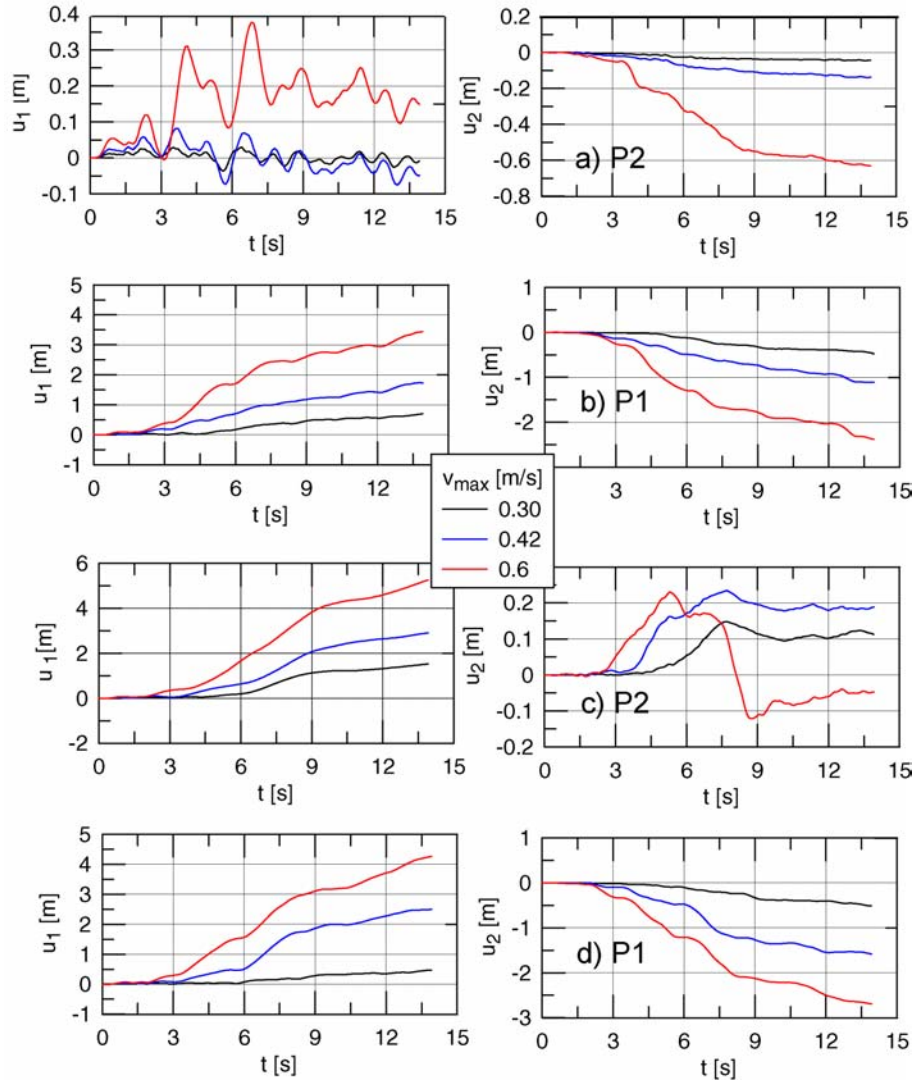


Figure 11. Evolution of vertical and horizontal displacements over time at the scarp (P1) and the toe of the slope (P2): a) and b) LC-1; c) and d) LC-2

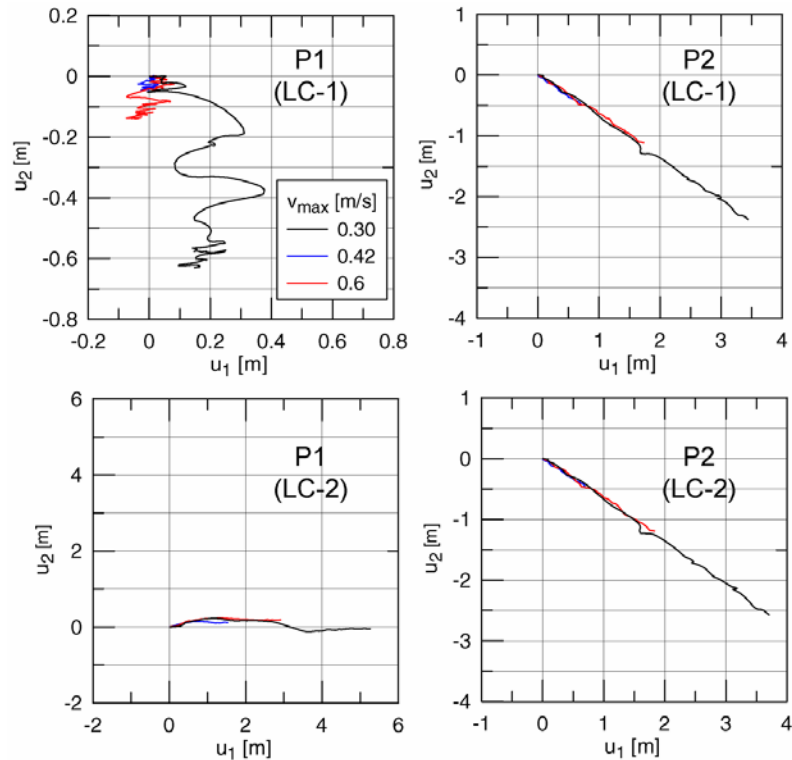


Figure 12. Displacement path at the scarp (P1) and the toe of the slope (P2): LC-1 (top), LC-2 (below)

CONCLUSIONS

A rational approach has been proposed to investigate the failure mechanism of a natural slope during a strong earthquake. In spite of the fact that the soil stratification has been strongly simplified in the simulations, our model is able to predict both, the failure of “Las Colinas” during the real earthquake and its stable behaviour during weaker earthquakes. The key for the successful prediction of the observed slope failure is a realistic modelling of the alternating shear behaviour of “tierra blanca”, which is the upper soil layer in which both the slope scarp and the toe failure were assumed to take place.

Comparing the magnitude of the scarp displacements in Fig. 11a and 11b, it becomes clear that the failure of the scarp takes place despite of the presence of water at the toe of the slope. Based on this result and assuming that ground water existed at the toe, it can be concluded that two mechanisms must have been responsible for the Las Colinas landslide: The achievement of a limit condition in a shallow shear zone parallel to the slope and the liquefaction of the soil at the toe. In the numerical simulations both failures are independent events and they occur almost simultaneously.

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