Failure mechanism of large landslides triggered by earthquakes in the El Salvador Fault Zone: the case of Jiboa landslide

Meaza Tsige(1), Martín Jesús Rodríguez-Peces(1), Ignacio García Flórez(1)

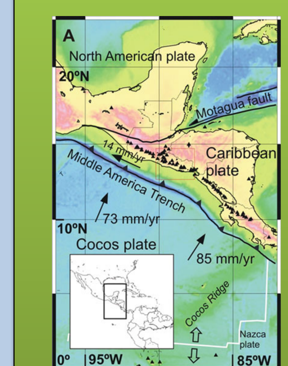
(1) Department of Geodynamics, Stratigraphy and Paleontology. Faculty of Geological Sciences. University Complutense of Madrid. *martinjr@ucm.es*

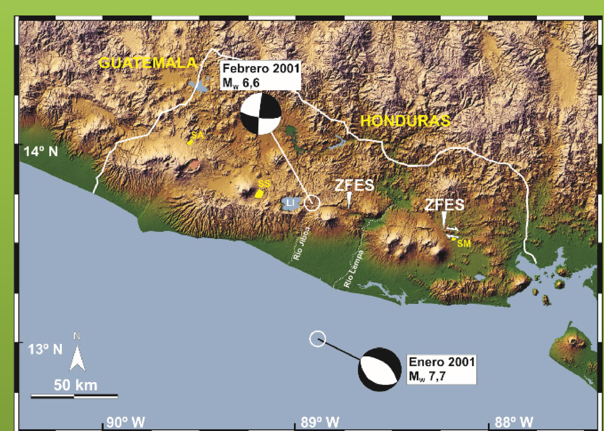
GSA 2018
4-7 November
Indianapolis, Indiana, USA

INTRODUCTION

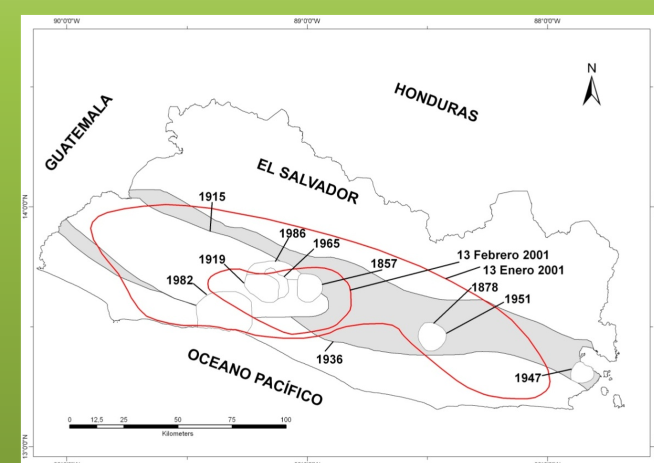
El Salvador, due to its geodynamic setting –close to the Cocos-Caribbean segment of the Middle American subduction zone, where the plates converge-, is affected by a great number of earthquakes of large and moderate magnitudes. One of the secondary effects associated with these events, which contributes to a large extent to increase the destruction and loss of life, are the landslides. During the last decades El Salvador has suffered many earthquakes of large and moderate magnitude that have caused severe damage and great social alarm, fundamentally because of the associated geological process (landslides, liquefaction, etc.) (White and Harlow, 1993; Bommer *et al.*, 2002). The impact that these phenomena can have was demonstrated with the two 2001 El Salvador earthquakes, that produced and reactivated a great number of landslides across the whole country but with a great concentration in the central part of the El Salvador. During these two events nearly 1,200 people died, from which around 500 casualties were directly related with the induced landslides (CEPAL, 2001).

In this work, we present the slope stability analysis and the failure mechanisms proposed for the Jiboa landslide, which is one of the greatest co-seismic slope instabilities triggered during El Salvador earthquake of February 13, 2001, with a magnitude of M_w 6.6. The seismic events that took place at the beginning of 2001, besides inducing a large number of shallow slope instabilities, triggered large landslides putting hundreds of thousands of cubic meters of material into motion. These large landslides produced the greatest damage in both economic losses and human lives.



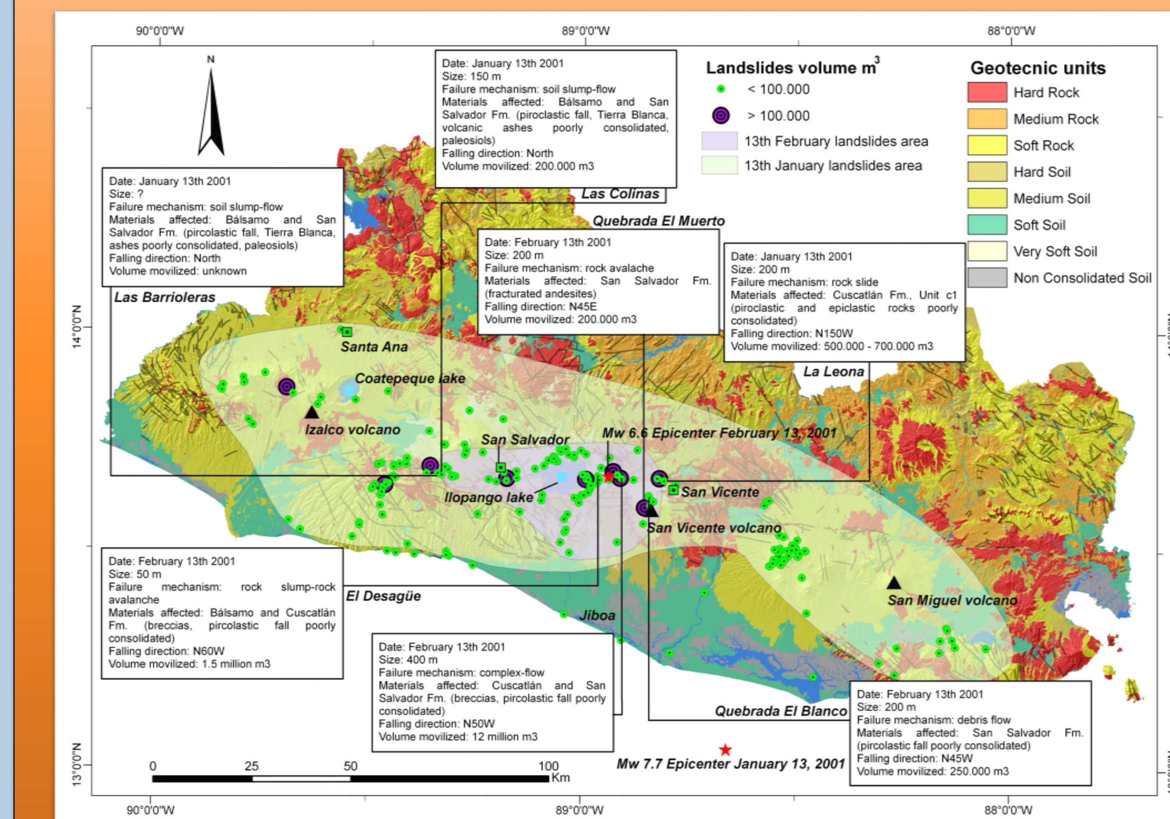


Location of the two 2001 El Salvador earthquakes (M_w=7.7 and M_w=6.6).



Areas affected by co-seismic landslides during historical and recent earthquakes (Rymer and White,1989; García Flórez and Tsige, 2011; García Flórez, 2014).

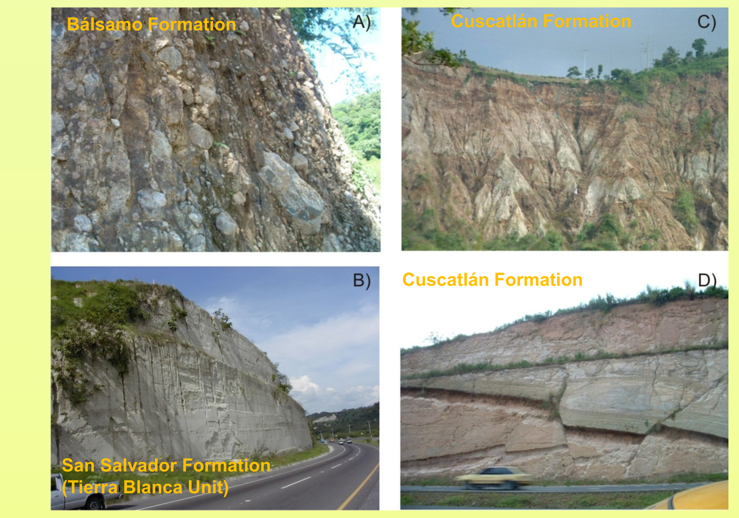
CO-SEISMIC LANDSLIDES IN EL SALVADOR

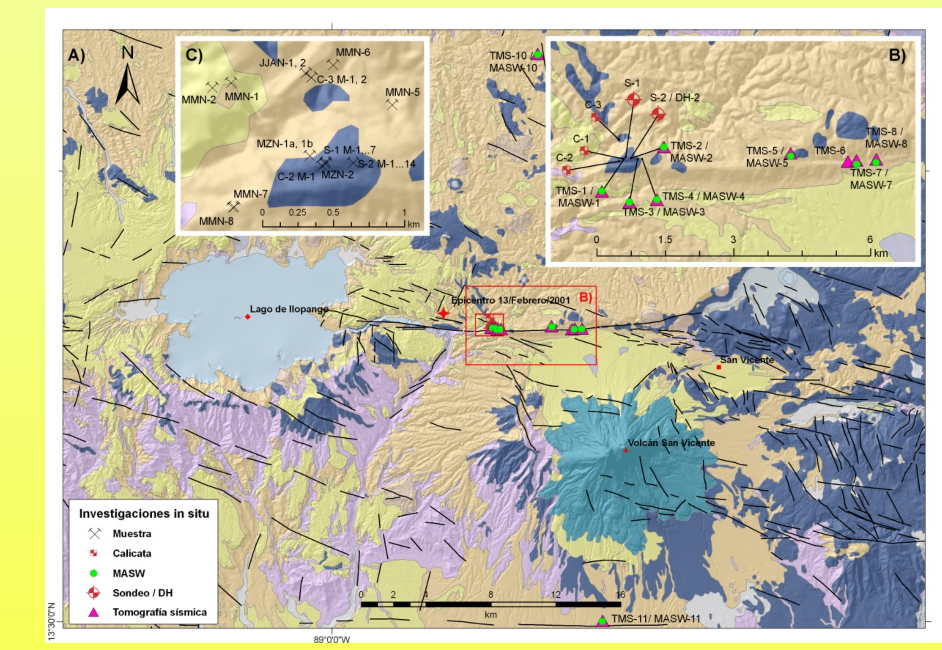


Distribution of landslides triggered by the 2001 El Salvador earthquakes (García Flórez, 2014).

Most of the landslides, especially the large-scale ones, are not associated to a specific geological material and steep slopes (Tsige *et al.*, 2010). They occur near or at the El Salvador Fault Zone, independent of the distance and origin of the earthquake, indicating an important control of the existing faults in guiding large liberation of seismic energy (García Flórez and Tsige, 2011). These elements can act as channels through which the seismic waves travel, resulting in an energy entrapment, and therefore in a larger ground motion that can trigger deep-seated landslides even in gentle slopes (Imposa *et al.*, 2004; Pischiutta *et al.*, 2017).

GEOLOGY AND *IN SITU* INVESTIGATIONS





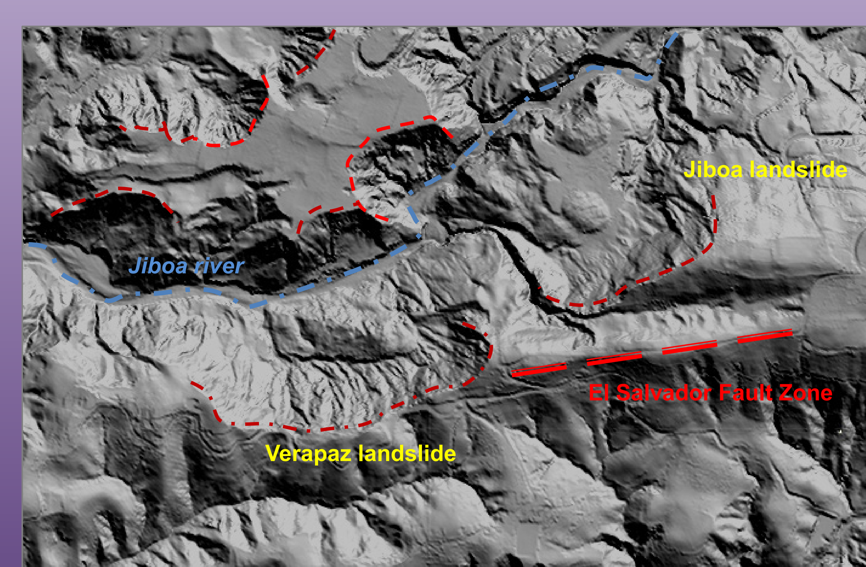
2 Boreholes (100 m)
3 Trenches
1 Down-hole test
10 Seismic tomography profiles

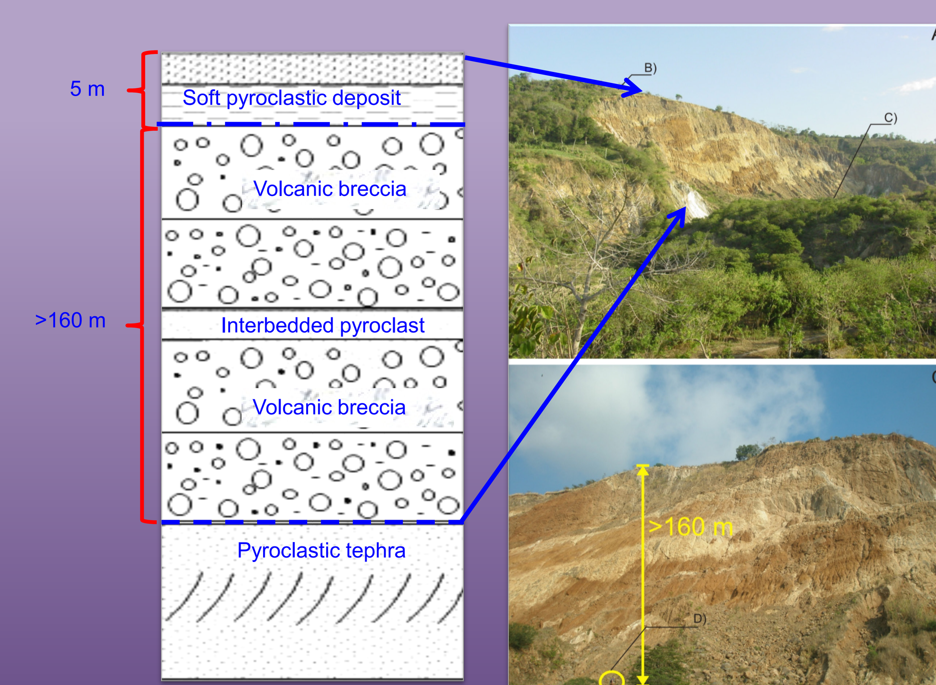
10 MASW profiles
Laboratory tests from samples
SEM Microfraphic studies
Bibliographic data

JIBOA LANDSLIDE

The Jiboa landslide volume is estimated > 12 million cubic meters with a vertical drop about 170 m. The landslide dammed with debris about 700 m long and 250 m wide of the valley of Jiboa river and the upstream lake could be about 60 m deep and 2 km long (Baum et al., 2001).

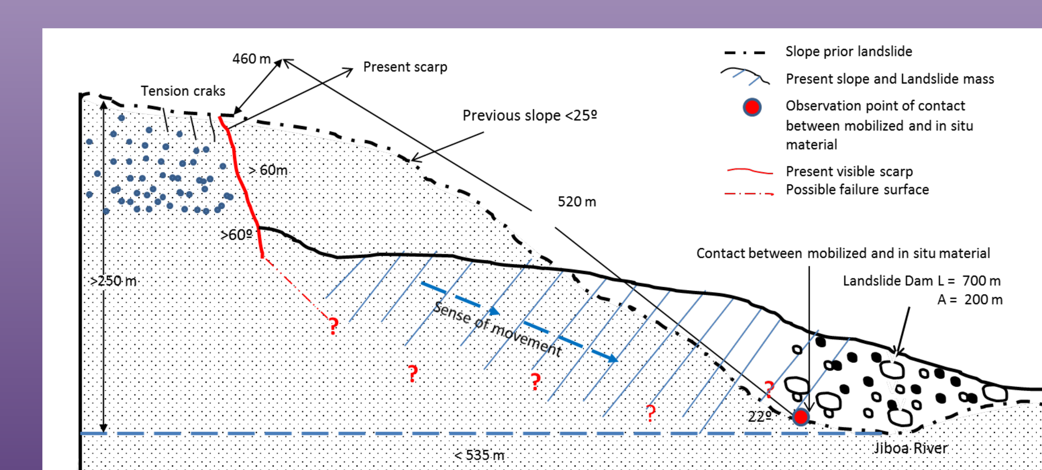
The Jiboa landslide occurred near the fault rupture zone in the confluence of the El Desagüe and Jiboa rivers. In the area where Jiboa landslide took place has been mapped several old landslides (e.g. Veracruz landslide) which may have been caused by similar past seismic events.





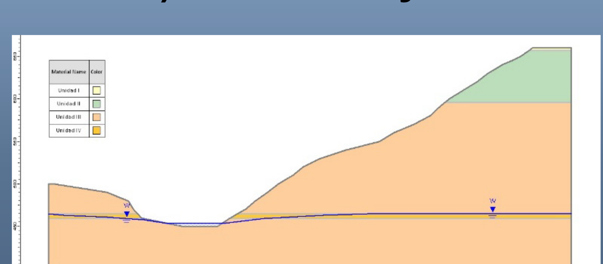
Simplified geological profile of Jiboa landslide caused by the February 13th 2001 El Salvador earthquake and detailed view of materials (C) at the slope.

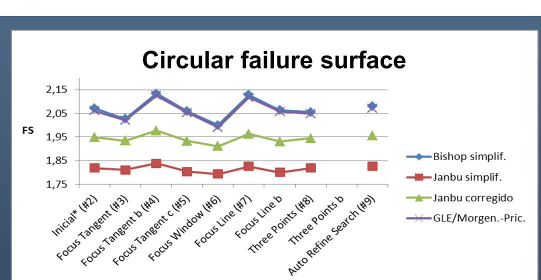
The Jiboa landslide slope comprises blocks of andesitic breccia (frequently interbedded with pyroclasts) and rhyolitic tephra from Cuscatlán Formation. The upper part of the slope is covered by a thin recent pyroclastic deposit of Tierra Blanca and paleosoils. The breccia (> 160 m thick) consisted of sand-sized to 50 cm-diameter rock fragments mainly basaltic and andesitic, and had poorly sorted interiors and coarse tops. The underling ryolitic tephra is a poorly compacted and very porous fine grained deposit. In situ and laboratory investigation has shown that these ryolitic tephra is frequently interbedded by thin highly porous and soft volcanic ash layers that are formed by silt and sand particles with a few amount of clay. These thin volcanic ash layers probably form a horizontal sliding surfaces which were essential for the generation of such deep landslide.

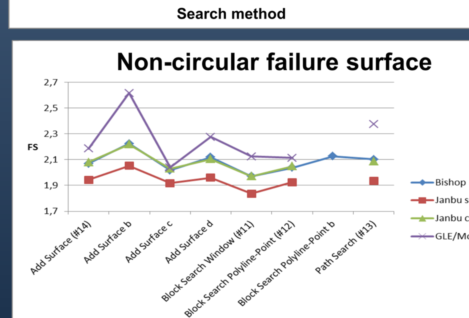


SLOPE STABILITY ANALYSIS OF JIBOA LANDSLIDE

1) Static analysis



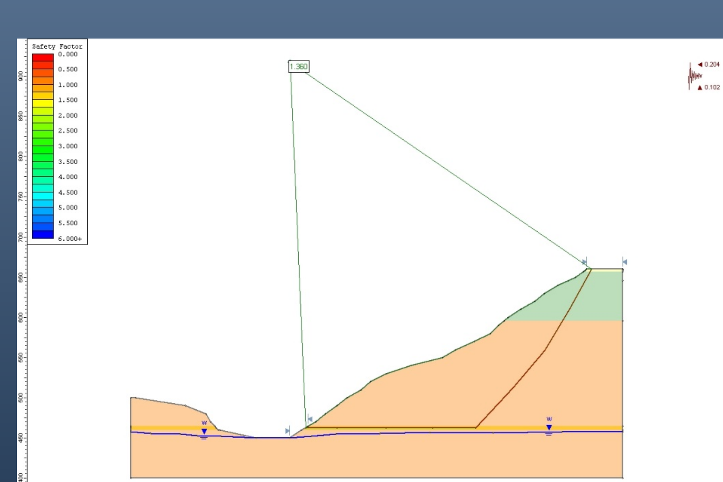




STABLE (FS > 1.7)

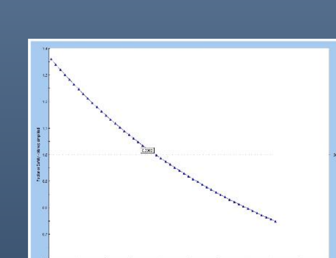
2) Pseudostatic analysis

a) Real PGA = 0,408g (Zacatecoluca seismic station)



STABLE (FS = 1.36)

b) Increasing PGA

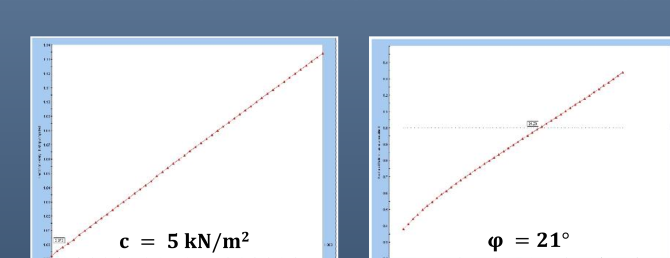


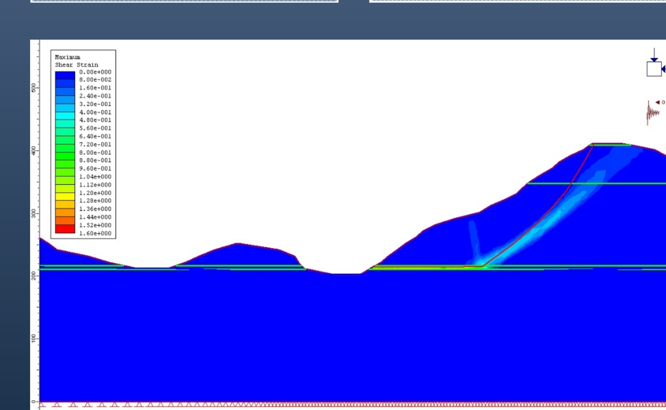
UNSTABLE

if PGA 1.9 higher than real registered

(not possible)

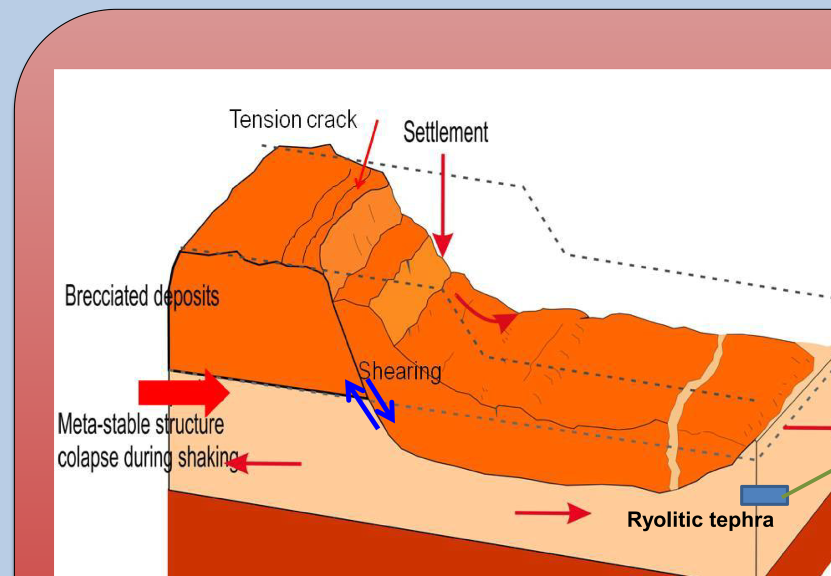
c) Reducing strength parameters of thin volcanic ash intercalations

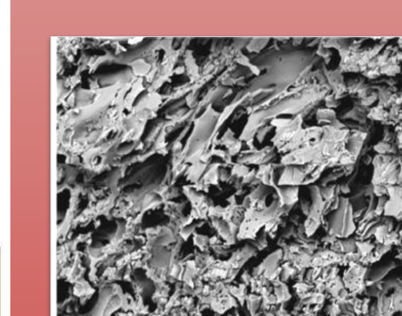




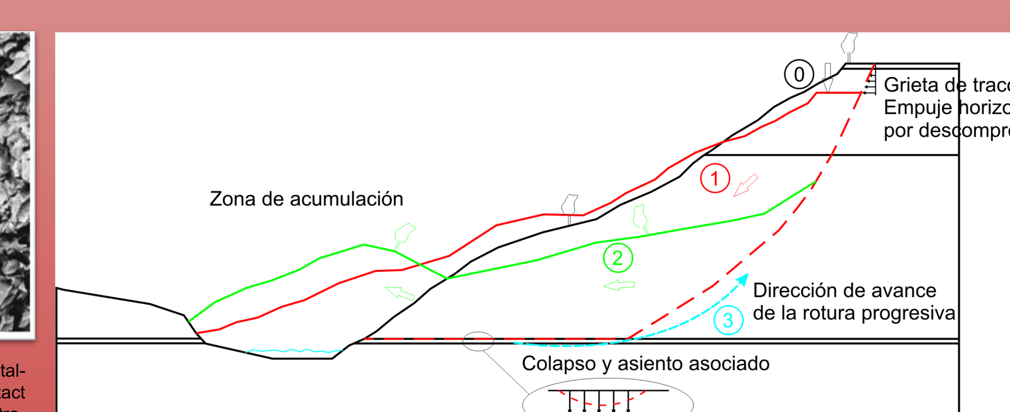
UNSTABLE

CONCLUSIONS





SEM photograph showing an open squeletal-like microstructure with a grain-grain contact and large pores, including important intra-crystalline pores.



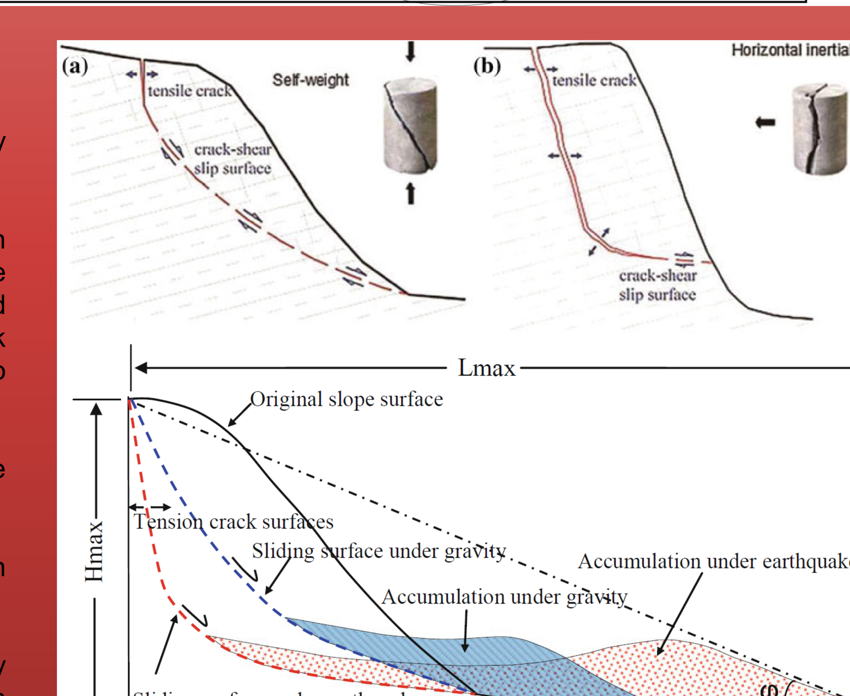
The geological and geotechnical studies carried out in situ, the laboratory tests, as well as the slope stability analysis, reveal that the failure of the Jiboa landslide took place in three independent phases:

Phase 1. The triggering factor of the landslide is attributed to the existence of very porous volcanic ash intercalations, which collapsed due to the released seismic energy and lost their strength parameters. The thin volcanic ashes have a very open texture with a meta-stable honeycomb like microstructure, high void ratio and low unit weight (1.2 kN/m^3). These materials have a high apparent strength due to primary weak chemical and silty-clay cementation, but they are susceptible to large reductions in their strength due to shaking and flow like a semi-liquid mass (quick-silt).

Phase 2. The collapse produced a large settlement and, consequently, a tension crack was generated in the head of the slope.

Phase 3. Finally, the movement propagated by shearing failure along a sub-horizontal surface located in such volcanic ash intercalations.

The suggested failure mechanism of Jiboa landslide could be valid for similar large landslides triggered by earthquakes in the El Salvador, and it is coherent with previous model developed for co-seismic landslides (Huang, 2015).



Sketches showing the tension-shattering-shearing failure of earthquake-triggered landslides and the consequent different geomorphic features different from those of landslides under normal gravity conditions (Huang, 2015).

References

Baum, R.L., Crone, A.J., Escobar, D., Harp, E.L., Major, J.J., Martinez, M., Pullinger, C., Smith, M.E. (2001). Assessment of landslide hazards resulting from the February 13, 2001, El Salvador Earthquake. U.S. Geological Survey Open-File Report, 01-119, 22 pp.
Bommer, J.J., Benito, M.B., Ciudad-Real, M., Lemoine, A., López-Menjívar, M.A., Madariaga, R., Mankelow, J., Méndez de Hasbun, P., Murphy, W., Nieto-Lovo, M., Rodríguez-Pineda, C.E., Rosa, H., (2002). The El Salvador earthquakes of January and February 2001: context, characteristics and implications for seismic risk. Soil Dynamics and Earthquake Engineering, 22(5): 389–418.
CEPAL (2001). El Salvador: Evaluación del terremoto del martes 13 de febrero de 2001. In: S.S.e.M (ed) Addendum al documento de evaluación del terremoto del 13 de enero, in Comisión Económica para América Latina y El Caribe (CEPAL). Naciones Unidas, México, 63.
García-Flórez, I., Tsige, M. (2011). Geological and structural control of earthquake-induced landslides in El Salvador. Landslide Science and Practice Vol. 5. Claudio Margottini, Paolo Canutí. Kyoji Sassa Eds. 287-293
García-Flórez, I (2014). Factores geológicos-geotécnicos que controlan los deslizamientos inducidos por terremotos en zonas de alta y media actividad sísmica: caso de El Salvador. PhD Thesis. University Complutense of Madrid.
Huang, R. (2015). Understanding the mechanism of large-scale landslides. In: Lollino G (ed) Engineering geology for society and territory—volume 2. Springer International Publishing, Switzerland.
Imposa S, Coco G, Corrao M (2004). Site effects close to structural lineaments in eastern Sicily (Italy). Engineering Geology, 72: 331-341.
Pischiutta, M. Fondriest, M. Demurtas, F. Magnoni, G. Di Toro, A. Rovelli (2017). Structural control on the directional amplification of seismic noise (Campo Imperatore, Central Italy). Earth Planetary Science Letters, 471 , 10-18.
Rymer MJ, White RA (1989). Hazards in El Salvador from earthquake-induced landslides. In: Brabb EE, Harrod BL (eds) Landslides: extent and economic significance. A. A. Balkema, Rotterdam, 105-109.
Tsige, M., I. García-Flórez, R. Mateos, (2010). Geological control of earthquake induced landslide in El Salvador. Vol. 12, EGU2010-13410-1, 2010, EGU General Assembly, Viena.
White, R.A., Harlow, D.H. (1993). Destructive upper crustal earthquakes of Central America since 1900. Bulletin of the Seismological Society of America, 83(4): 1115–1142.

Acknowledgments

This study was supported by research project CGL2017-83931-C3-1-P (MINECO) and the research group "Planetary Geodynamics, Active Tectonics and Related Risks", UCM-910368 of the University Complutense of Madrid.