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Landslide Hazard in El Salvador

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Abstract

The destructive seismic events of January 13 (M_L: 7.6) and February 13 (M_L: 6.1) 2001 in El Salvador, with origin in the subduction area and the volcanic chain, respectively, provide an ideal scenario to analyse the factors that define the landslide hazard in this country. In this paper we analysed the events in terms of strong-motion and precedent climatic condition and their relation with the landslides induced; establishing a great opportunity to compare some hazard assessment methods as those proposed by Mora and Vahrson (1994) and Rodríguez (2001) which define the hazard in terms of the interaction between triggering agents and susceptibility conditions.

Historically both rainfalls and earthquakes have shown to be important triggers for landslides in El Salvador, and results show how the combination of these factors are also critical in defining trigger thresholds and in controlling failure mechanisms. It was found that the Mora and Vahrson method underestimates the landslides hazard; as was discussed by Bommer and Rodríguez (2002), this is mainly due to the rainfalls levels used by the method which were defined for the Costa Rica conditions, which are markedly different to those in El Salvador. The Rodríguez model describes in a better way the landslides hazard, however in some areas the hazard is overestimated due to the way as weighting factors for lithology shades the influence of topography, this suggests that assignment of weighting values in the model must be reviewed implementing a multivariate correspondence analysis instead of the bivariate model used so far.

Introduction

Landslides are one of the most devastating natural threats which produce large number of deaths and economical losses each year worldwide. In 2001 the 13 January and 13 February earthquakes in El Salvador left around 1000 deaths due to the landslides induced (Bommer and Rodriguez, 2002). Landslides induced during these events were associated with susceptible slopes highly intervened by anthropogenic activities. The present paper focuses on the seismic and rainfall conditions related to those earthquakes and the way rainfalls and seismic loads can be combined in order to evaluate landslide hazard. Landslide inventories during the 2001 earthquakes are used to evaluate the Mora and Vahrson (1994) and Rodriguez (2001) models that have been proposed for the area. Rainfalls due to Hurricane Mitch in 1998 and Hurricane Stan in 2005 produced exceptional large economical and social losses in the country, distribution of landslides in these cases are less regular than those induced during earthquake, which makes their analysis much more complicated, then just general conclusions about these cases are included in this study.

Landslides in El Salvador

Earthquakes and rainfalls have been common triggers of landslides in El Salvador; however, earthquake magnitude or rainfall intensity alone does not reflect the effects on landslides characteristics. Slope susceptibility also controls both spatial and temporal distribution of slides.

Slope susceptibility. Landslide characteristics are influenced by slope susceptibility to failure, which depends, among other factors, on slope geometry, lithology, climatic conditions and human intervention.

Lithology. Common geological material related to landslides in El Salvador is volcanic and residual soils. Transported deposits with high water tables, this kind of deposits includes alluvial flood plains, alluvial fans, alluvial terraces, lacustrine and deltaic deposits, and coastal deposits like beaches and tidal flats have also been shown to be very susceptible compared with other soil deposits. Landslides in volcanic and sedimentary rock deposits have also been shown to be common, and their frequency seems to be associated with structural controls such as the basal discontinuity inclination and orientation, these being more critical when discontinuities dip out from the slope face. Soil structure, mineralogy and saturation have shown to control strain-stress behaviour of volcanic and residual soils.

Stability of natural residual soil is controlled by discontinuities and open structure given by bonding, which in turn is a function of the weathering process. Strength on residual soils has been found to depend on the void ratio, which is defined by the interaction between the coarse grains and clay formed during weathering. Bonding supplies high peak strength to soil, which shows brittle behaviour. Strength supplied by bonding can be mobilised by small strains or can be removed by leaching of bonding agents due to water flow within the soil. Soil/rock interface in residual soil creates an impermeable barrier that allows rainfall infiltration to perch and increase soil saturation and consequently reduction on soil suction and strength, this interface, when shallow, becomes a potential failure plane.

Geographic distribution of main geological units in El Salvador is shown in Figure 1. This map shows that most of the country is covered by extrusive volcanic rocks highly fractures by continuous tectonic activity. Toward the northern boundary some intrusive rocks can be found. Recent volcanic activity covers the old volcanic formations of interbedded sequences of ashes and lavas. To the north-eastern of the country some sedimentary marine formations have been identified. Superficial units are associated to volcanic ashes, volcanic and sedimentary fractured rocks and residual soils of these previous units.

Slope geometry. Natural slopes in volcanic soils, especially those formed along the banks of deeply eroded ravines and cuts for roads and urbanisation are commonly nearly vertical and they can reach heights of several meters. These slopes can remain stable for long periods of time, but they can become unstable during heavy rainfalls or seismic shaking. Residual soils on steep slopes show to be shallower than those on gentle slopes, this condition controls the failure mechanism; shallow soils tends to fail along soil/rock interface as planar traslational slides, whereas deep soils tend to show rotational failure.

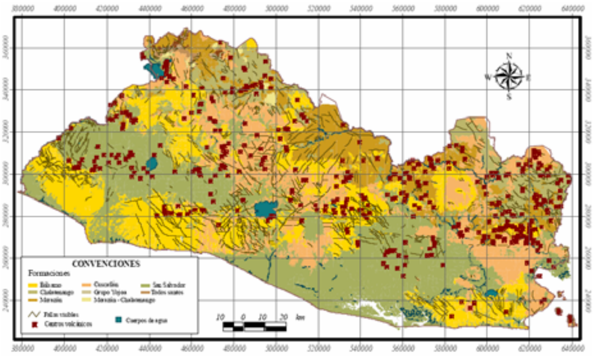

Figure 1. Geological map of El Slavador. Based on 1:500,000 Geological map.

Volcanic soil-filled bedrock hollows are particularly susceptible to initiating debris flows because of ground water flow convergence. Debris flows are common in first-order drainage or on hillsides with concave topography covered by volcanic or residual soils. However, debris flows have also been noted on planar or slightly convex hillsides. Deep slumps occurred at middle to low positions on concave slopes probably due to throughflow from site slopes. Despite their low relative position on hillsides these failures are associated with gully erosion or undercutting by streams. Shallow slumps and slides within soil occurred predominantly at middle to upper positions of planar to slightly concave hillsides. Very shallow slides over bedrock between 0.2 and 0.5 m depth occurred on steep slopes. These slides occurred on planar and even slightly convex middle and upper positions of hillsides. Figure 2 shows the DTM model of El Salvador obtained from 1:50,000 topographic maps supplied by the Salvadorian government.

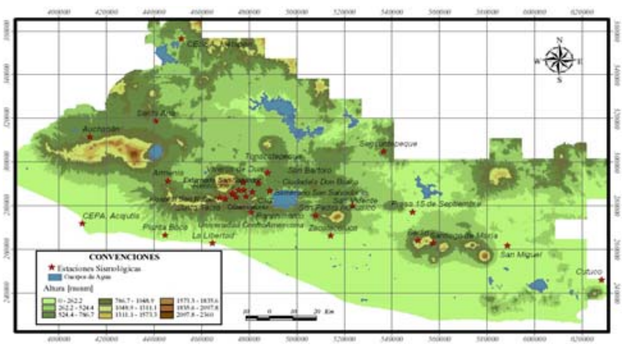

Figure 2. Topographic map of El Salvador. Stars represent the location of seismic station in the country.

Climatic conditions. Antecedent rainfall is important for establishing soil-moisture conditions conductive to rapid infiltration and build up of high pore water pressures during subsequent major storms. Prior to the development of positive pore water pressures, the infiltration of rainfall reduces intergranular capillary tension in unsaturated or partly saturated soils. The reduction of capillary tension and the increase of positive pore water pressure reduce soil strength and have been linked with triggering landslides and debris flows. The moisture also determines how much more water is required to bring a soil to saturation and, consequently, controls the magnitude of pore pressure generated during and following the storm. Figure 3 shows that rains are higher in the northern ridge and in the coastal mountains, this produces that northern ridge have been more affected by rainfall-induced landslides than the rest of the country.

Rainfall-induced landslides. Rainfall stimulates landslides by increasing the weight of soil mass and by reducing the strength. Intense rainfalls such as induced by hurricanes and tropical cyclones cause shallow and quick landslides on shallow residual and volcanic soils, even if the duration is short, while deep seated and slow landslides are stimulated by successive rainfalls. The significant period of antecedent rainfall varies from days to months depending on local site conditions, particularly soil permeability and thickness. In the case of high permeability soils, as volcanic deposits, the period of necessary antecedent rainfall may be extremely short or the amount of antecedent rainfall may be supplied by the early part of a storm. Major and more extensively distributed landslides caused by rainfalls have been produced during tropical storms and hurricanes common in the Caribbean Sea. Particularly, El Salvador has been strongly struck by Hurricane Mitch in 1998 and by Hurricane Stan in 2005.

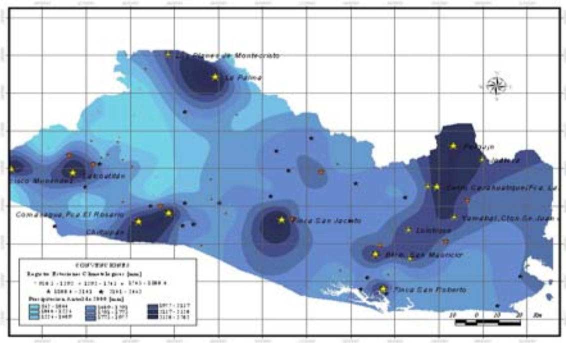

Figure 3. Climatic stations (stars) in El Salvador and annual rainfall distribution for year 2000. Spatial interpolation was done by using a Kriging approach.

Most of the rainfall-induced landslides in volcanic and residual soils in El Salvador are translational shallow movements of superficial unconsolidated materials, which become mud and earth flows that can travel very long distances, even kilometres. Landslides generally have a slip surface along the interface between volcanic soil and rocks. Slope failures begin as small block slides moving down along the slip surface until a topographic change stops its movement. Depending on the travel distance, during this step, high internal disruption of material can be induced. In some cases, high water content is enough to transform slide material into a mud or debris flow. Along channel banks, mud and debris flows produce intense lateral and bottom erosion inducing soil falls and slumps, as occurred along the Gualcho River (El Salvador) during the Hurricane Mitch Crone *et al*. (2001).

From the previous description it is apparent that shallow slides induced by rainfalls are structurally controlled by shallow soil/rock interface. If this condition does not exist, intensive erosion may dominate over landsliding. Thus, for landslides to be generated a flow barrier is necessary for pore water pressures to be increased and trigger slope failure. For this mechanism to be possible materials must already contain enough moisture to fill the capillarity porosity and neutralise the soil suctions in dry soils. This requirement implies that for short intense rains an important antecedent accumulative rainfall is necessary for landslides to be triggered, as was the case during the Hurricane Mitch. This condition concentrates the occurrence of rainfall-induced landslides in the middle of a rainy season, as reported by Crone *et al*. (2001) for cases induced during the Hurricane Mitch.

Deep traslational slides are generated by long rainfalls over deep volcanic weathered deposits. Volcanic soils due to brittleness behaviour used to show crack behind the slope crown, which promote soil falls especially in vertical artificial or natural cuts induced by water pressures behind the cracks. Along river banks, due to increase of water flow level erosion precedes soil falls. Shallow and deep slides becomes mudslides, earthflows or debris flows due to the high mobility that material acquire after desegregation especially when saturated although saturation is not a necessary condition. Rainfall is not the unique condition for flows to occur, it must exist sufficient unconsolidated material at the catchment basin.

Earthquake-induced landslides. During an earthquake mass movements may be induced by a combination of increased shear stresses and reduced in material strength due to the cyclic loads. However, landslides may also be seen along the surface expression of the fault rupture. For the former cases, inertial loads induced by the earthquake are the principal agent of slope instability, while others landslides are expressions of the fault rupture, or are generated by gravitational processes along rupture scarp instead of being triggered by seismic shaking.

For Central America, data compiled from literature review of earthquake-induced landslides were presented by Rodriguez (2006). There the main characteristics of these earthquakes and the distribution of areas affected by landslides they caused are presented. Although major concentration of landslides has been found to correlate with volcanic tuff distribution, there are other susceptible lithologies such as residual, lacustrine, deltaic and coastal deposits, which are spread around the country. Principal events which have induced landslides are the 1982 and the January 2001 subduction earthquakes and the 1986 and February 2001 volcanic chain earthquakes. Figure 4 shows the isoseismal map for February 2001 earthquake, regular almost concentric lines are due to these isoseimal lines do not consider local effects.

Rock falls and soil falls are one of the most common landslides during earthquakes; they originate on slopes steeper than 40º and come to rest on talus accumulation at the base of the slope on which they originate. Most individual rock falls triggered during historical earthquakes are very small in volume (Bommer and Rodriguez, 2002); Rodriguez, 2006). Individual rock block falls, during the January 2001 earthquake in El Salvador, were more common in the rocks of the El Bálsamo Formation because of the prevalence of persistent discontinuities in the form of bedding and cooling joints. Rockslides have also reported for the El Salvador 1986 and 2001 earthquakes; this kind of slide is also very frequent in weakly cemented rocks such as volcanic tuff. The occurrence of rock and debris falls in the Tierra Blanca deposit affected an extensive area around Comasagua Road on the El Bálsamo Ridge during the January 2001 earthquake in El Salvador.

Disrupted slides are probably the most dangerous events, during the January 2001 El Salvador two large slides also occurred which were the responsible for more than half the deaths during the earthquake: the Las Colinas and Las Barrioleras landslides. These slides, which occurred in young unconsolidated ash showed significant travel distances. The February 2001 earthquake triggered additional landslides to those reported in January. Along the Panamerican Highway new landslides were observed at Las Leonas and adjacent locations. On the slopes of the San Vicente volcano, disrupted slides were reported along the El Muerto and El Blanco creeks. El Blanco landslide mobilised silty and sandy gravels and blocks coming from pyroclastic flows (Rodriguez, 2006).

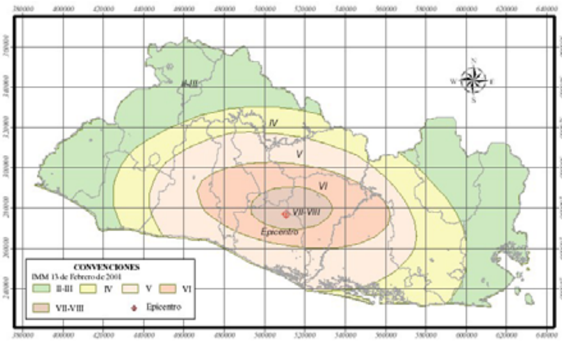

Figure 4. Isoseismal map for the February 2001 earthquake in El Salvador.

Rock slumps and large rock slide are less frequent but some have been reported during the 1854, 1986 and 2001 earthquakes in El Salvador. A large slump that blocked the course of the Rio El Desagüe was reported during the February 2001 earthquake; in this case a volume between 1 and 2 x 10^6 m^3 was mobilised, consisting of andesitic breccia blocks of around 0.5-2.0 m in diameter embedded into a Tierra Blanca matrix. Other large slides occurred in the water head part of the Rio Jiboa; it was estimated that the volume of sediments yielded by in this area was between 10 and 15 x 10^6 m^3.

Liquefaction was observed at various locations along the coast in central and eastern El Salvador during the January 2001 earthquake, accompanied by lateral spreading and consequent damage to some houses. Similar observations were made on the shores of Lake Ilopango, where lateral spreading was significant. The most serious effects of lateral spreading occurred on the banks of Lempa River at San Nicolás Lempa that resulted in collapse of a railway bridge.

Landslide hazard in El Salvador

In order to explore and analyse factors related to landslide hazard in El Salvador, the Mora and Vahrson (1994) and Rodriguez (2001) models were implemented in a GIS scheme and result were compared with landslide distribution during the January and February 2001 earthquakes.

Analysis was done by including seismic loads, rainfall conditions, lithology and topographical setting. In the case of seismic parameters, a numerical modelling for the S wave's propagation was implemented. Assessment of rainfall parameters was achieved by applying a geostatistic model based on the space structure of the local measurements using a Kriging approach. Lithology and topography were considered by using GIS models obtained from data supplied by the local government.

Mora and Varhson approach. A method for regional landslide hazard assessment, considering simultaneously earthquake and rainfall events, has been developed in Costa Rica by Mora and Vahrson (1994). This method considers the landslide hazard as the product of the a susceptibility function times a triggering function. Susceptibility is defined by in situ slope features as relative relief, lithology and soil humidity. Triggering function considers the effect of rainfalls and earthquakes. Applicability of the method was discussed by Bommer and Rodríguez (2002), and application to El Salvador analysed by Rodríguez (2006). In this case isoseismal maps are used for considering earthquake effects. Figure 5 shows result of the model compared with landslide distribution during the January and February 2001 earthquakes. Figure shows that this model underestimates the hazard level mainly due to the low weighting value given to moderate rainfalls.

Rodriguez approach. This model also combines a susceptibility and a triggering function, in this case both functions are used to define a hazard space, in which each susceptibility and triggering function are divided into different levels according to the frequency of historical cases. In this case levels were defined based on values of susceptibility and triggering containing 15%, 30%, 45%, 60% and 75% of the slides induced during the January and February 2001 earthquakes. Susceptibility function considers lithology, slope angle and precedent rainfall conditions, whereas a strong motion parameter, in this case Peak Ground Acceleration, is used to define the trigger. Based on statistical analysis of correspondence of historical cases, weighting values are given to each variable. Details of the method and applicability can be found in Rodriguez (2006). In this case seismic wave's propagation was modelled and acceleration values obtained for each slope including topographic and geology effects. Figure 6 shows the result of the model and the distribution of landslides induced during the 2001 earthquakes. This figure shows that this model describes in a better way the landslides hazard, however in some areas the hazard is overestimated due to the way as weighting factors for lithology shades the influence of topography, this suggests that assignment of weighting values in the model must be reviewed implementing a multivariate correspondence analysis instead of the bivariate model used so far.

Conclusions

Earthquake- and rainfall-induced landslides in El Salvador start mainly as disrupted slides and falls in residual, alluvial, volcanic-ash, and volcanic-rock deposits. When the intensity of the triggering events is sufficient to induce large displacements or the soils are sufficiently contractive, landslides can transform into debris flows that travel long distances. As a result initially small, isolated events can have consequences that reach far beyond their immediate source area. Spatial distribution of these slides is controlled by topographic, climatic and seismicity distribution around the country.

Temporal occurrence is controlled by the rainfalls and earthquakes sequences, precedent rainfalls, particularly shows a strong influence on intensity of rainfall or seismic events able to induce failures. This spatial and temporal variability can be considered in landslide hazard analysis by taken models which include local and regional conditions as those proposed by Mora and Vahrson, however care must be taken when applying this model which was developed under different conditions than those present in El Salvador. The Rodriguez model shows better result in defining spatial distribution of landslide hazard however important improvements are needed in order to improve predictions, particularly weighting values for different variables must be review in order to avoid overestimation on gentle slope of susceptible soils.

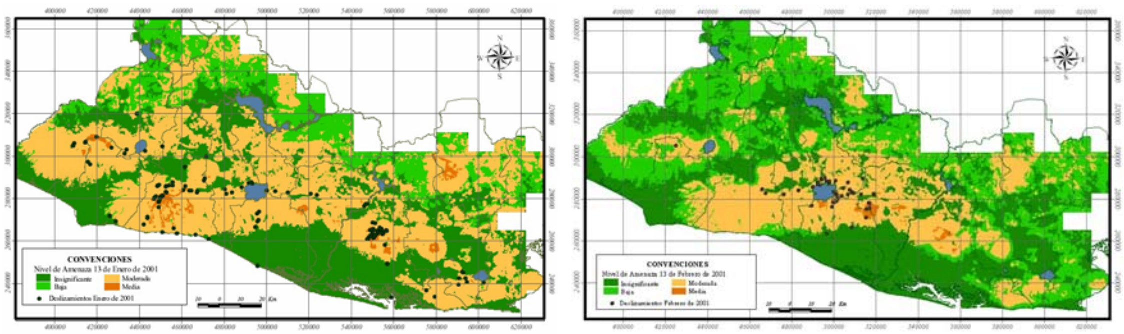

Figure 5. Hazard maps for the January (left) and February (right) 2001 earthquake scenarios based on Mora and Vahrson approach. Black points are landslides induced during these events.

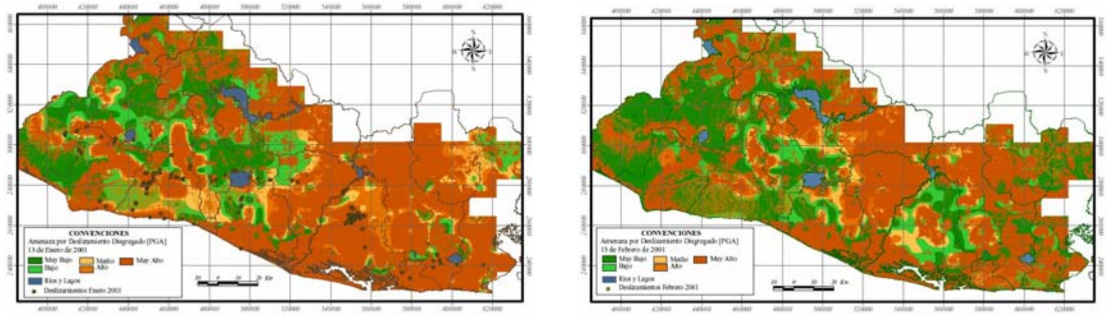

Figure 6. Hazard maps for the January (left) and February (right) 2001 earthquake scenarios based on the Rodriguez approach. Black points are landslides induced during these events.

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