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LAS COLINAS LANDSLIDE CAUSED BY THE JANUARY 13, 2001 OFF THE COAST OF EL SALVADOR EARTHQUAKE

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ABSTRACT: El Salvador was struck by two devastating earthquakes within a month. The first quake of Jan. 13, 2001, which was centered off El Salvador's southern coast, damaged and/or destroyed nearly 108,000 houses, and killed at least 944 people, including hundreds of residents buried in a huge amount of soil slipped down Las Colinas mountainside in the city of Neuva San Salvador (Santa Tecla). This report outlines the findings obtained through the reconnaissance by the JSCE team and laboratory tests that followed it.

Key Words: El Salvador earthquake, landslide, pumice

INTRODUCTION

Nearly 800 volcanoes are active today or known to have been active in historical times. Of these, more than 75 percent are found in the Pacific Ring of Fire, the belt, partly coinciding with the young mountain ranges of western North and South America, and the volcanic island arcs fringing the north and western sides of the Pacific basin, includes Japan, Peru and El Salvador. The locations of the great majority of earthquakes also correspond to this belt. In these countries, landslides and debris flows are serious threats because of their extremely large travel distances. In the 1970 Peru Earthquake, for example, the huge soil mass of a couple of tens million m^3 was initiated at the top of the Mt. Huascaran (6,700m EL), and ran about 4 km down to Yungay killing more than 20,000 people.

El Salvador, one of the smallest and most crowded nations in Central America, extends about 240 kilometers westward from the Gulf of Fonseca to the border with Guatemala. This country was struck by two devastating earthquakes within a month. The first quake of Jan. 13, 2001, which was centered off El Salvador's southern coast, damaged and/or destroyed nearly 108,000 houses, and killed at least 944 people. One of the most spectacular aspects featuring heavily in the January 13 earthquake was the damage inflicted by landslides. Among them, Las Colinas landslide was the most tragic. A huge amount of soil mass (about 200,000 m^3) was thrown off the rim of a mountain ridge rising south behind Las Colinas area of Nueva San Salvador (Santa Tecla), and flushed many houses and therefore more than 500 lives to death. This report outlines some important features of this landslide and discusses possible measures for reducing preventive loss of human lives and social disruptions.

OVERVIEW OF LAS COLINAS LANDSLIDE

A mountain ridge called El Balsamo rises south behind the city, and the slope failure took place in its northern side (**Fig. 1**). Other small landslides and cracks are also found along the mountain ridge. Just behind the top scar is a flat area slightly slanting southwards, and there were two unfinished brick houses, which were supposed to become a school. A coffee plantation spreads along the ridge keeping the soil moistened in places.

Fig. 1. Bird's eyes view of the Las Colinas landslide

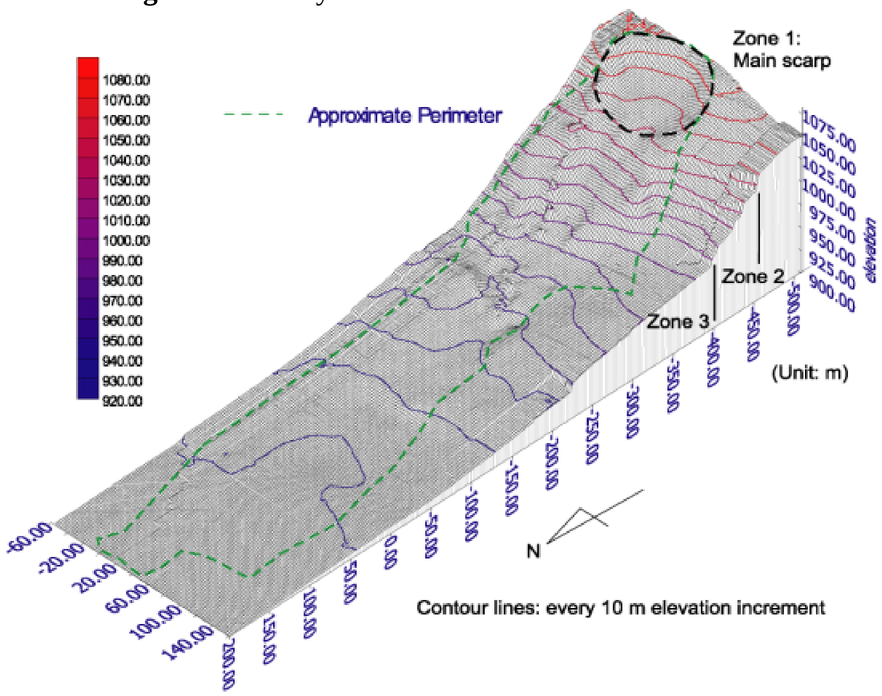


Fig. 2. Surveyed Slope plotted with surfer with green dashed perimeter.

The Las Colinas sliding surface was surveyed with a laser based theodolite (Laser Ace 300), connected to a portable computer. The theodolite has a built-in digital compass, and with its laser beam, it calculates the azimuth, dip angle, and horizontal distance to a point. The exposed failure surface can be roughly divided into three zones (**Fig. 2**). The uppermost zone (**Zone 1**) is a hollow of about 100m in diameter, which was caved in some 20-30 m from the original ground surface. South beyond the hollow, there appears a steepest slope (**Zone 2**), which becomes gradually gentle as it comes close to the toe. In **Zone 3**, the slid soil mass and flushed houses had been removed already, and the cleared area was totally white with disinfectant (**see Fig. 1**).

DETAILED FEATURES OF THE SLOPE

Uppermost main scarp (Zone 1)

Two photos (**Fig. 3**) of the same soil layers appearing on the west half of the uppermost scar were taken on January 14 and February 4, respectively. Dark and blight colored stripes appearing on the scarp shows a stratified soil profile with the top lapilli tuff layer of about 2.0 m thickness overlying a pair of two differently colored (ocher and white) pumice layers of about 11.9m thickness. Some bedding planes separate the lapilli tuff into some sub-layers of varying thickness (10cm to 25cm). Dark brown color of soil indicates that the soil is moistened, and this pair of photos shows that the dark colored stripes were steadily thinning, in other words, exposed soils were drying. This fact may evidence that the intact soils along the slip surface were wet before the event. Beneath the dark and wet soils, there appear white and/or ocher colored pumice soils. They were also moistened and weakly cemented. The pumice is easily broken into small pieces or into powder just by rubbing together with fingers. Broken fragments of this pumice have sub-angular or angular shapes. Some pieces were medium-sized (1 mm × 4 mm × 7 mm for example) and some were fairly large reaching 12 mm × 25 mm × 35 mm (**Fig. 4**). As shown in **Fig. 5**, cracks and joints were observed even on an intact part of pumice.

(a) January 14
Photo. by Mr. Jose Antonio Rivas

(b) February 4

Fig. 3. West slope of main scarp

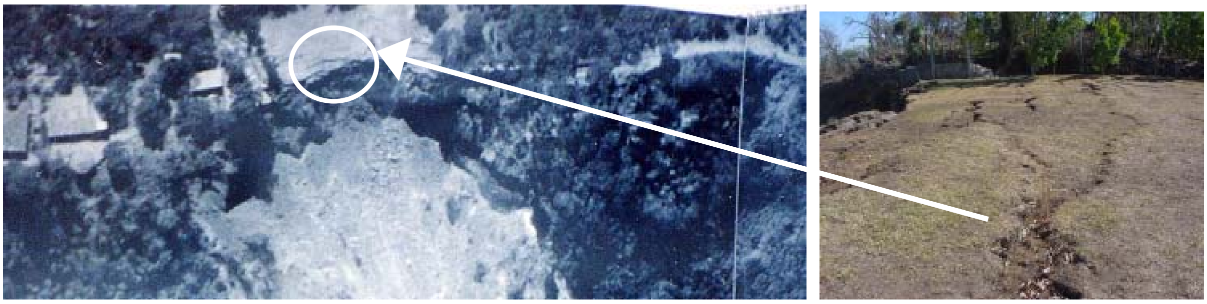
Fig. 4 A piece of lapilli tuff

Fig. 5. Cracks and joints on the exposed intact pumice

Table 1 Crack openings along Line **A-A'** in **Fig. 6** (see next page)

No.	Distance from A (cm)	Vertical offset (cm)	Opening (cm)	Cumulative opening (cm)	Depth (cm)
1	180-240	10	60	60	122
2	390-410	7	20	80	65
3	460-471	5	11	91	60
4	580-581	0	1	92	20
5	590-593	0	3	95	20
6	780-782	0	2	97	20
7	833-834	0	1	98	20
8	1215-1217	0	2	100	30
9	500-1502	0	2	102	20
10	1525-1535	0	10	112	20
11	1841-1859	0	8	120	50
12	2234-2249	0	5	125	20

Total 43 points were marked along the perimeter of the scar using a GPS receiver (**Fig. 6, next page**). Behind the scar, there were extensive cracks running in almost west-east (See **photos in Fig. 6**). Crack openings (12 visible cracks; **Table 3.2.1** and **Figure 6**) were measured along Line **A-A'**. Total 1.25 m's opening was reached over the 22 m's distance of Line **A-A'**. Namely, about 5% average strain was induced within the soil behind the scar. Extensive cracks were found along the ridge crest even in areas that did not slide (see **Fig. 14**); the cracks can certainly cause further slides.



Cracks appearing on the top terrace behind the scar (**Zone 1**): Cracks map is shown below.

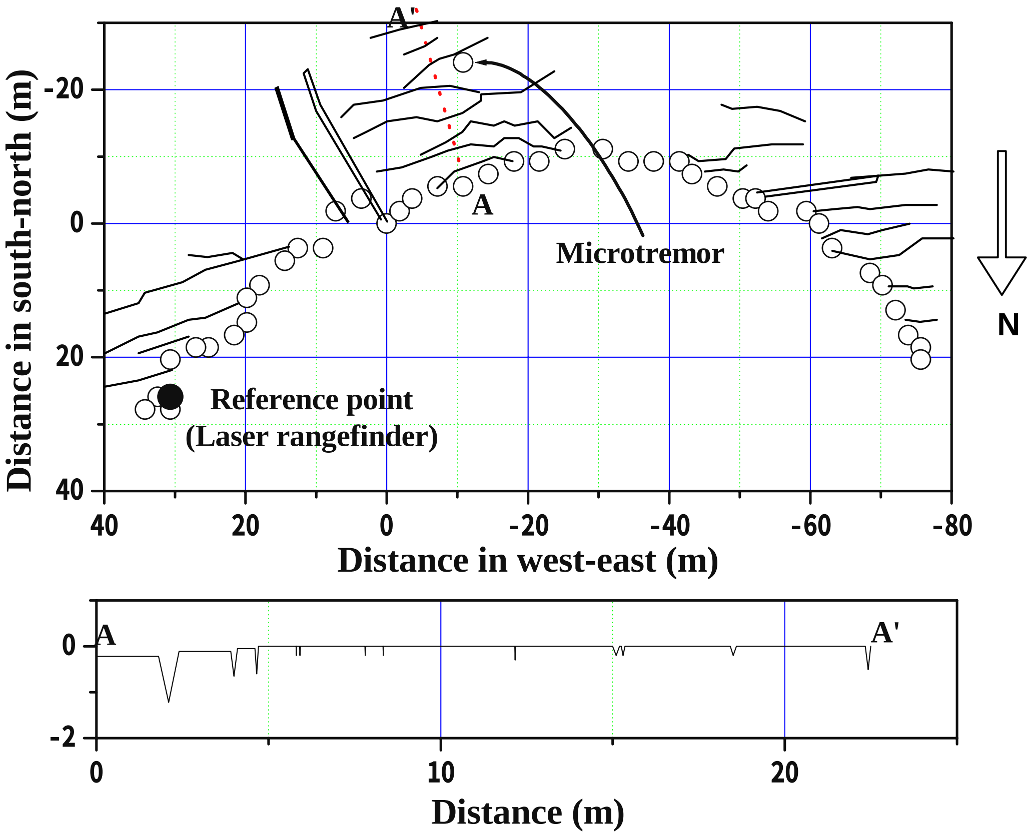


Fig. 6. Perimeter of scar, Las Colinas Landslide

Fig. 7. Crack at the top terrace (photographed on Jan. 14 by Mr. Jose Antonio Rivas)

A pair of photos (**Fig. 7** by Jose Antonio Riva, Geotérmica Salvadoreña) was taken on January 14, a day after the earthquake. Both pictures show that edges of cracks were lightly dusted with fine sand. This fact may evidence that the landslide caused some soils to liquefy though the underground water level did not seem to be substantially high from the field observation. There was no written material available showing the possible underground water level.

There are some downward streaks remaining on the bottom of the uppper hollow (arrow in **Fig. 8**), and broken pieces of a mortar-block fence were caught on the soil mass remaining on the outer edge of the hollow (arrow in **Fig. 9**). These may evidence that most soil mass, which originally fitted into the hollow, seems to have been pushed forward, and flown down the lower steep slope. Along the streaks, a number of broken pieces of lapilli tuff and some uprooted trees were found. The largest piece of the lapilli tuff remaining there was 88 cm×64 cm×14 cm.

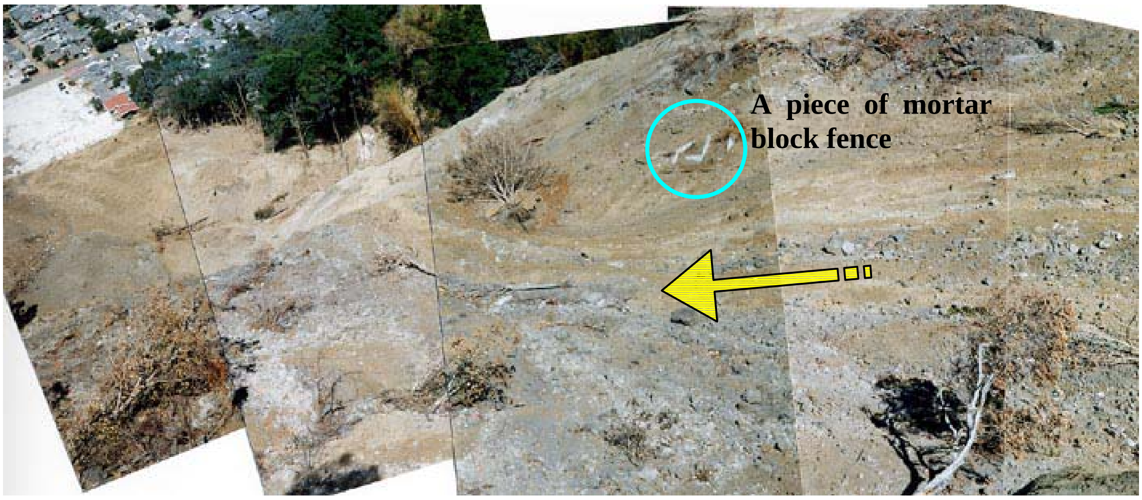


Fig. 8. Lower part of the hollow: A piece of mortar block fence (within the circle) is caught on the small amount of the soil mass stopped at the lower edge of the hollow.

Fig. 9. Fallen block fence

Steep slope in the middle (Zone 2)

Fig. 10 shows the lapilli tuff exposed on the lower steep slope (**Zone 2**). This surface exhibits an arrangement of volcanic products in strata of varying thickness (7 to 30 cm) and about general 10 degrees dip toward the toe of the slope.

As shown in **Fig. 11**, the steepest slope in **Zone 2** was covered thin with a film of mud including porous fragments of pumice; the film was noticeably stiff after totally dried up. The film covered trees, bamboo and other plants pushed down on the slope. This fact suggests that the original slope in **Zone 2** was not scraped off, and is consistent with the result from the 3D survey of the slope configuration. This fact also suggests that the bottom surface of the slid soil mass was wet, and may have liquefied (Sassa, 2000), possibly related to some weak tephra layers spreading over less permeable paleosols.

Fig. 10. Steep slope (**Zone 2**)

Fig. 11. Thin mud film

Gentle toe slope leading to the flushed residential area (Zone 3)

The slid soil mass seems to have surged across a small ravine coming down from east mountainside, and splashed up a small bank. Some splashes were remaining 6-8 m high on some tree trunks on this bank (**Fig. 12**). The huge amount of slid soil mass flooded many houses and thus caused more than 500 deaths. A complete view of Zone 3 was taken from the toe of the exposed slip surface (**Fig. 13a**). The slid soil mass and destroyed houses had been removed, and the cleared area was totally white with disinfectant.

There were many splashes of mud remaining on house walls, trees and etc. In general, the splashes seem to be higher at around the toe of the slope than those in the middle or close to the distal end of the soil deposition zone. The highest splash of about 8 m was found on a trunk near the toe. **Fig. 13b** shows the walls of a dwelling on the eastside perimeter of the slid soil mass, the wall spotting in parabola with mud splashes. The parabola with its peak of about 4.5m high drops downward, and reaches the ground after about a 5m horizontal run. This fact suggests that the time *t* needed for the splashes to reach the ground from their peak height Δh (= 4.5 m) was about 1s ($\Delta h = g \cdot t^2 / 2$), and during this time, the splashes ran about the 5m horizontal distance (5 m/s). The main stream of the soil mass flow might have faster than this speed after running through dwellings standing close together.

Fig. 12. Photos from the toe of the slope

(a) Complete view of **Zone 3** (Feb. 4, 2001)

(b) House wall spotting with splashes

Fig. 13. Photos from **Zone 3**

SOIL TESTS

In-situ test

In order to sound the strength of the soils in Las Colinas Mountain, portable cone penetration tests (Japan Geotechnical Society, 1995) were performed at three points along the mountain ridge. Among them, Point C1 is located slightly west off the main scarp (see **Figure 14**).

Variations with depth of the equivalent Ns-values at the three points are shown in **Figure 15**. As contrasted with other points, all equivalent Ns-values at Point C1 are considerably low as a whole. Among them, extremely low values reaching zero were found at about 1.2m and 2.5m depths. These two small Ns values suggest the presence of two weak layers, which can be the pumice and/or fragmental volcanic products judging from their depths.

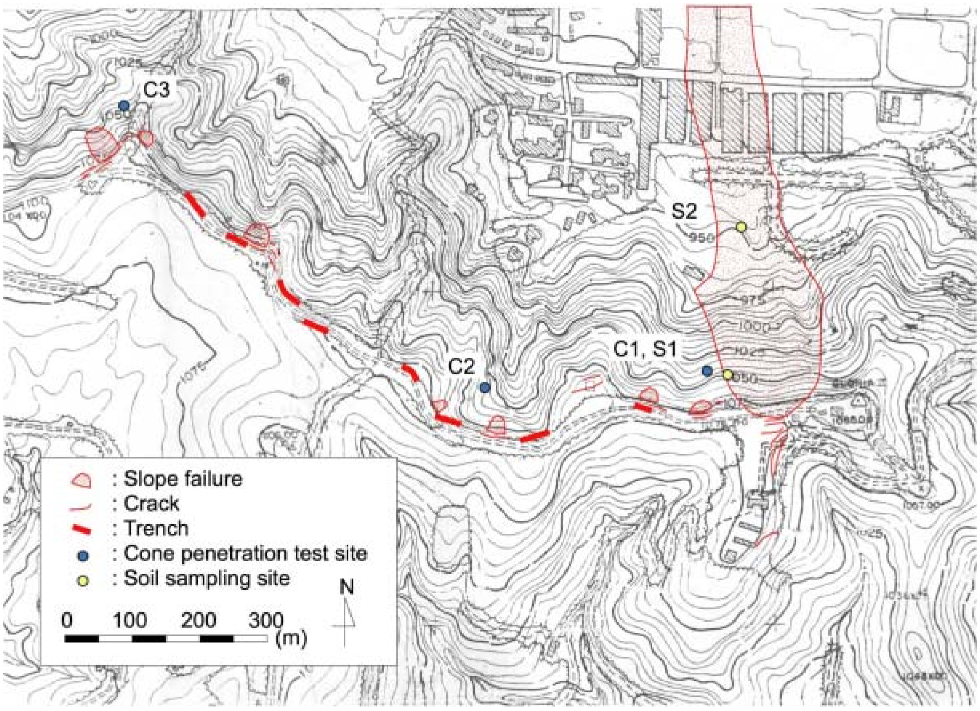


Fig. 14. In-situ tests and sampling sites in Las Colinas (Topography: Ministerio de Obras Públicas, 1970)

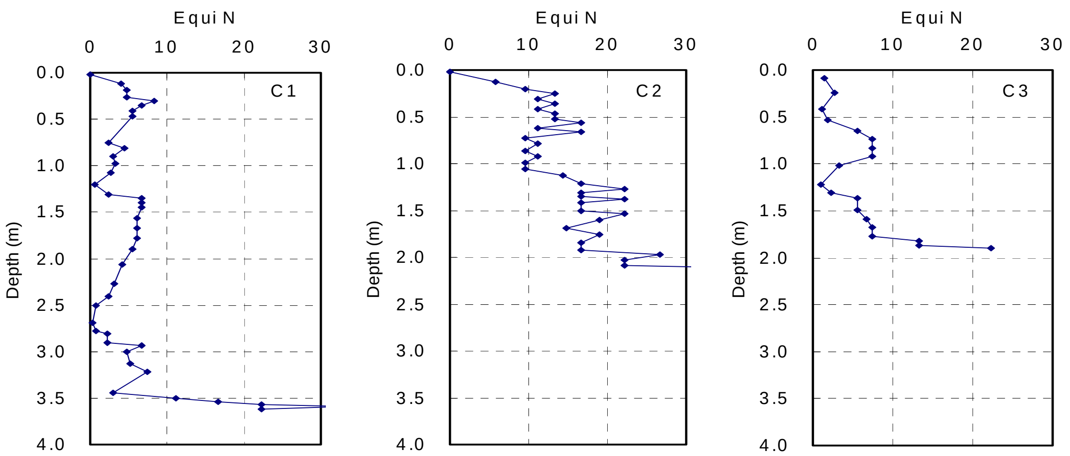


Fig. 15. Equivalent Ns-values at three sites: *Ns*= *Nd*/1.5, where *Nd* is the number of blows when the penetration depth of 10 cm is reached.

Ring shear test

(2) Ring shear apparatus

The undrained ring shear apparatus (DPRI-5: **Fig. 16**) was used to examine dynamic characteristics of the pumice in rapid shear (Sassa, 1998). Outer and inner diameters of the cylindrical shear box are 120 and 80 mm, respectively. The maximum shearing velocity of 10 cm/sec is realized within this box.

The concept of ring shear landslide simulation test is illustrated in **Fig. 17** (Sassa, 2000). Shear/normal stresses along a sliding surface in place are realized in the interior of the shear box, and necessary physical quantities of the soil sample in shear (resistance, pore water pressure, shearing velocity and accordingly the mobilized apparent friction angle) are monitored in real time. An upright cross-section of the shear box with the pore pressure measuring system built in is shown in **Fig. 18** (See Sassa (1998 and 2000) for further details).

Table 2 Mechanical properties of the sample

Sample	**Pumice**
Mean grain size, D_{50} (mm)	0.91
Effective grain size, D_{10} (mm)	0.25
Uniformity coefficient, U_c	5.0
Specific gravity, G_s	2.28

Fig. 16. Ring shear apparatus

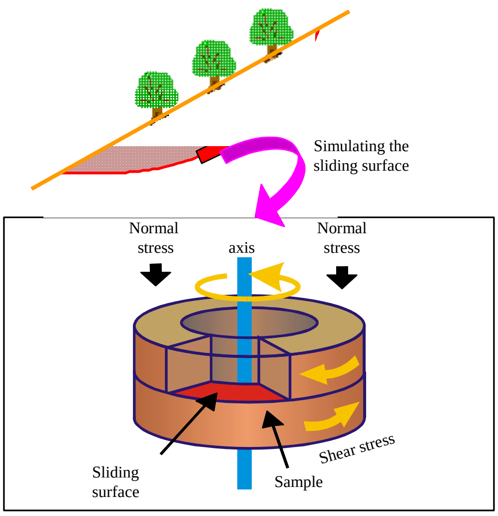


Fig.17 Concept of ring shear landslide simulation test (Sassa, 2000)

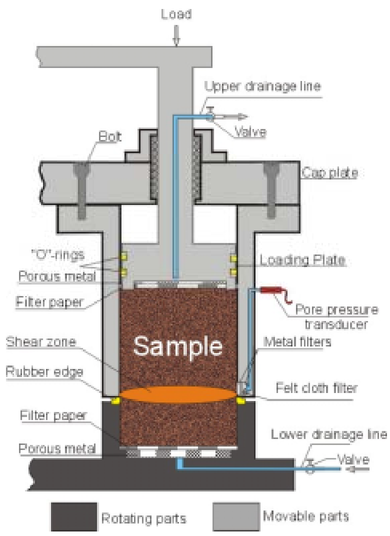
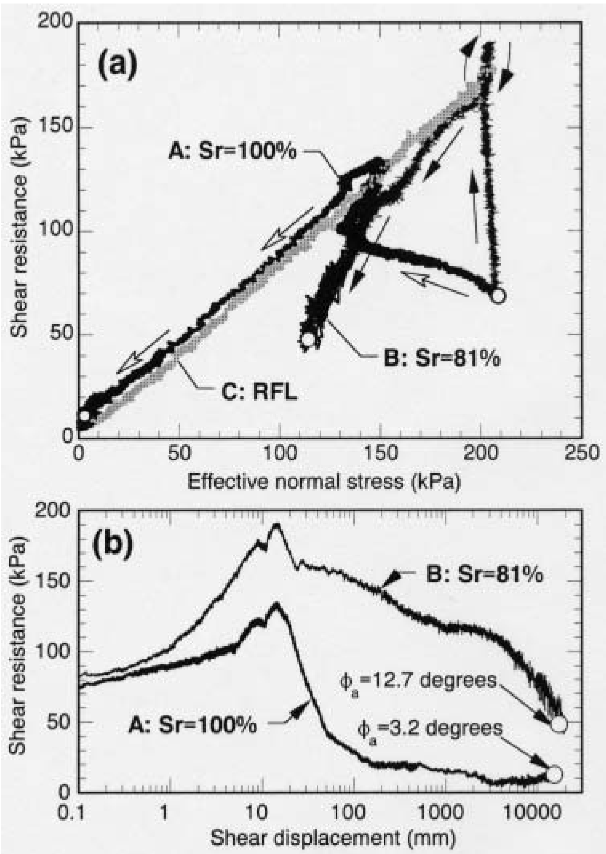


Fig.18. Cross-section (right half) of undrained ring shear box (Sassa, 2000)

Two ring shear tests were performed to examine the liquefaction possibility of the landslide soils with the mechanical properties listed in **Table 2**. Samples of pumice with different saturation degrees were prepared, and normally consolidated under the stress state corresponding to a slope of 20° inclination. Shearing stresses were subsequently applied to the undrained samples after the consolidation at a loading rate of 0.098 kPa/s for both loading and unloading processes. The sample was twisted off and began rotating when the stress state reached the failure line. Shearing was continued until 15-20 m displacement was reached.

Fig. 19a shows the effective stress paths for the performed two tests (arrow signs with open triangle heads for **TEST A** and solid ones for **TEST B**). As soon as the shearing of the sample started in **TEST A (Sr=100%)**, there appeared an excessive pore pressure buildup, which was then followed by dilation of the pumice. When the residual failure line (RFL) was reached, a sudden decrease of apparent friction angle along the RFL was observed. The drop of the shear resistance is also plotted in **Fig. 19b** with respect to the increasing shear displacement. When the twisted pumice sample had slipped 20m distance, the apparent friction angle of about 3.2 degrees was reached, the fact suggesting that a sliding-surface liquefaction occurred in the saturated soil sample (Sassa, 1996). The average slope gradient, however, was measured to be about 13 degrees over the entire travel distance, much higher than 3.2 degrees reached in **TEST A**.

For this reason, **TEST B** was carried out for smaller value of Sr **(Sr =81%)**. In this test, the stress path went almost straight up until the RFL was reached (**Figure 19a**), and then the apparent friction angle began dropping along RFL. The path, however, deviated from the RFL as it went further down, presumably because the sensor did not keep a good track of pore pressure of the unsaturated pumice sample. Finally the apparent friction angle of 12.7 degrees was reached, the angle closer to the slope gradient; the result indicates that the soil in situ was not completely saturated.



(a) Effective stress path

The RFL (**C** line**)** was obtained after **TEST A** by the following procedure: (1) The drainage valve on the top of the shear box was opened, and the pore pressure built up in the specimen was released. (2) Normal stress was then gradually decreased at a constant rate of 0.2 kPa/sec to zero keeping the constant shearing speed of 0.2 mm/sec.

(b) Shear strength vs. shear displacement

Fig. 19. Ring shear test results

MICROTREMOR MEASUREMENT

Microtremors were measured at both the top terrace behind the uppermost scar of the Las Colinas landslide (El Balsamo ridge: **Figs. 1** and **2**) and its toe.

Fourier Spectra of three components of the tremor as well as the H/V ratios are shown in **Figs 20** and **21**. Thin (blue) lines correspond to four separate windows of 40.96sec opening and the thick (red) lines show the averages. At the top of the ridge, two peaks at 0.6 and 1.1Hz (on the H/V diagram) are distinguished for the EW and NS components, while 0.75Hz component in NS direction is predominant at the toe, and no clear peak is observed for the EW component there.

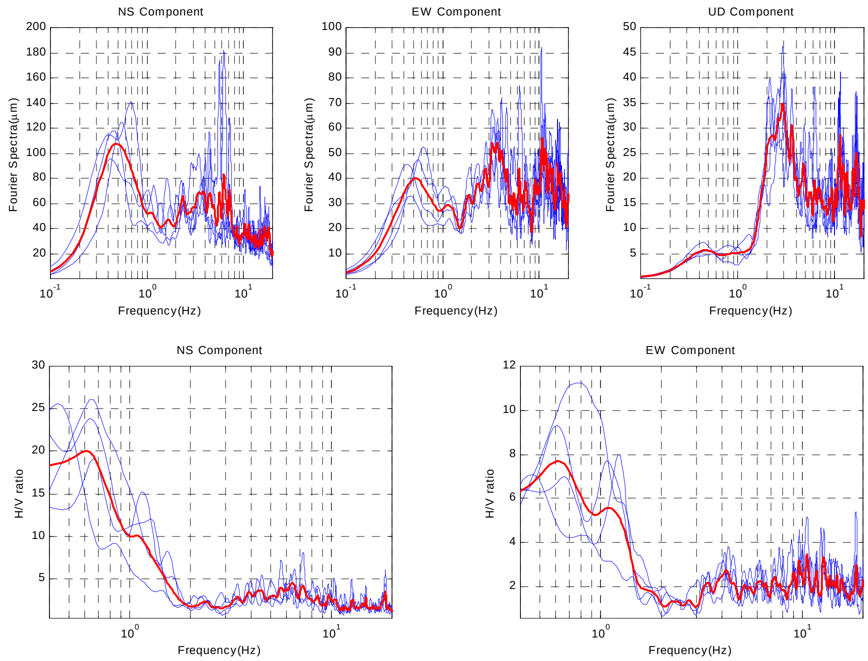


Fig. 20. Fourier spectra of microtremors at the top of El Balsamo ridge

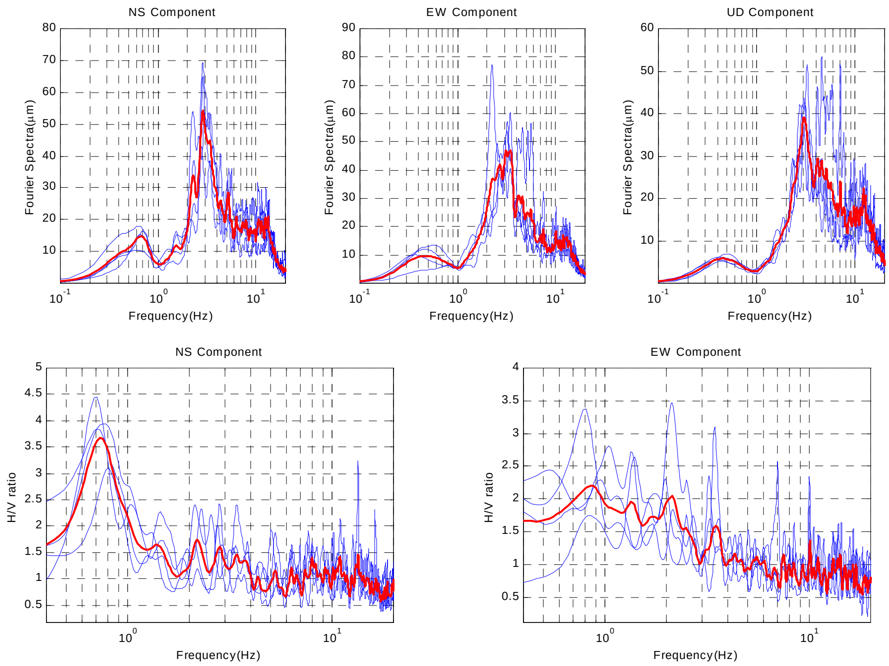


Fig. 21. Fourier spectra of microtremors at the toe of El Balsamo ridge

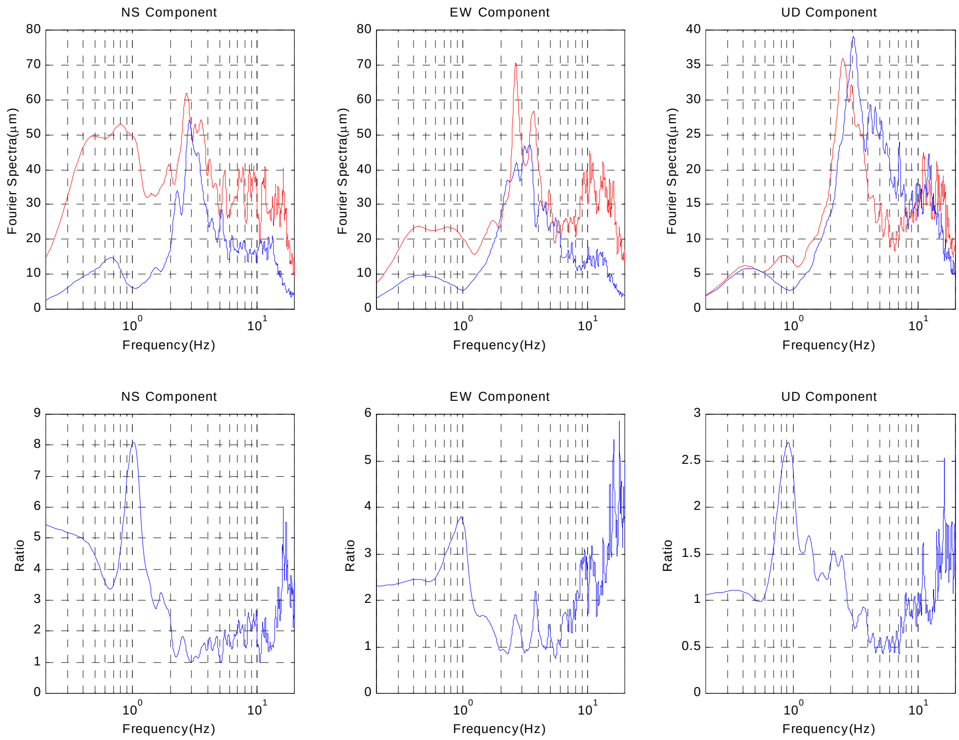


Fig. 22. Ratios of Fourier Spectra (top of the ridge / toe of the ridge)

In order to evaluate the topographical effect at Santa Tecla, the microtremors at the top and toe of the El Balsamo ridge were compared. The Fourier Spectra of the three components at the top of the ridge were divided by the corresponding components at the toe. The results are shown in **Fig. 22**. The three upper graphs depict the average of the Fourier Spectra at the top (red) and the toe (blue) of the ridge, respectively. The three lower graphs show the ratios of the Fourier Spectra (top of the ridge /toe of the ridge). The spectral ratios of all NS, EW and even UD components show clear peaks equally at around 1Hz, and the peak is the highest in NS direction, the direction normal to the rim of the ridge, probably reflecting the topographical effect.

SUMMARY AND RECOMMENDATIONS

The January 13 Earthquake triggered total 445 landslides in El Salvador, and they were mostly initiated from volcanoes and/or thick sediments of volcanic products. Among them, the Las Colinas Landslide was the most tragic. A large amount of soil mass (about 200,000 m^3) was thrown off the rim of a mountain ridge rising south behind Las Colinas area of Nueva San Salvador. This amount of soil is not surprisingly large as contrasted with the huge soil mass of a couple of tens million m^3, which was initiated at the top of the Mt. Huascaran (6,700m EL), and ran about 4 km down to Yungay town killing more than 20,000 people (1970 Peru Earthquake). The Las Colinas landslide, however, was substantially large in terms of damage because the slid soil mass surged across a residential district of Las Colinas, and flushed many houses and thus more than 500 lives to death.

Extensive cracks remaining along El Balsamo ridge are certainly the serious threat of further slides The city of Santa Tecla was controlling the potential hazard zones, the red zone with the highest risk and the yellow zone of slightly less danger. A week after the earthquake, the number of residents evacuated from the zones exposed to the menace of possible landslides reached 14,000, and as of Feb. 3, about 4,000 refugees were still being forced to live in tents. Since the rainy season starts in April or May, necessary countermeasures should be taken because even flat-lying areas away from sudden changes in slope angle may be still within the possible reach of the soil mass.

Landslides range in size from small movements of loose debris to massive collapse of the entire summit or sides of thick sediment of volcanic products. For small to medium slopes, the following measures will be effective.

Short-term measures:
(1) Crack maps
(2) Stopping water to permeate soils through cracks
(3) Continuous monitoring of crack openings

Full measures:
(1) Removing remaining soil masses
(2) Preventive and/or drainage works
(3) Anchoring
(4) Reinforcing with concrete crib arrangement
(5) Piles

As for extremely large slope failures, however, it is very difficult to stop them. It is therefore strongly recommended to develop and enforce land-use building ordinances that regulate constructions in areas susceptible to landslides and debris flows. For this, it is necessary to study basic features of such volcanic products as pumice and tuff. This information will allow us not only to simulate the possible travel distance and the velocity of a soil mass, but also to set up an alarm system.

"Training Trainers Program" will be also effective. If local people and/or officers are familiar with the land around them, they will be able to catch an early signs of a landslide. The ring shear test of the water-saturated pumice soil in this paper clearly shows that the apparent friction angle can drop down even to a few degrees after slipping some distance. This indicates that the soil deposit is particularly susceptible to landslides during intense rainfall. Any changes in patterns of water drainage should be watched; the early signs include steadily developing cracks, some fragments of rocks coming off, or progressively tilting trees – all necessary pieces of information for the local people and authorities to be prepared for a possible evacuation.

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Lastly, all the members of the JSCE Reconnaissance Team would like to express hereby their sincere sympathy to the people affected by the two devastating earthquakes in El Salvador, and they wish to further collaborate with Salvadorian specialists for possible countermeasures, e.g., reconstruction of damaged structures, retrofitting of existing structures and reducing landslide hazards.

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