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

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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, 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*

1. INTRODUCTION

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 the basic features of this landslide.

2. OUTLINE OF SLOPE FAILURE

A mountain ridge rises south behind the city, and the slope failure took place in its northern side (**Figure 1**). Just behind the top scar is a flat area slightly slanting southwards. A coffee plantation spreads along the ridge.

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 (**Figure 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 Figure 1**).

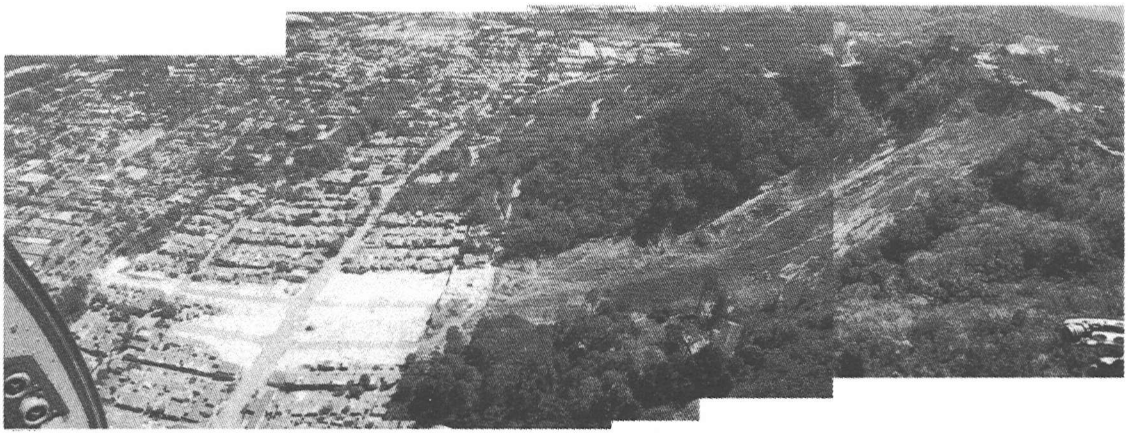

Figure 1 A bird's eyes view of the Las Colinas landslide from a helicopter

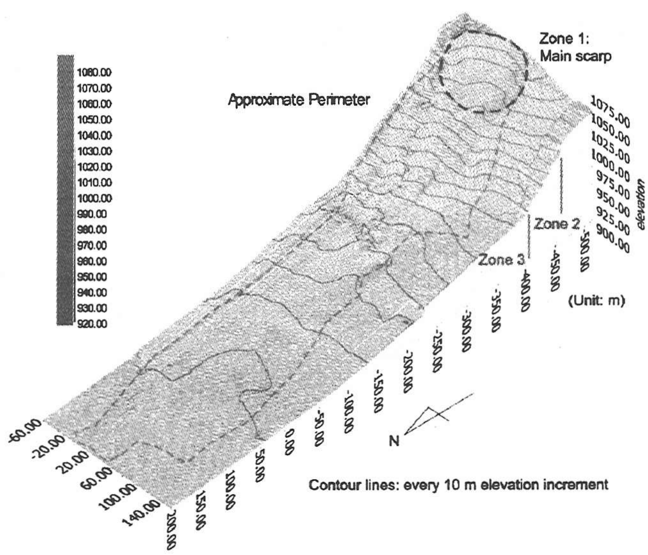

Figure 2 Exposed slip surface surveyed by using a laser based theodolite

Figure 3a West scar, January 14

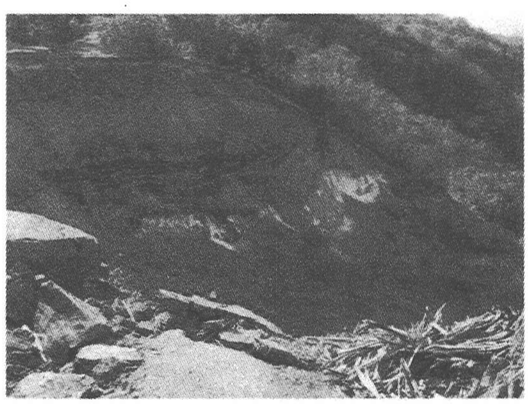

Figure 3b West scar, February 4

3. DETAILED FEATURES OF THE SLOPE

(1) Zone 1

Figures 3a and **3b** show the same soil layers appearing on the west half of the scar photographed on January 14 and February 4, respectively. Differently colored stripes appearing on the scar show a stratified soil profile with the top lapilli tuff layer (dark bluish gray) of about 2.0 m thickness overlying a pair of two differently colored (white and ocher) pumice layers of about 11.9m thickness. Dark colors of the top lapilli tuff layer 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.

Total 43 points were marked along the perimeter of the scar using a GPS receiver **(Figure 4)**. Behind the scar, there were extensive cracks running in almost west-east **(middle in Figure 4)**. Crack openings (12 visible cracks, **bottom of Figure 4)** 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; the cracks are certainly the threat of further slides.

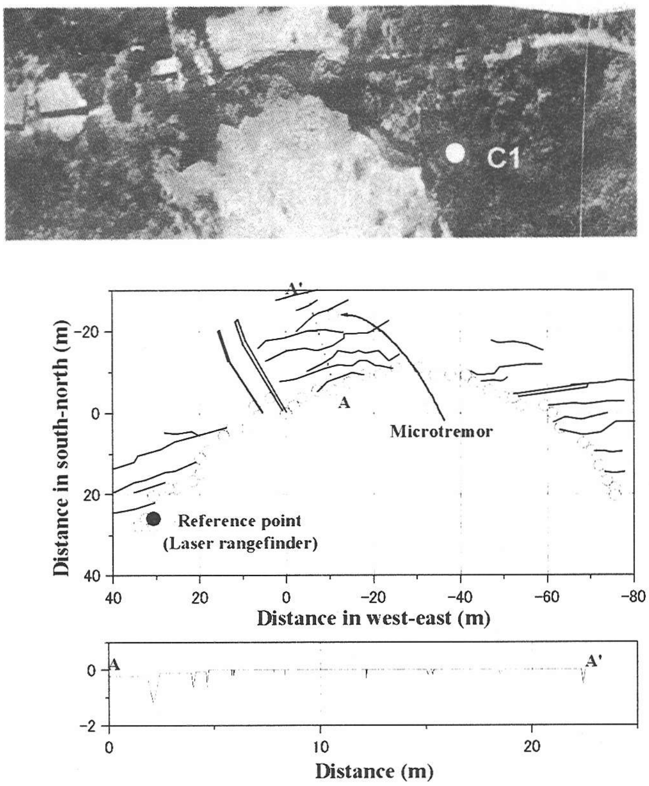

Figure 4. Perimeter of scar, Las Colinas Landslide

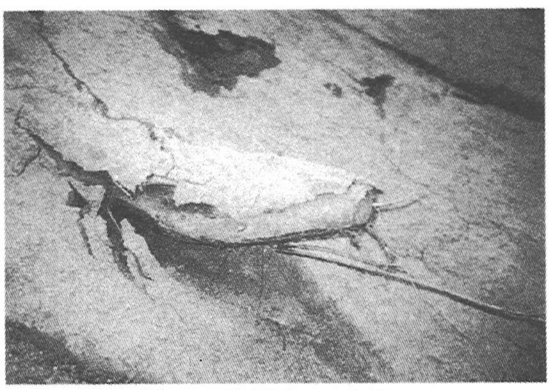

Figure 5 Thin mud film

(2) Zone 2

As shown in **Figure 5**, the steepest slope in zone 2 was covered thin with a film of mud including porous fragments of pumice; the film is noticeably stiff after totally dried up. The film covered trees, bamboo and other plants mowed 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 been liquefied (Sassa, 2000), possibly related to some weak tephra layers spreading over less permeable paleosols.

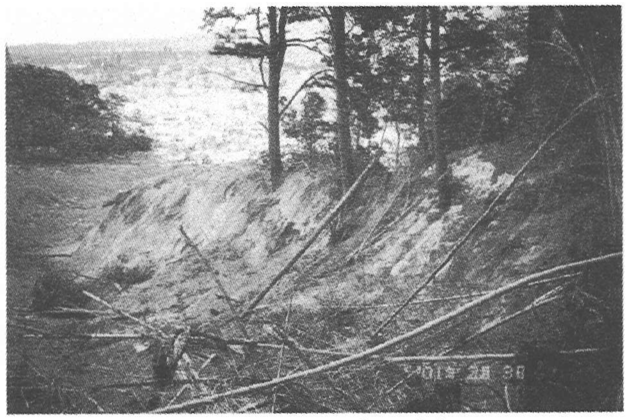

Figure 6 Trace of mud flow

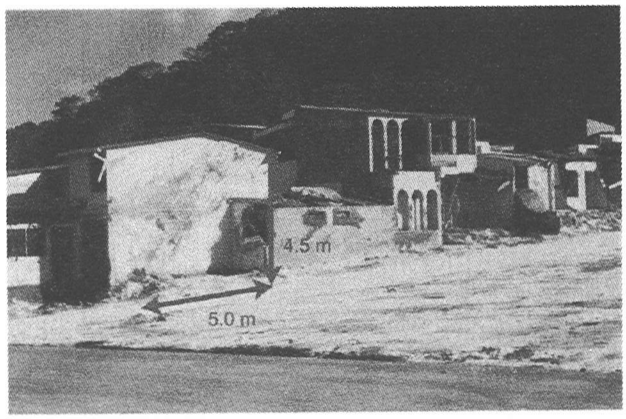

Figure 7 House wall spotting with splashes

(3) 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 (**Figure 6**).

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. There was water stopped on a pavement. **Figure 7** 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 even after running through dwellings standing close together.

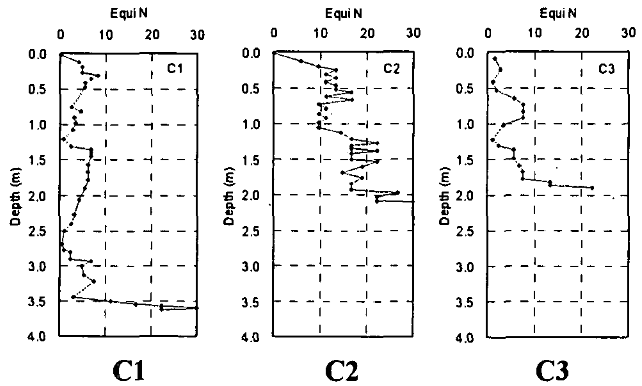

Figure 8 Equivalent Ns-values for three sites

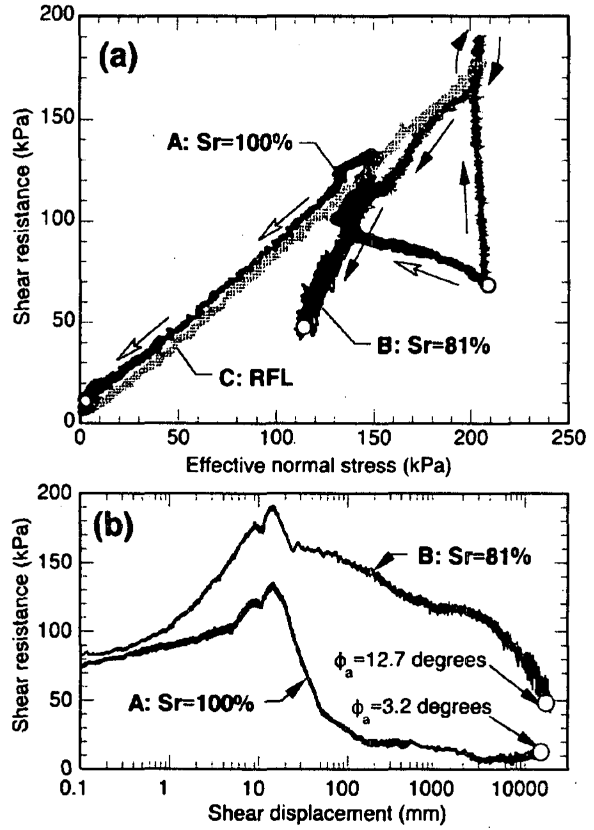

Figure 9 Ring shear test results

4. SOIL TESTS AND DISCUSSIONS

(1) 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 4**).

Variations with depth of the equivalent Ns-values at the three points are shown in **Figure 8**. 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.

(2) Ring shear test

Two ring shear tests were performed to examine the liquefaction possibility of the landslide soils. 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 at a loading rate of 0.098 kPa/sec after the consolidation. 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.

Figure 9a shows the effective stress paths for the performed two tests (**A** and **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, which was obtained from a drained speed control test, **TESTC**, was reached, a sudden decrease of apparent friction angle along the RFL was observed. The drop of the shear resistance is also plotted in **Figure 9b** 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 apparent friction angle mobilized in place, however, was seemingly about 13 degrees, much higher than 3.2 degrees reached in **TEST A**.

For this reason, **TEST B** was carried out for a smaller value of Sr **(Sr =81%)**. In this test, the stress path went almost straight up until the RFL was reached **(Figure 9a)**, and then the apparent friction angle dropped down to 12.7 degrees, which is closer to the angle roughly evaluated over the entire travel distance. The path deviated from the RFL presumably because the sensor did not keep a good track of pore pressure of the unsaturated pumice sample.

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