2.5 LAS COLINAS LANDSLIDE

General

A mountain ridge called El Balsamo rises south behind Las Colinas, and the slope failure took place in its northern side (**Figure 2.11**). 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. The geological map of El Salvador (**Figure 2.1**) shows that most formations found around the mountain ridge belong to the Balsamo group. The geological map also shows that pyroclastic and volcanic epiclastic deposits ("tobas color cafes") are found there. The presence of both a top layer of dacite lava and a white pumice lying underneath was confirmed through the field investigation of the upper hollow of the exposed slip surface.

Figure 2.11 Bird's eyes view of the Las Colinas landslide

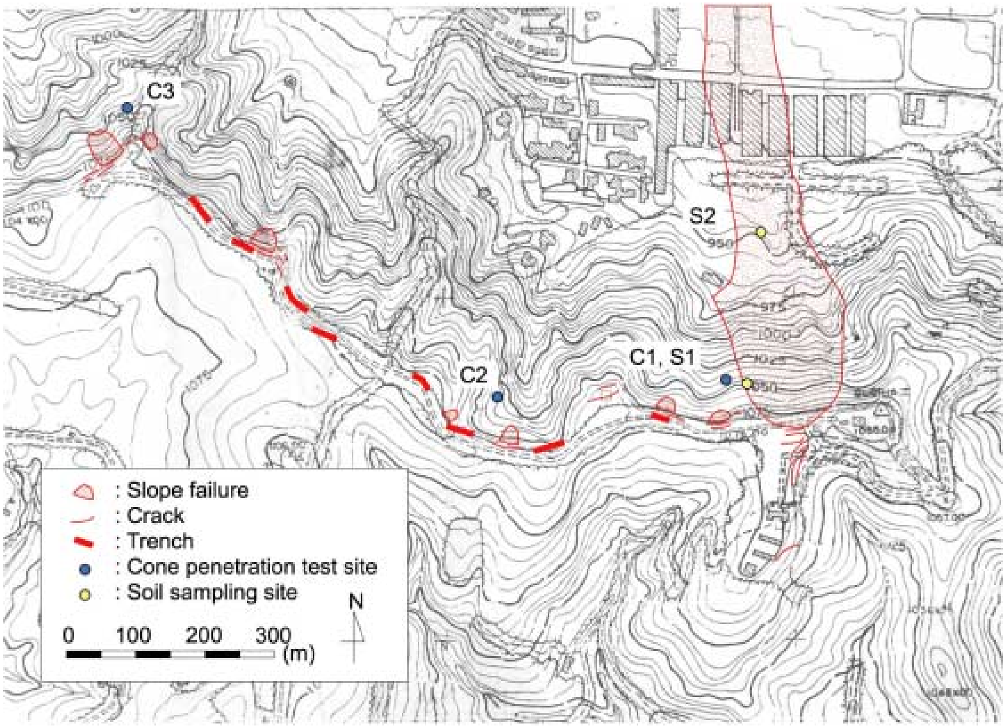


Figure 2.12 In-situ tests and sampling sites in Las Colinas
(Topography: Ministerio de Obras Públicas, 1970)

3D configuration of the slope

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, which the theodolite data are then converted into relative x-, y-, and z-coordinates with respect to the theodolite.

The surveyed slope was plotted with the map software SURFER (see **Figure 2.13**). The distances from the top end of the scar to the toe of the slope and to the farthest reach of the soil mass are 480m and 700m respectively. The elevation of the head-scarp and the toe of the slide are 1080m and 920m, respectively, namely, there is an average gradient of 160 m over 700 m distance in the damaged area. The average inclination from the top of source area to the toe of the deposit is about 13 degrees.

The failure surface can be roughly divided into three zones in **Figures 2.11** and **2.13**. The uppermost zone (**Zone 1**) is a hollow of about 100m in diameter, which was caved in some 10-20 m from the original ground surface. North beyond the hollow, there appears a steepest slope (**Zone 2**) which becomes gradually gentle as it comes close to the toe (**Zone3**). The inclination of the slope is about 26 degrees above the elevation of 960 m in **Zone 2**, and is about 9 degrees below the level in **Zone 3**.

In **Zone 2**, two ravines coming down from both sides of the slope curve forward and meet at the middle of the slope width. These ravines are shown also in the original topography. Therefore, the surface configuration in **Zone 2** after the earthquake roughly remained as it was. It will be shown later on that an accurate comparison between the original and surveyed slope leads to the same conclusion.

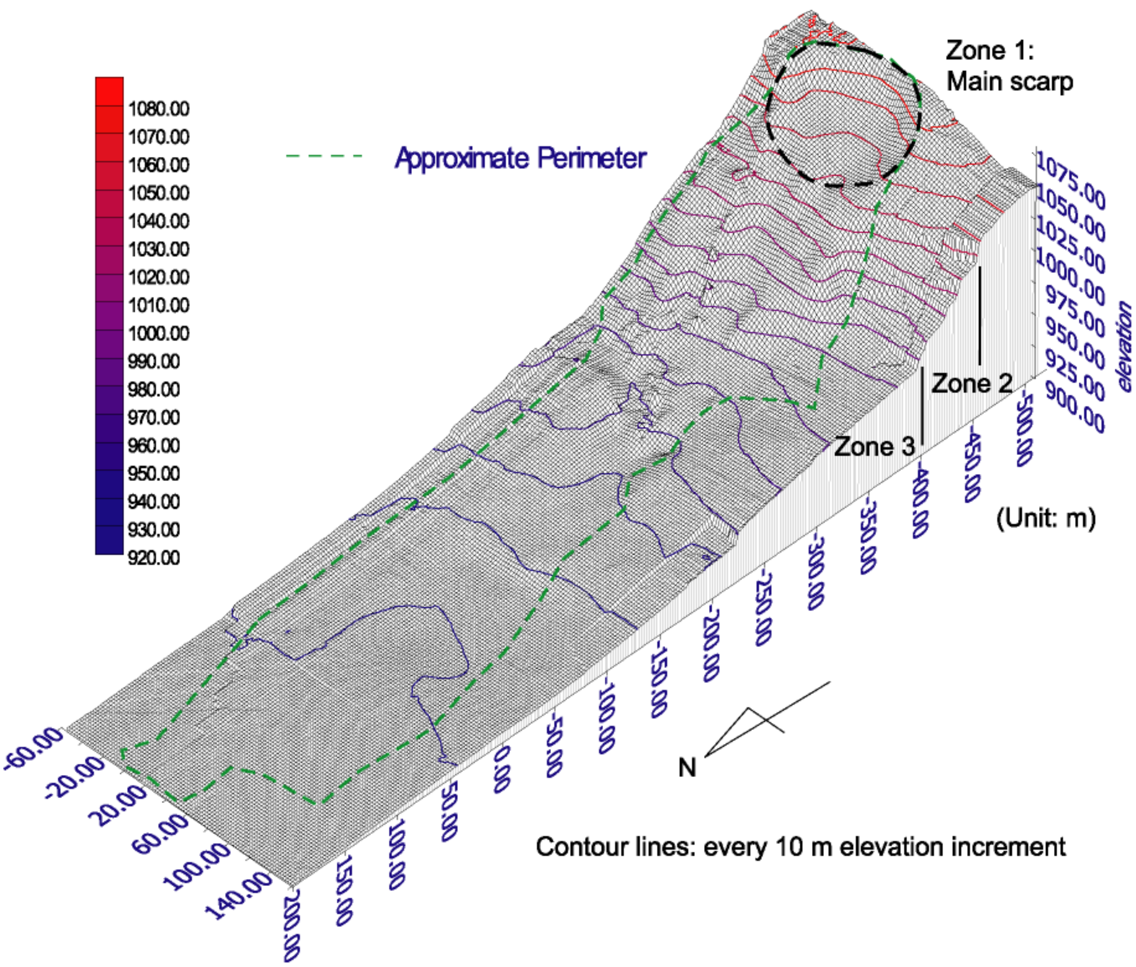


Figure 2.13 Surveyed Slope plotted with surfer with green dashed perimeter.

To estimate the total volume the original slope data is needed. A 1:5000 scale topographic map (Ministerio de Obras Públicas, 1970) was scanned and the original elevation contours were digitized with AutoCAD. The elevation data was plotted in **Figure 2.14** and compared with the survey slope data (**Figure 2.15**).

Matching original and surveyed origins were carried out as shown in **Figure 2.16**. The Latitude and Longitude of the point of origin was measured with GPS: N 13.665907, W –89.286890. The origin is located about 920 meters above the mean sea level.

The slope data was interpolated to an x-y grid with 2.5 meters spacing and the surveyed slope height i.e. the z-coordinates where subtracted from the original slope z-coordinates. Since the surveyed slope was slightly higher than the original slope in some areas (see yellow areas in **Figure 2.16**), these areas were excluded from the volume calculation by only considering positive values of the slope height differences between the original and the surveyed slope data. The slope height differences were added together and finally multiplied by 6.25 (2.5x2.5) to obtain the volume. The total slide volume is estimated to be about 200,000 cubic meters.

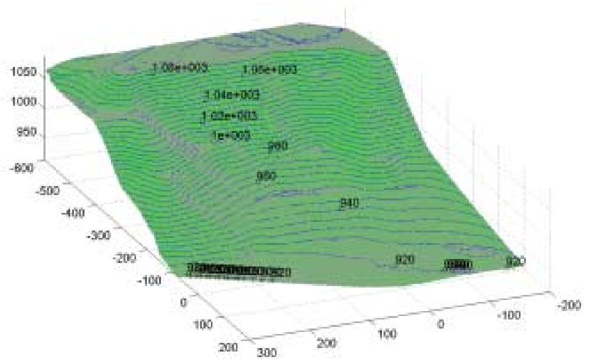


Figure 2.14 Original Slope plotted with Matlab, as seen from the North East.

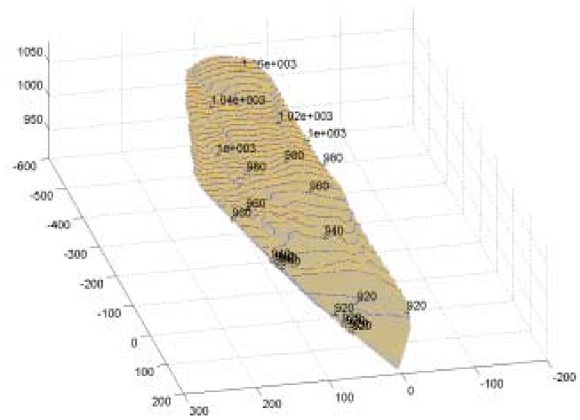


Figure 2.15 Surveyed slope plotted with MATLAB. The slope is in the North-South direction with higher elevations in the south.

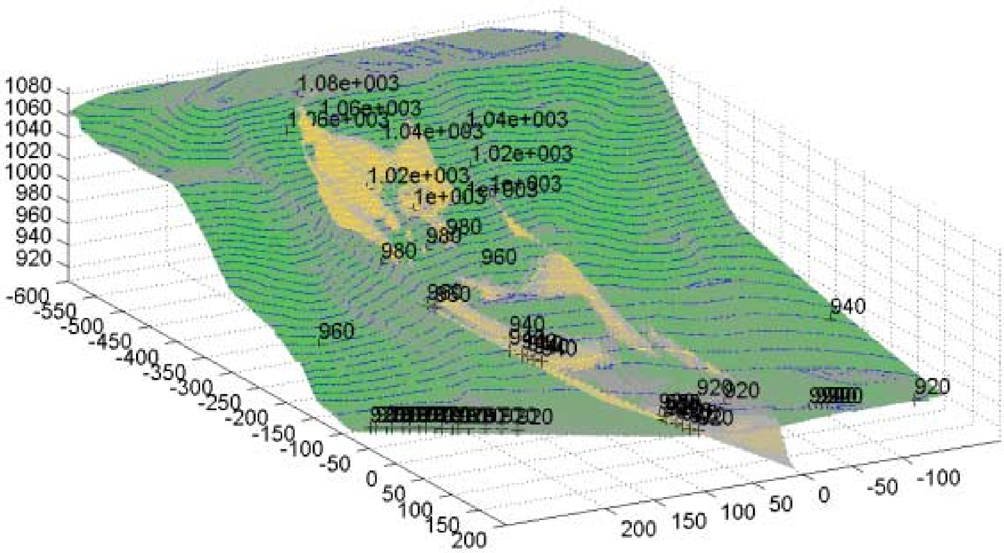


Figure 2.16 Survey and Original Plot over lap. Volume was estimated from regions were original slope lies above the surveyed slope.

Figure 2.17 shows contour plots of the original and surveyed slopes. In the figure the locations of the survey points (**SP1-6:** red solid circles), surveyed points (red crosses) and the slope perimeter (blue upside-down triangles) can also be seen.

A section plots of the surveyed and original slopes are shown in **Figure 2.18**. The baseline of the cross section was drawn from point {0,0} to {-520, 100}. In the plot, the heights (z-coordinates) are plotted against the x-coordinates. The steep slope configuration in zone 2 after the earthquake roughly remained unchanged as mentioned before.

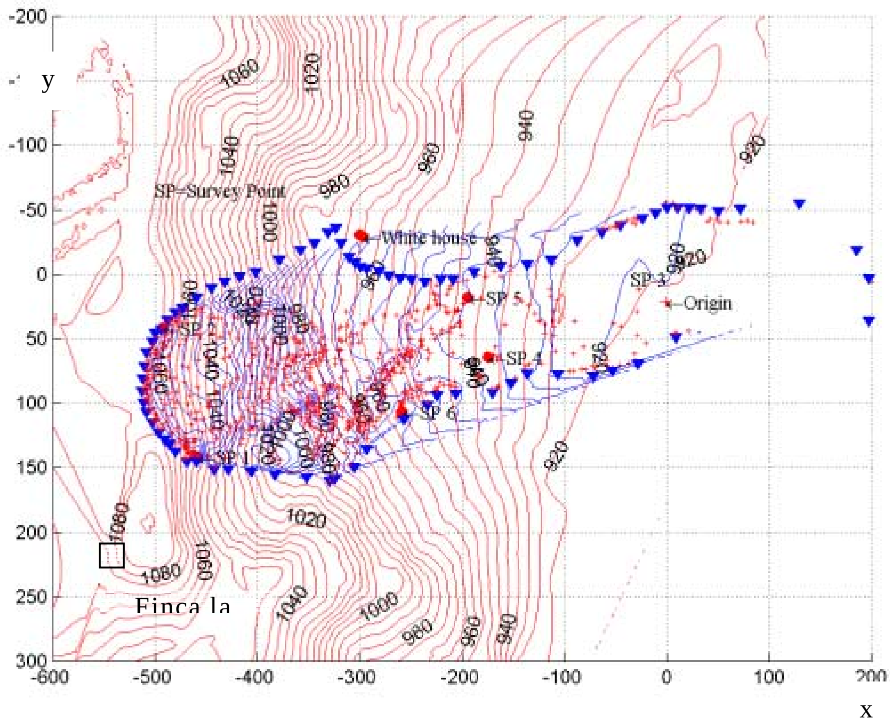


Figure 2.17 Original Slope with Surveyed slope slide perimeter (blue triangles), Red dots are Survey Points, red crosses are surveyed points.

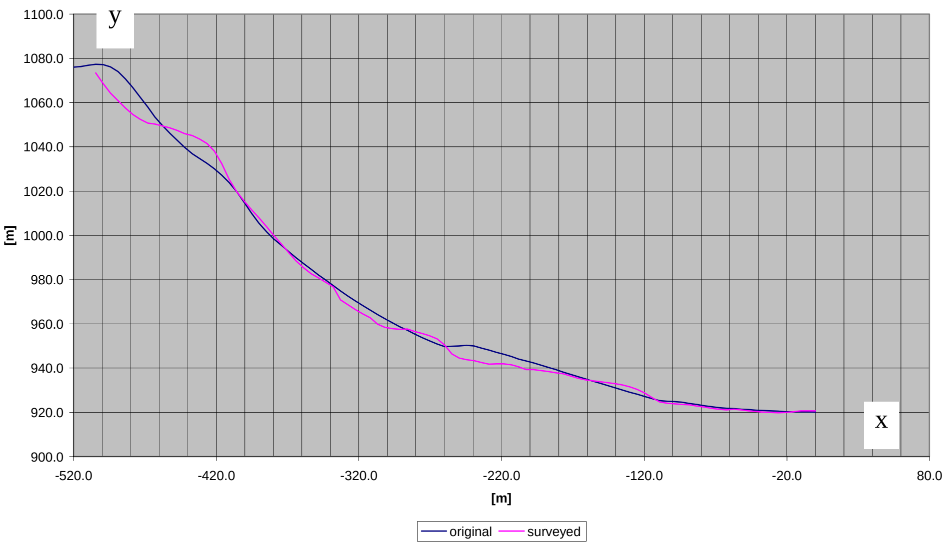


Figure 2.18 Section of original and surveyed slope(s). The three black lines correspond to the surveyed slope and the shifted positions.

Detailed features of the slope

(1) Uppermost main scarp (Zone 1)

Two photos (**Figure 2.19**) 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 (**Figure 2.20**). As shown in **Figure 2.21**, cracks and joints were observed even on an intact part of pumice.

(a) January 14

Photo. by Mr. Jose Antonio Rivas

(b) February 4

Figure 2.19 West slope of main scarp

Figure 2.20 A piece of lapilli tuff

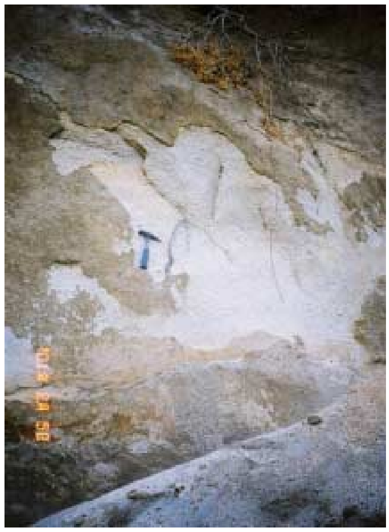
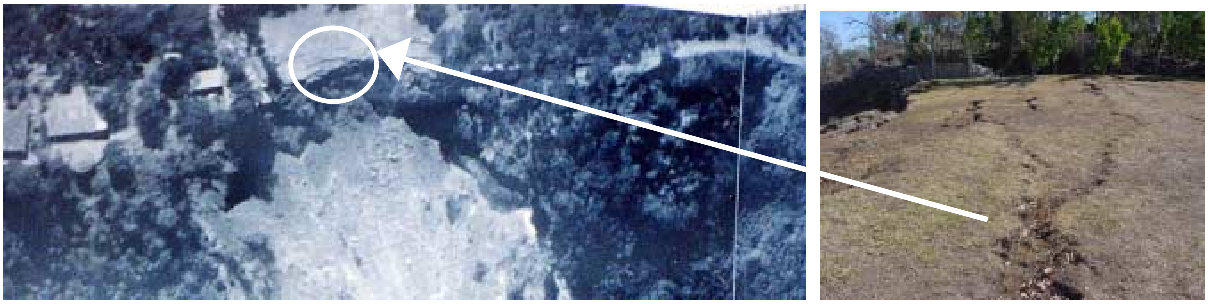


Figure 2.21 Cracks and joints on the exposed intact pumice

Total 43 points were marked along the perimeter of the scar using a GPS receiver (**Figure 2.22**). Behind the scar, there were extensive cracks running in almost west-east (See photos in **Figure 2.22**). Crack openings (12 visible cracks; **Table 2.2** and **Figure 2.22**) 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 **Figure 2.12**); the cracks can certainly cause further slides.



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

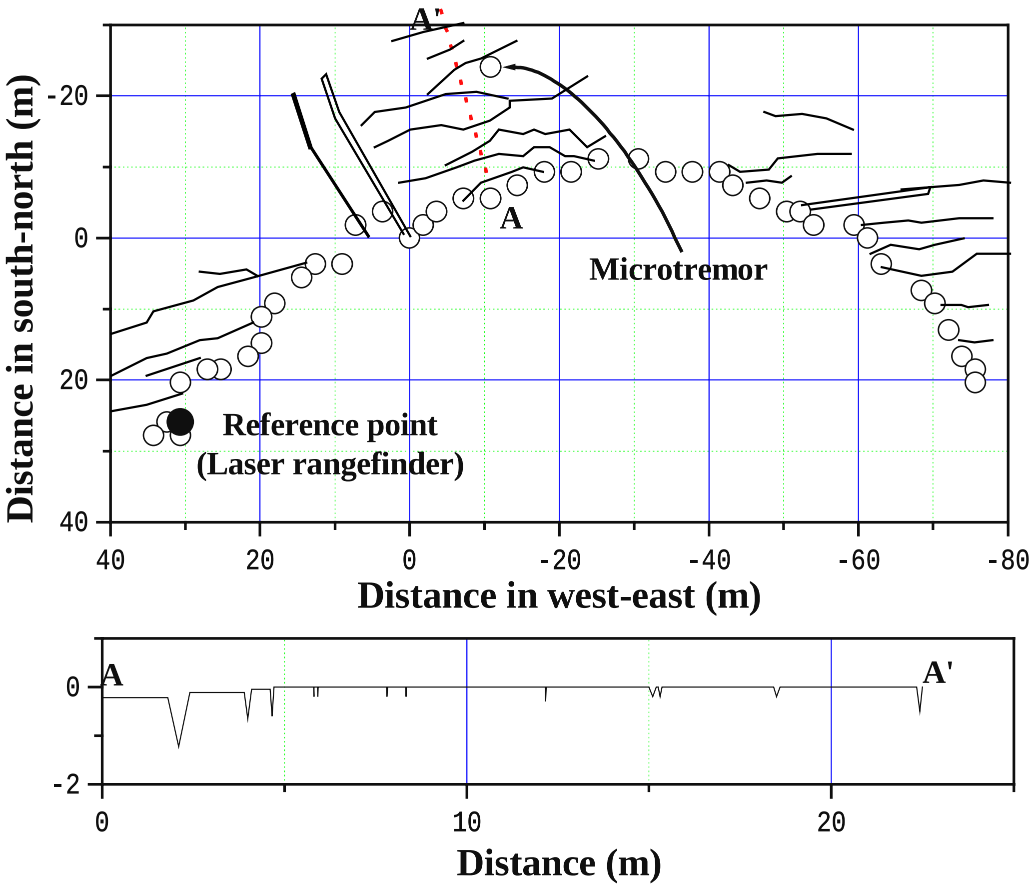


Figure 2.22. Perimeter of scar, Las Colinas Landslide

Table 2.2 Crack openings along Line **A-A'** in **Figure 2.22** (see the previous 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

Figure 2.23. Crack at the top terrace (photographed on Jan. 14 by Mr. Jose Antonio Rivas)

A pair of photos (**Figure 2.23** 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 **Figure 2.24**), and broken pieces of a mortar-block fence were caught on the soil mass remaining on the outer edge of the hollow (arrow in **Figure 2.25**). 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.

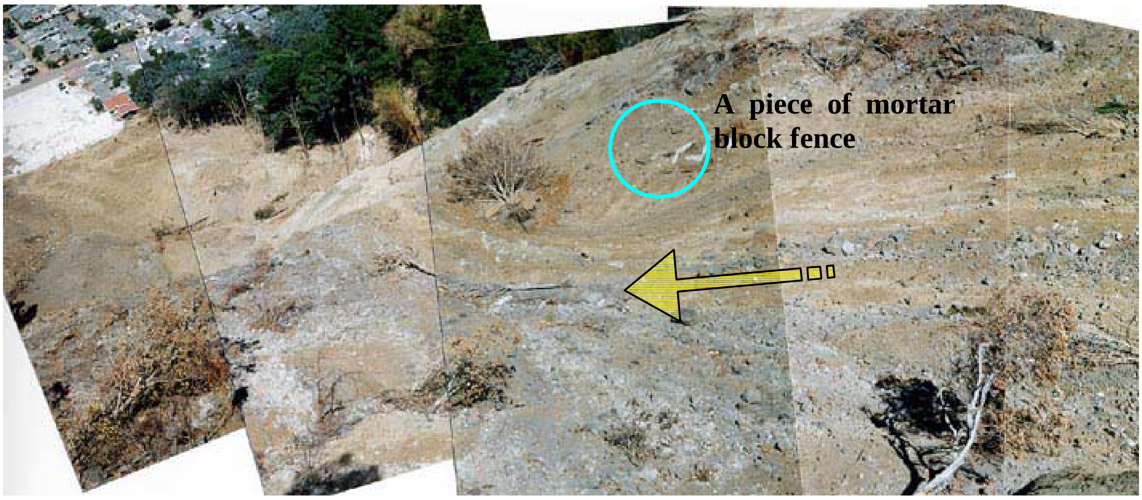


Figure 2.24. Lower part of the hollow: A piece of mortar block fence (within the circle) is caught on the small amount of the soil mass stopped at the lower edge of the hollow.

Figure 2.25. Fallen block fence

(2) Steep slope in the middle (Zone 2)

Figure 2.26 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 **Figure 2.27**, 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.

Figure 2.26. Steep slope (**Zone 2**)

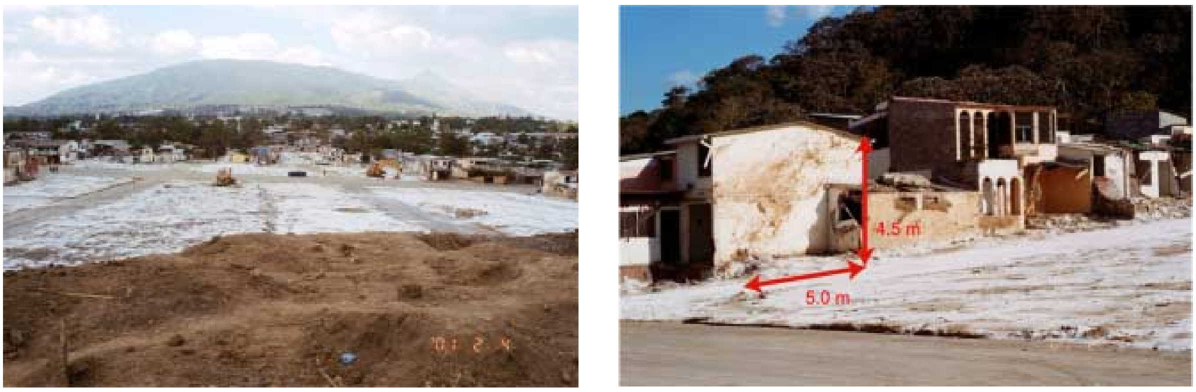
Figure 2.27. Thin mud film

(3) 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 (**Figure 2.28**). 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 (**Figure 2.29a**). 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. **Figure 2.29b** 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.

Figure 2.28. Toe of the slope



(a) Complete view of **Zone 3** (Feb. 4, 2001)   **(b)** House wall spotting with splashes

Figure 2.29. Photos from **Zone 3**

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