Microtremor measurement

Microtremors were measured at both the top terrace behind the uppermost scar of the Las Colinas landslide (El Balsamo ridge: **Figure 2.22**) and its toe.

Fourier Spectra of three components of the tremor as well as the H/V ratios are shown in **Figures 2.47** and **2.48**. 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.

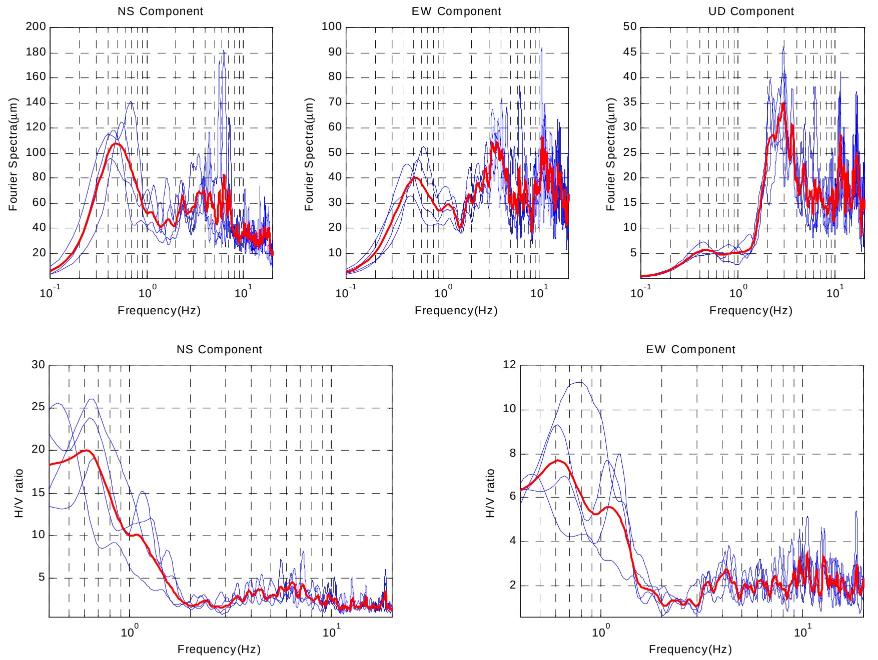

Figure 2.47. Fourier spectra of microtremors at the top of El Balsamo ridge

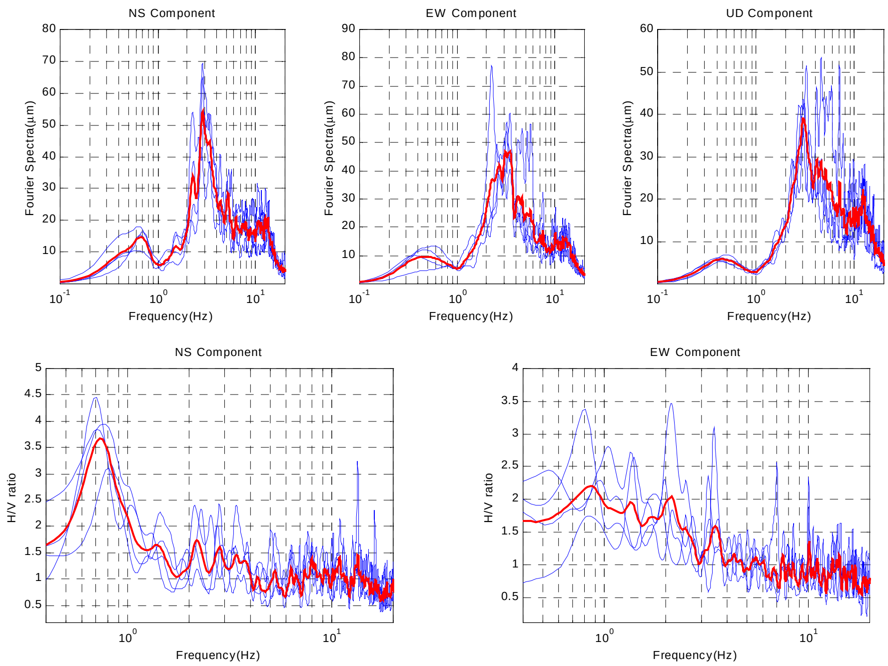

Figure 2.48. Fourier spectra of microtremors at the toe of El Balsamo ridge

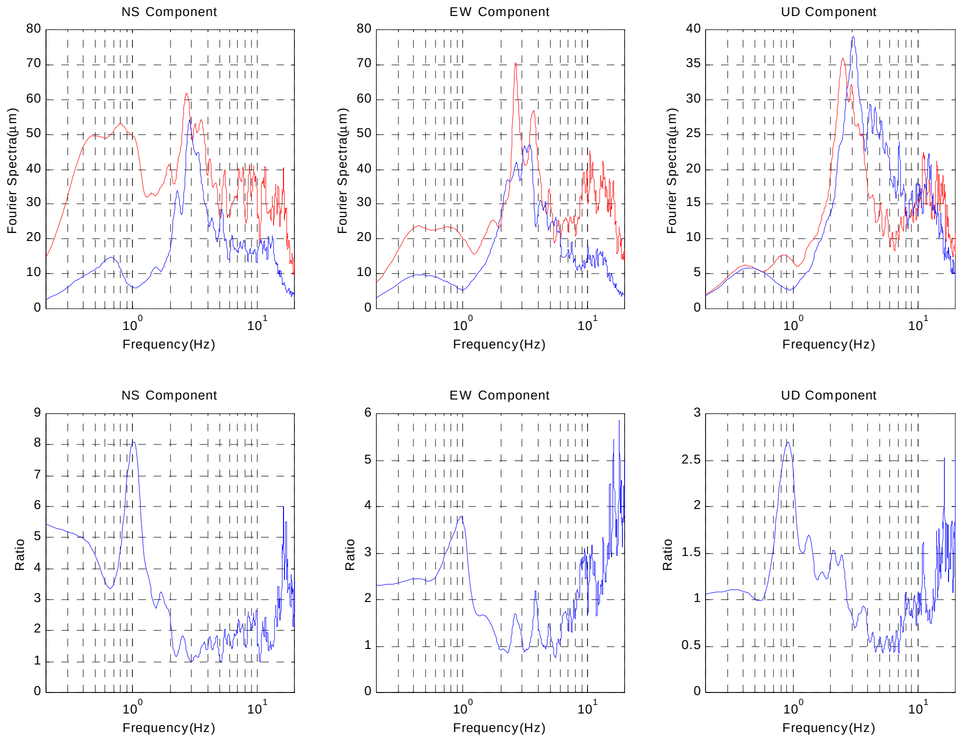

Figure 2.49 Ratios of Fourier Spectra (top of the ridge / toe of the ridge)

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 **Figure 2.49**. 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).

Our findings are as follows:

1. Fourier Spectra of the horizontal components at the top of the ridge are larger than the corresponding components at the toe of the ridge.
2. Fourier Spectra of the UD components at the top and the toe of the ridge are generally similar to each other. A slight shift of the latter towards higher frequencies can be observed.
3. NS components below 1.5Hz are about twice as large as the EW components at the top of the ridge. This is not the case for the rest of the frequency range.
4. The spectral ratio of the NS, EW and even UD components show a clear peak at around 1Hz.
5. For NS, EW and UD components, another peaks at around 18Hz can be identified.

Findings 1 and 2 suggest that lateral components of the ground motion have been amplified at the top of the mountain ridge due to the topographical effect, and from **Finding 3**, the effect was more pronounced in the transverse direction of the ridge. The fundamental resonance frequency of the ridge is considered to be about 1Hz judging from **Finding 4**.

Summary of Las Colinas Landslide

The Las Colinas landslide started on a steep slope of El Balsamo ridge rising south behind Nueva San Salvador, and caused extensive damage in the area. The failure surface can be roughly divided into three zones (**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 its toe (**Zone3**). The average inclination of the slope is about 26 degrees above the elevation of 960 m in **Zone 2**, and is about 9 degrees around the toe in **Zone 3**. The distance from the top end of the scar to the farthest reach of the soil mass was about 700m. The average inclination over the entire extent of the slide is thus about 13 degrees.

Dark and bright colored stripes appearing on the uppermost hollow in **Zone 1** shows a stratified arrangement of tuff and pumice layers. The pumice is easily broken into small pieces or powder just by rubbing together with fingers. Photos of the scarp taken at different times show that the exposed soils were gradually drying, and that the intact slip surface was somehow wet before the event. Micro-tremors observed at both the top terrace and the toe of El Balsamo ridge show the possible topographical effect of the ridge, in which the shake in NS direction seems to have been more intense, and 1Hz component of the shake might have amplified considerably. Roughly estimating from the response spectrum for the record at San Rafael Hospital, Santa Tecla (**Figure 1.14**), peak acceleration larger than 0.5G might have been reached at the top of the slope.

The steep 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 pushed down on the slope. This fact suggests that the original slope in **Zone 2** was not scraped deep, and the bottom surface of the slid soil mass was wet. The wet sliding surface must have accelerated the rapid downhill movement of the soil mass.

The slid soil mass, when it reached the toe in **Zone 3**, seems to have surged across a small ravine coming down from east mountainside, and splashed up a small bank. The soil mass then flushed many houses and therefore more than 500 lives to death, and the distal end of about 700m from the top source was reached. 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. A wall of a dwellings remaining on the perimeter about 200m south behind the furthest reach of the soil mass spotted in parabola with mud splashes. The parabola with its peak of about 4.5m high dropped downward, and reached the ground after about a 5m horizontal run. From this fact, the splashes seem to have run at the speed of about 5 m/s there. The main stream of the soil mass flow might have even faster than this speed after running through dwellings standing close together.

The results of the ring shear tests for the pumice from **Zone 1** showed that grain crushing during a shear of the sample of even 81% saturation can cause a high pore water built up. The apparent friction angle for this sample dropped down to 12.7 degrees after a 20 m shear displacement was reached. This angle is about identical to the average inclination of the slope over its entire travel distance.

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 (**Figure 2.50**). 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 (**Figure 2.51**). 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. Recommendations will be given in Section **2.6**.

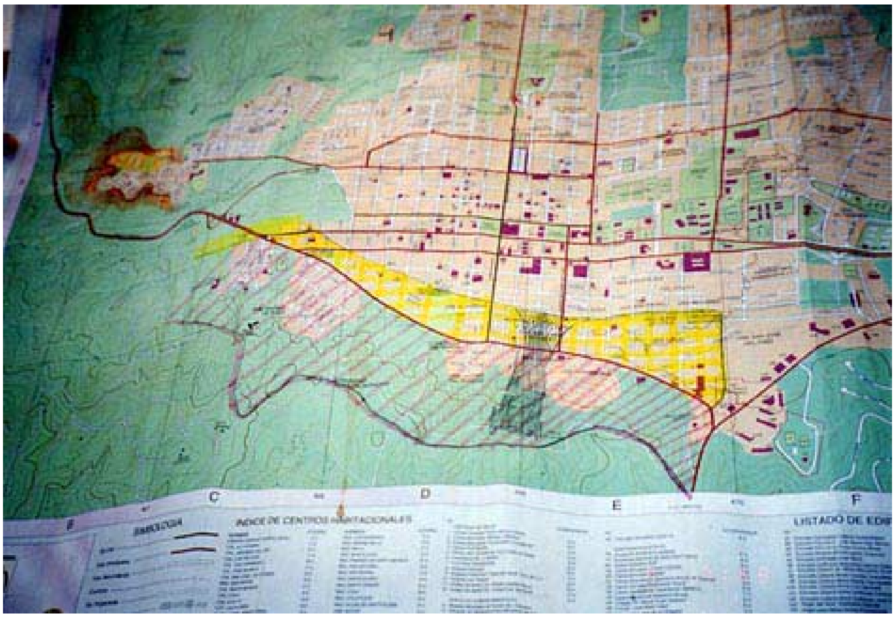

Figure 2.50. Zones of potential risk

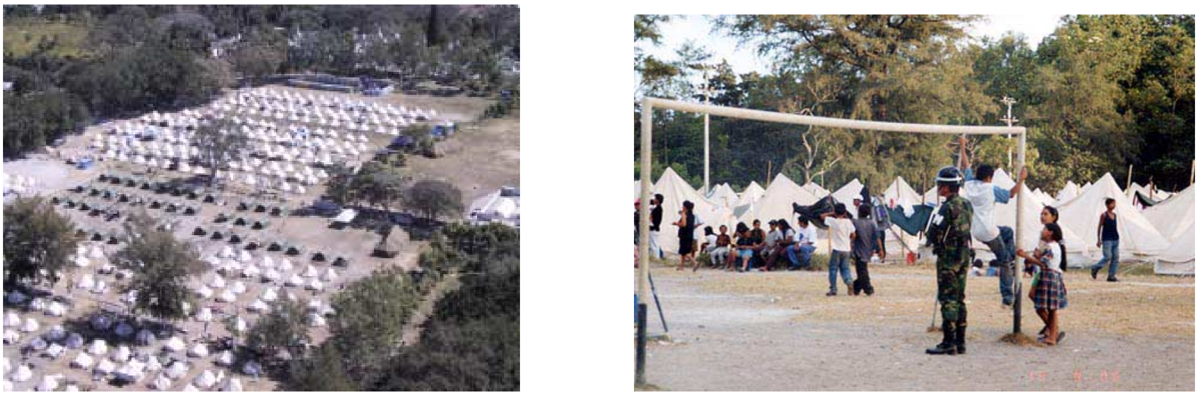

Figure 2.51. Refugees' camp

2.6 OTHER LANDSLIDES

This section describes the other landslides that the JSCE team investigated. The team had little chance to cover a wide area of the nation during their short stay, and thus they narrowed their target mostly to the slides in the vicinity of Nueva San Salvador (see **Figure 2.52**: Ministerio de Obras Públicas, 1984). They include:

Point A (Some landslides along El Balsamo ridge rising south behind Neuva San Salvador. Las Colinas landslide is the biggest among them.)

Point B, C* and *D (Some landslides in Los Chorros area. ***Points B*** and ***C*** are found along the Pan-American highway. **Figure 2.7** in Section **2.3** shows the slide at ***Point D***.) and

Point E (Slope failures in Nueva Cuscatlán).

In addition, ***San Vicente landslide*** that blocked the PanAmerican Highway was investigated.

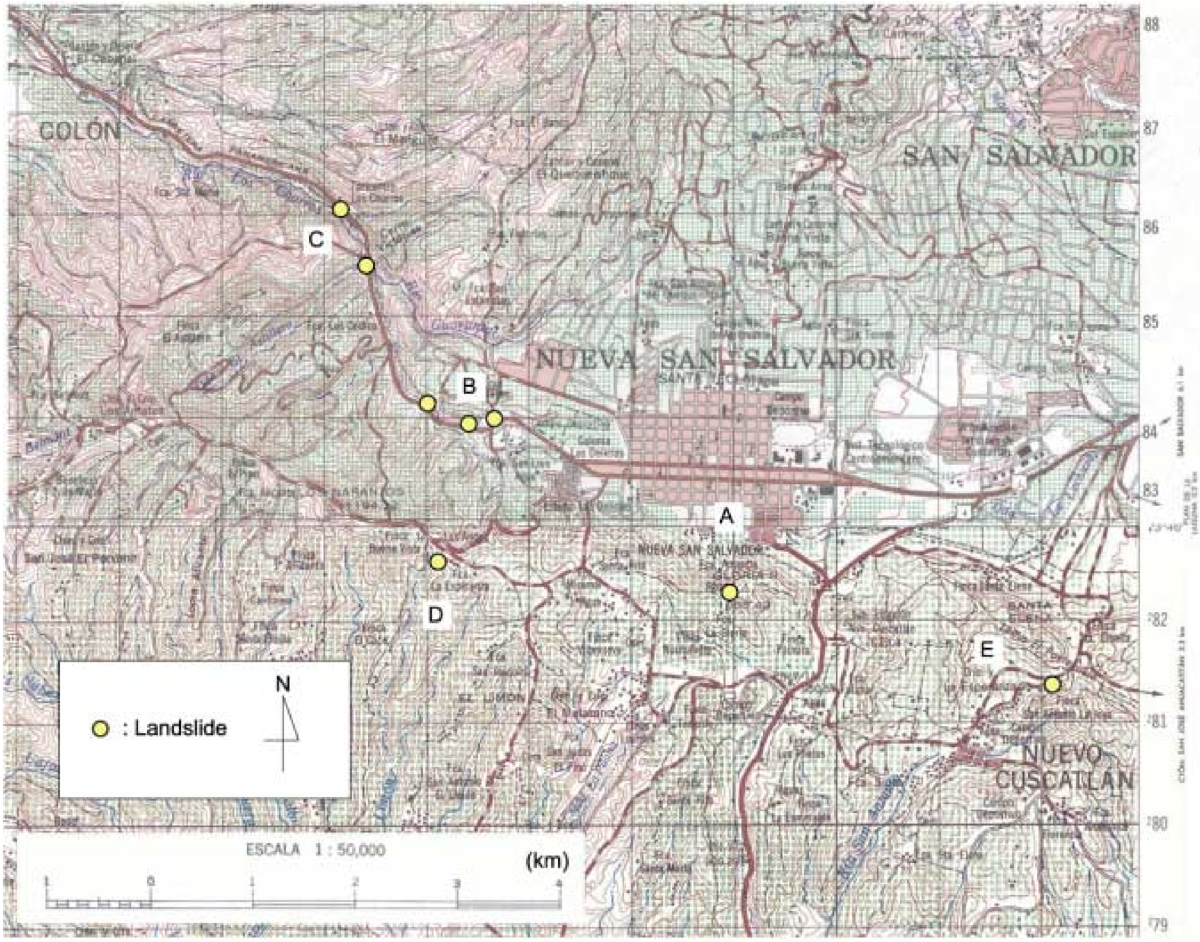

Figure 2.52. Locations of landslides in the vicinity of Nueva San Salvador
(Topographical map: Ministerio de Obras Públicas, 1984)

POINT A: Slope failures along El Balsamo ridge, Las Colinas

El Balsamo ridge rising south behind Neuva San Salvador is shown in **Figure 2.53** (Ministerio de Obras Públicas, 1970). Red spots and lines at the top or along the nose of the ridge show landslides and cracks. The largest red zone is the Las Colinas landslide. Since the north slope of the ridge is much steeper than its south side, slope failures were found on its north side. Salvadorian army took a quick action of excavating trenches (thick red lines in **Figure 2.53**), and they were all grouted with soil cement to stop water soaking into the soils. The sizes of these slope failures are roughly described in **Table 2.6** in terms of their heights and widths measured by using a laser rang finder.

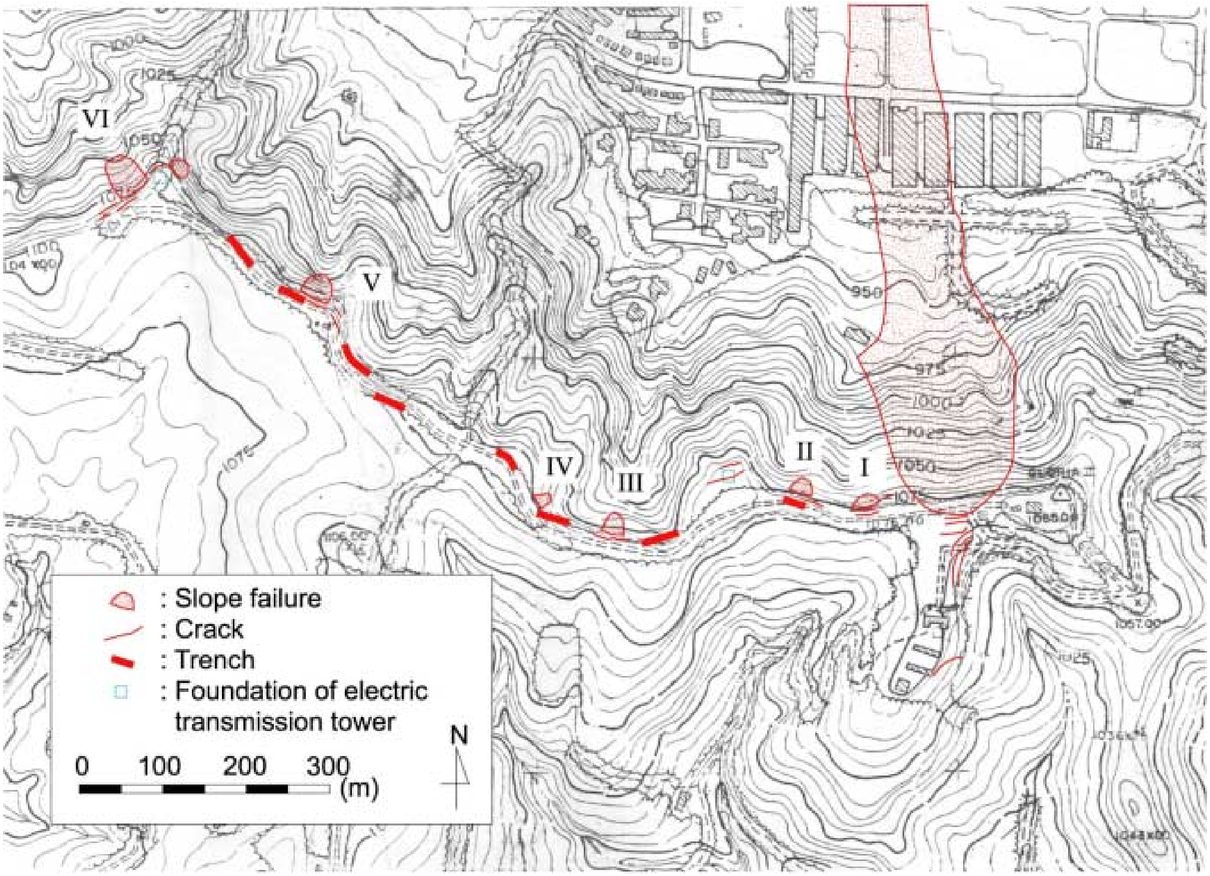

Figure 2.53. Slope failures along El Balsamo ridge
(Topographical map: Ministerio de Obras Públicas, 1970)

Table 2.6. Scale of slope failures

Sites	Width (m)	Height (m)
I	23	15
II	15	21
III	22	32
IV	10	22
V	40	40
VI	30	51

Figures 2.54-2.56 show a slope failure at **Site III,** 22.3 m wide, and 32 m long, on a steep slope of about a 45degrees inclination. A longitudinal crack was open wide and deep along the nose of the ridge (**Figure 2.55**) The slope shows a stratified soil arrangement with a top lapilli tuff layer (dark bluish gray) of about 90 cm thickness overlying a pumice soil deposit (grayish ocher: see **Figure 2.56**). A couple of thin lapilli tuff films were bedded in the pumice. The pumice grains that came off the intact surface are rather coarse (1.2 mm×2.3 mm×3.5 mm, 1.3 mm×2.3 mm×3.5 mm, e.g.). The stratified soil arrangement with the inclusion of weak pumice might be the cause of this slide.

Figure 2.54. Slope failure at **Site III**

Figure 2.55. Longitudinal crack at **Site III**

Figure 2.56. Stratified soil arrangement at **Site III**

Figures 2.57-2.58 show an about 30 m wide and 51 m long slope failure at **Site VI**. The soil exposed on the top terrace is a pyroclastic flow sediment of 2.5 m thickness overlying a pumice sediment. The stratified structure is about the same as those abovementioned. Some cracks appearing close to the nose of he ridge were 1.3 m wide and 1.0 m deep e.g. (**Figure 2.58**).

Figure 2.57. Slope failure at **Site VI**

Figure 2.58. Crack at **Site VI**

POINTS B, C and D: Slope failures at Los Chorros

A number of slope failures occurred on slopes excavated for the Pan-American Highway in Los Chorros area. The exposed failure surfaces are classified in the following three geological categories: 1) stratified arrangement of lapilli tuff and pumice (**Figure 2.59**), 2) pyroclastic flow sediment (**Figure 2.60**), and 3) fresh volcanic rock (**Figure 2.61**).

Figure 2.59. Failure surface exhibiting an arrangement of volcanic products in strata. Two lapilli tuff layers (dark gray) lie between the loose pumice soil sediment (ocher).

Figure 2.60. Exposed failure surface of pyroclastic flow sediment.

Figure 2.61 (left) Slope failure on fresh volcanic rock

Slope failures at Nueva Cuscátlan

Some slope failures took place at Nueva Cuscátlan. **Figure 2.62** shows the largest one among them, 19.5m wide and 6 m high, on an about 50 degrees slope of weathered lapilli tuff (dark gray). Two adobe houses were broken under the slid soil mass. Some cracks were found wide open along the nose of the mountain ridge cutting roots of coffee trees, while a pressure ridge of about 22 cm high was found around the toe of the slope (**Figure 2.63**).

Figure 2.62. Slope failure on weathered tuff

Figure 2.63. Pressure ridge

Slope failures at San Vicente

At the 53rd km of the Panamerican Highway, in San Vicente, a slid soil mass blocked the road (**Figure 2.64 (a),(b)** and **(c)**). Three-dimensional shape of the slip surface (hollow) was measured by using a laser-rangefinder (**Figure 2.65**), and the volume of the slid soil mass was roughly estimated to be about 300,000 m^3. A dipping joint surface seems to have served as a slide plane. It is noted in **Figure 2.64(c)** that there are some suspect old scarp-like marks (white curves) recognized on both sides of the slide. Some cracks were found further above the upper end of the scar.

(a)

(b)

(c)

Figure 2.64. San Vicente landsile

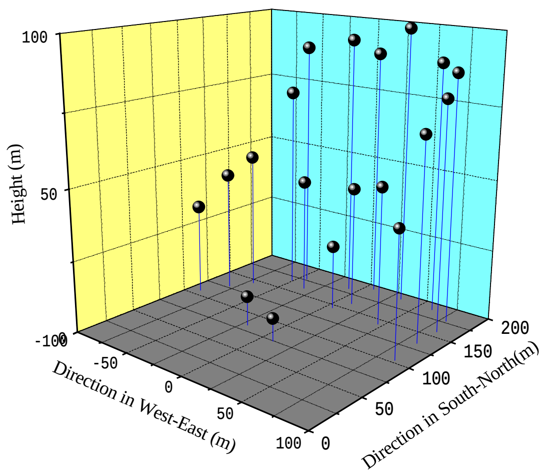

Figure 2.65. Configuration of San Viente Landslide

Figure 2.66 shows bahareque house near San Vicente landslide. This bahareque house, standing on the terrace high above the headscarp of the slide, performed quite well, though it suffered some diagonal shear cracking.

Figure 2.66. Bahareque house near San Vicente landslide

2.7 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 you and/or your local officers are familiar with the land around you, you will be able to catch an early sign of a landslide. Watch the hillsides around you. The ring shear test of the water-saturated pumice soil in Section **2.6** shows clearly 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. Watch any change in patterns of water drainage. If you find slowly but steadily developing cracks, some fragments of rocks coming off, or progressively tilting trees, contact your authorities and be prepared for a possible evacuation.

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