

Provisional Report on the June 23, 2001 Atico Earthquake, Peru (Updated 04, September, 2001)

PREFACE

This report is compiled from observations by the Japan-Peru Joint Reconnaissance Team that followed the June 23, Atico Earthquake, Peru. Before this earthquake, members of IIS (Institute of Industrial Science, University of Tokyo) and CISMID (Japan-Peru Center for Earthquake Engineering and Disaster Mitigation) were organizing an EQTAP* workshop at Lima for a possible collaboration on researches for earthquake disaster mitigation. One of the main goals of this workshop was to discuss a rational methodology for earthquake damage surveys, in which some measured key indexes would provide experts and decision makers with clear criterions for their necessary actions and possible countermeasures. PGA, PGV and SI are useful indexes, to be sure but they are only available where well-maintained instruments are available. In addition they do not always relate physical aspects of an earthquake to necessary actions that we should take. To discuss this issue on the spot, IIS group and CISMID experts decided to perform a joint reconnaissance survey in the affected areas as a pre-workshop arrangement. The team, with a limited number of experts, had little chance to cover up every specialty of civil engineering, seismology, surface geology and tsunami during their short stay there. The team, however, was offered every convenience by the Japan Society of Civil Engineers (JSCE), and adding two experts, Dr. Hiroshi SATO (ERI, University of Tokyo, Surface geology) and Dr. Koshimura (NOAA, Tsunami), the JSCE/EQTAP team was finally organized as listed in the table on the following page.

Though tragic, the death toll was fairly light considering the magnitude of this earthquake, the largest one to occur anywhere in the world in the past 25 years, and the damage seemed to be greatly localized even in a small area. One of the objectives of the team was to inspect this aspect of the earthquake. However, only one strong ground motion record of the main event has been recovered from a station in Moquega. Two other instruments in the epicentral area apparently malfunctioned. The reconnaissance survey of the JSCE/EQTAP team was thus performed in such a way that spatial distributions of the earthquake effects could be clarified. For this, the team members measured microtremors, cracks on utility poles, which can be found everywhere, and analyzed nighttime imageries from satellites.

This provisional report outlines the findings obtained through the reconnaissance survey and some comments by some individuals, which are not yet the conclusions reached after a thorough discussions among the members. The final report should be released after we obtain the results from microtremor analyses and etc. However, providing quickly both Japan and Peruvian specialists and persons in charge with a rough-and-ready overview will be important for taking measures for the disaster relief and precautions against possible secondary disasters. All the members of the EQTAP/JSCE Reconnaissance Team would like to express hereby their sincere sympathy to those people affected by the Atico earthquake, and they wish to further collaborate with each other for possible countermeasures, e.g., reconstruction of damaged structures and retrofitting of existing structures.

* EQTAP: “Earthquake and Tsunami disaster mitigation in the Asia and Pacific region” project, Ministry of Education, Culture, Science and Technology.

JSCE/EQTAP TEAM MEMBERS

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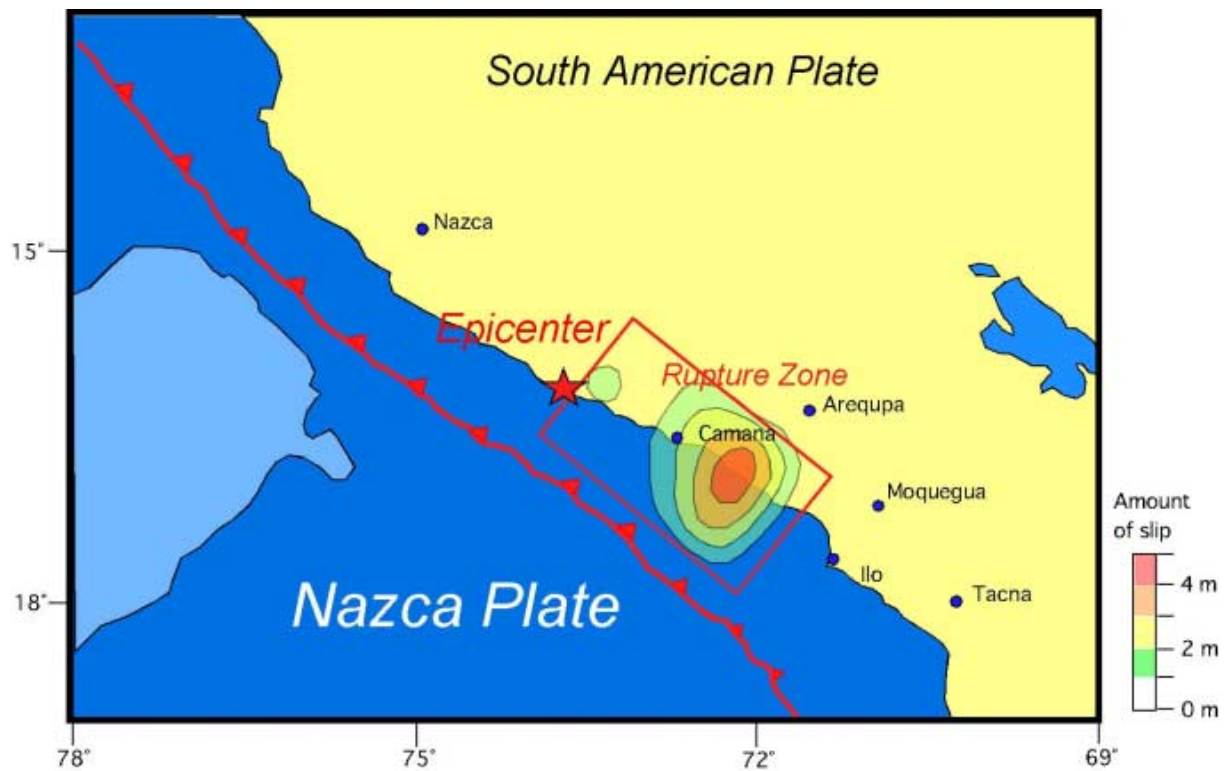
* Dr. Shunnichi KOSHIMURA is joining the NSF Tsunami Survey Team, USA (July 5-15).

Peruvian side

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SOURCE CHARACTERISTICS AND STRONG GROUND MOTION

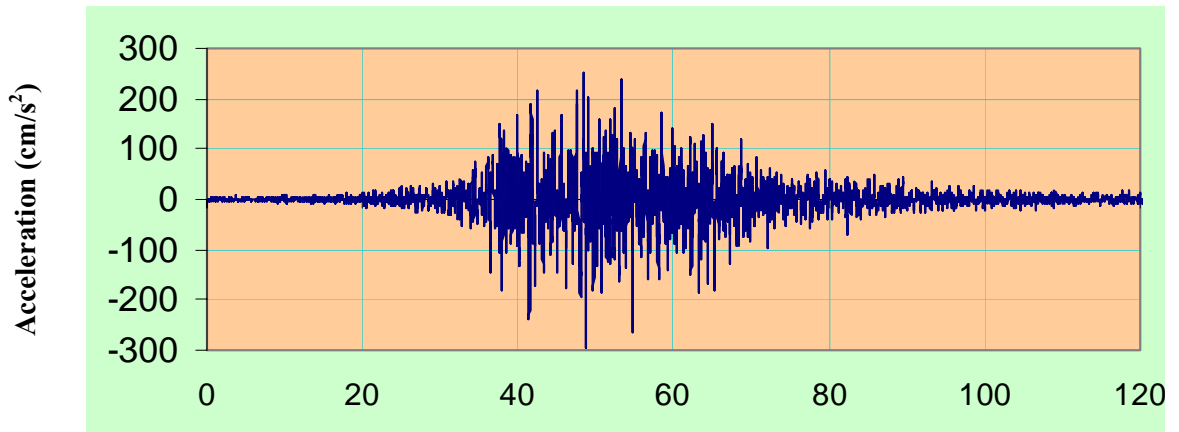
Atico Earthquake occurred off the coast of southern Peru, about 175 km west of Arequipa or about 595 km southeast of Lima at 4:33 PM EDT on Jun 23, 2001 (3:33 PM local time in Peru). A revised moment magnitude of 8.4 (Harvard) was computed for this earthquake, making this the largest earthquake to occur anywhere in the world in the past 25 years. The focal depth was shallow, with estimates from 9 km (Sipkin, USGS), 26 km (Harvard) to 40 km (Univ of Tokyo). This earthquake was produced by the subduction of the Nazca plate beneath the South American plate. The final slip distribution of the main event, from the inversion of teleseismic body-waves (Kikuchi and Yamanaka) shows a 300-km zone striking northwest extending from Chala to south of Motegua with two asperities: a large asperity is located at the southeast side of the zone and a smaller asperity located in the northwest end of the zone.



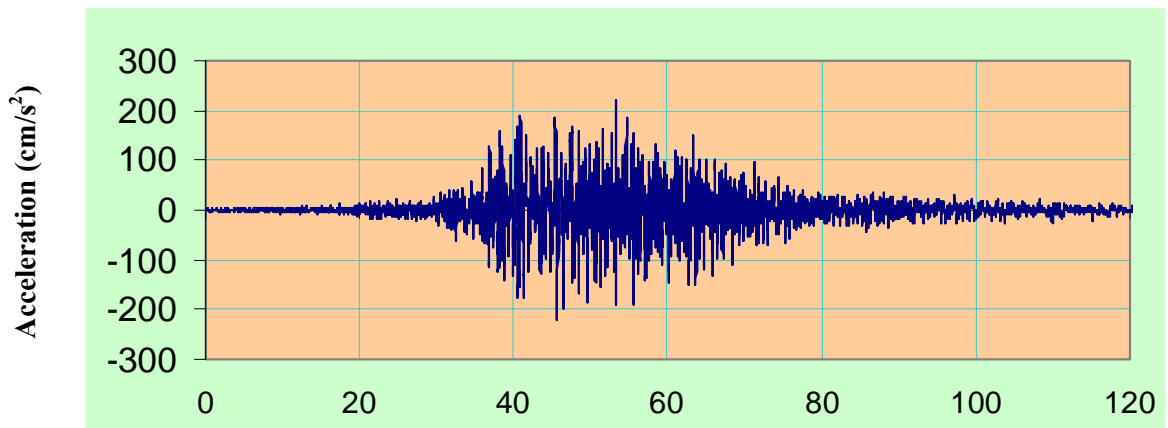
Location of epicenter is after USGS, fault parameters are after ERI (Kikuchi and Yamanaka)

Figure 1. Source Inversion of the teleseismic body-waves (IRIS-DMC) of the June 23, 2001 Atico Earthquake (Kikuchi and Yamanaka).

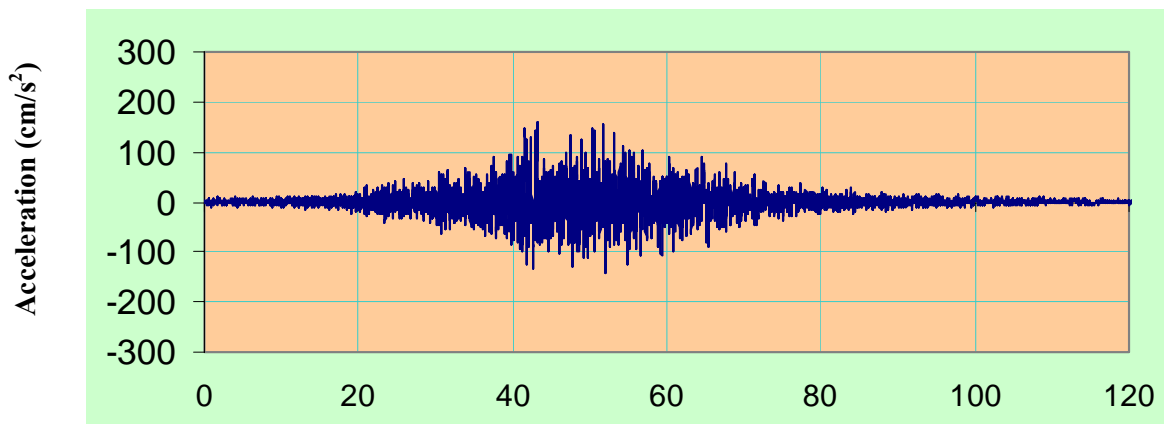
CISMID (Japan-Peru Center for Earthquake Engineering and Disaster Mitigation) has recovered and processed the information from only one instrument that triggered in Peru, the one in the city of Moquegua. Two other instruments in the epicentral area apparently malfunctioned. **Figures 2 and 3** show the corrected ground acceleration time histories and the corresponding acceleration response spectra obtained from that instrument recording in East-West, North-South, and Vertical directions.



(a) EW component

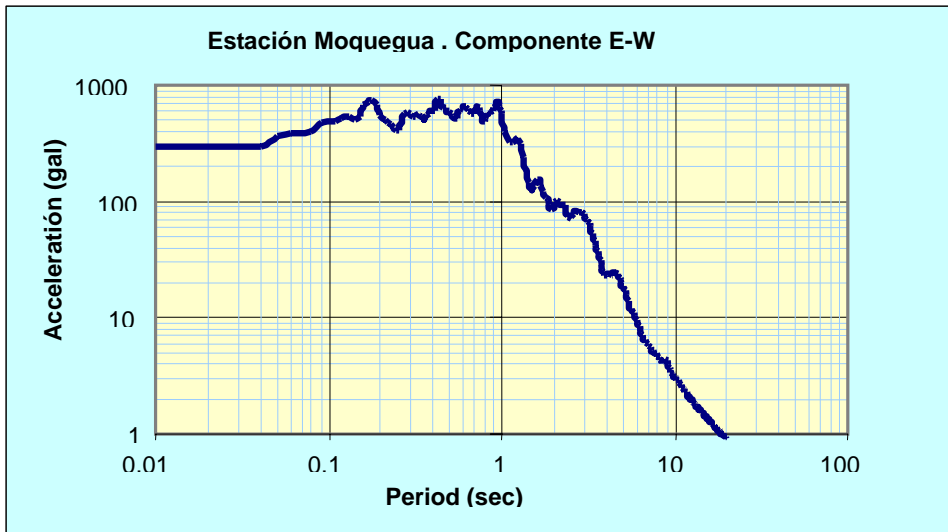


(b) NS component

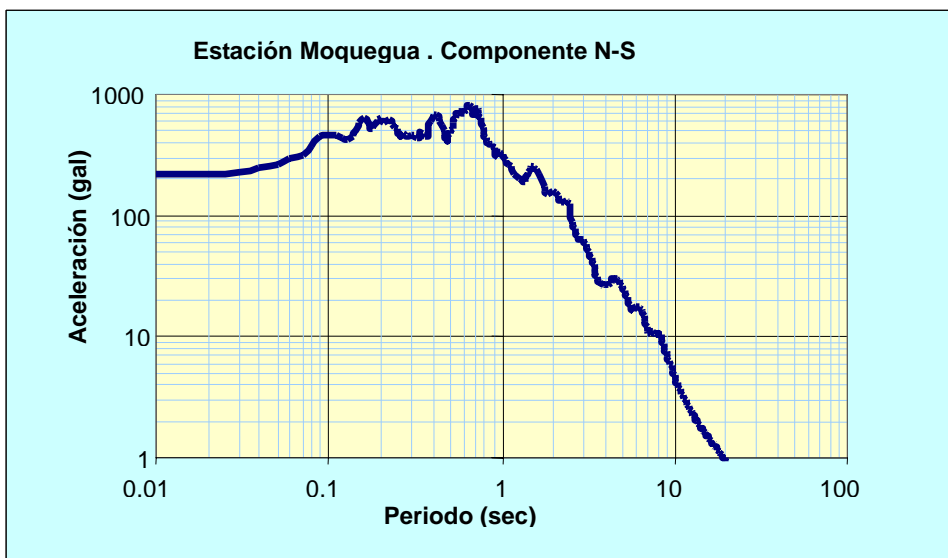


(c) vertical component

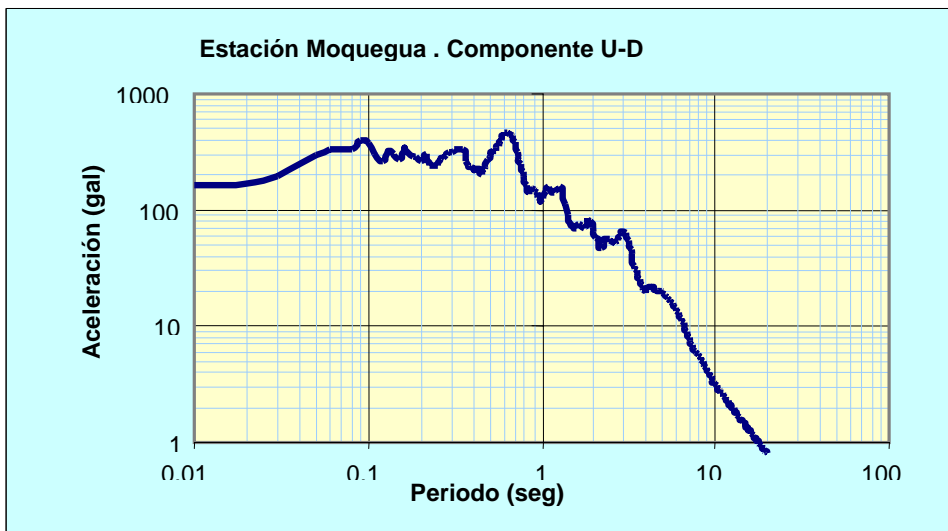
Figure 2. Acceleration time histories at Moquegua



(a) EW component



(b) NS component



(c) UD component

Figure 3. Acceleration time histories at Moquegua

TACNA (Kazuo KONAGAI)

This city spreads along a dry valley extending from Northeast to Southwest. Tops of hills on both sides of the city are completely flat and about of the same level. Soils making up the hills are mostly pumice and weakly cemented tuff.

The northeast area, which has been being developed since 1980's along the northwestern hillside, was the most seriously damaged. Most dwellings there were RC framed with infill walls of mortar blocks and/or bricks (**Figure 4**).

Utility poles (5m tall) are embedded upright in concrete-paved sidewalk. Cracks developing outwardly on the pavement from these poles were mapped. Some poles are very close to the step-shaped edge of the sidewalk. The thin cover concrete thus might have affected the crack pattern. Though the number of the examined utility poles is not sufficient for thorough statistical manipulations, some poles seem to have been forcibly shaken in about Northwest –Southeast direction, transverse direction of the valley (**Figure 5**).



Figure 4

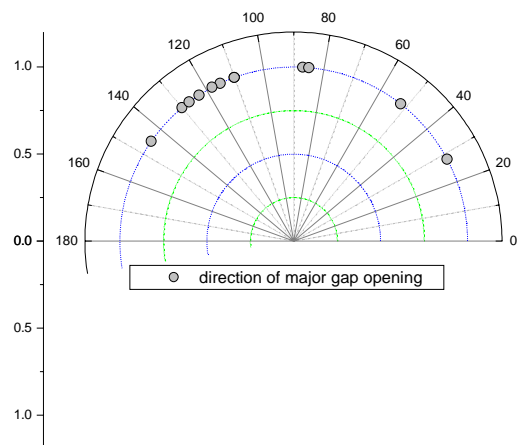


Figure 5 Directions of major gap openings at bottom ends of utility poles (Tacna)

MOQUEGA

Adobe buildings

(1) San Francisco area (Kazuo KONAGAI, MEGURO and Paola MAYORCA)

Moquega was the hardest hit city by this earthquake. A number of adobe buildings collapsed in the downtown area and many others sustained heavy damage. A thin mountain ridge, the northeast extension of a sand rock terrace rising behind the central area of Moquegua city, dips gently towards northeast. This ridge is densely covered with adobe dwellings, and the damage to dwellings was the severest there (**Figure 6**).



Figure 6 View of the terrace next to San Francisco hill

Distribution of cracked utility poles is considered to be a good index for discussing possible spatial distribution of intense ground motions. Observed crack intensities on total 59 utility poles were roughly classified into the following 4 groups:

Group 1: no visible crack.

Group 2: with hair cracks (>0.1 mm)

Group 3: with cracks (0.1-0.3 mm)

Group 4: with cracks (<0.3 mm) that can be seen at a distance of about 2m

Figure 7 shows the observed distribution of crack intensities. Arrows indicate the inferred directions of strong ground motions. In this figure, the first, second and third lines from left to right lined up with the inspected utility poles are streets along a narrow valley, along the ridge and on the other hillside, respectively. It is noted that no utility pole along the valley was cracked while those around the highest peak of the ridge near a water tank (green solid circle) were severely cracked. This contrast suggests that some topographical effect must have been responsible for amplifying ground motions. The arrows along the ridge show that the effect was more pronounced in the transverse direction of the ridge.

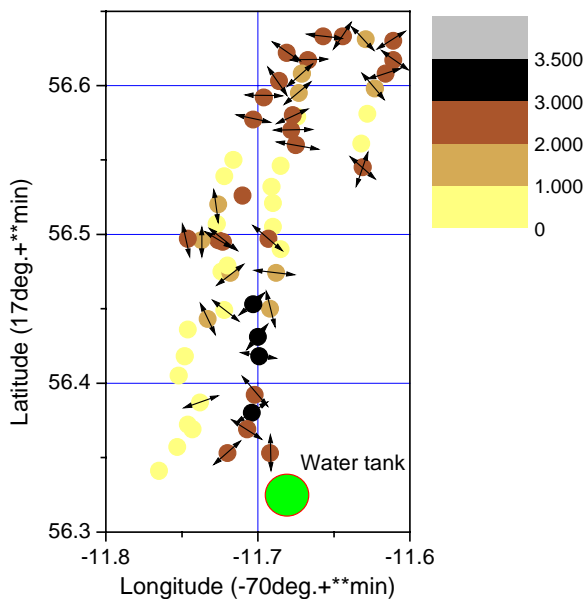


Figure 7. Distribution of cracked utility poles in San Francisco area, Moquega

In order to evaluate the topographical effect in a different way, microtremors at the top and toe of the ridge were measured, and at each site, the ratio of the horizontal component spectra to the vertical one (H/V ratio) was calculated in order to get the predominant period of the site [Nakamura, Y., 1989]. The H/V ratio is fairly flat at the toe, which might indicate the stiff soil nature of the site (**Figure 8**). On the other hand, at the top of the ridge, a peak can be identified at around 4-5Hz, the fact indicating the topographical effect. EW component at around this peak is about twice as large as the NS component in **Figure 9**. Since EW direction is about normal to the ridge, this fact is consistent with the finding from the investigation of cracked utility poles.

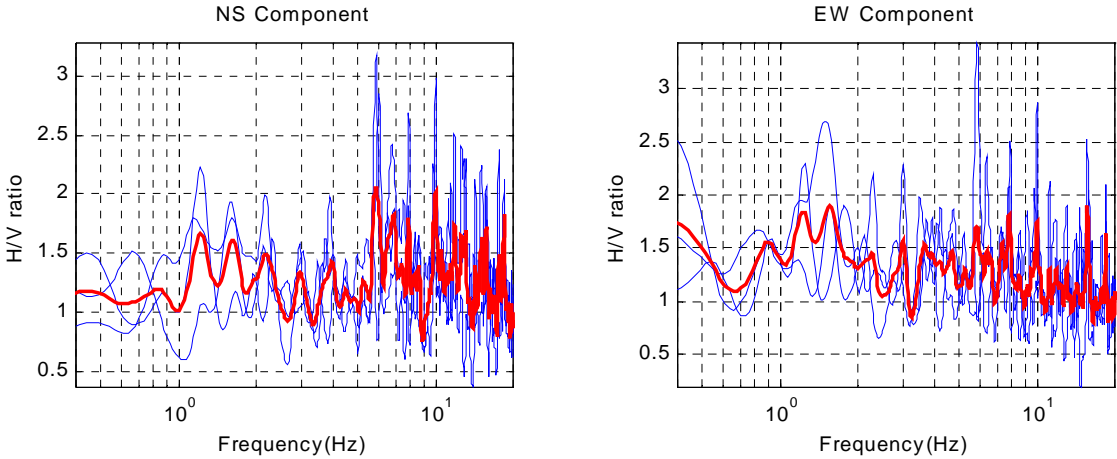


Figure 8. H/V ratio at the toe

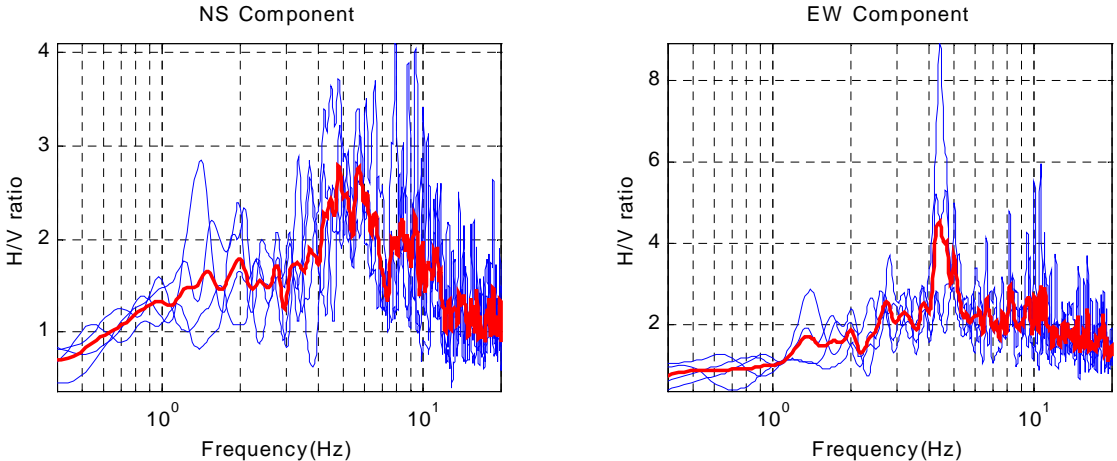


Figure 9. H/V ratio at the top

Performance of reinforced masonry vs. adobe (Jörgen JOHANSSON)

Structures of adobe performed in general badly as observed in many other earthquakes. Below follows a sketch and some figures showing collapsed adobe structures whereas neighboring reinforced masonry structures suffered on only minor damage (**Figure 10**). **Points (b)** and **(c)** show that a corner of an adobe structure is a weak point.

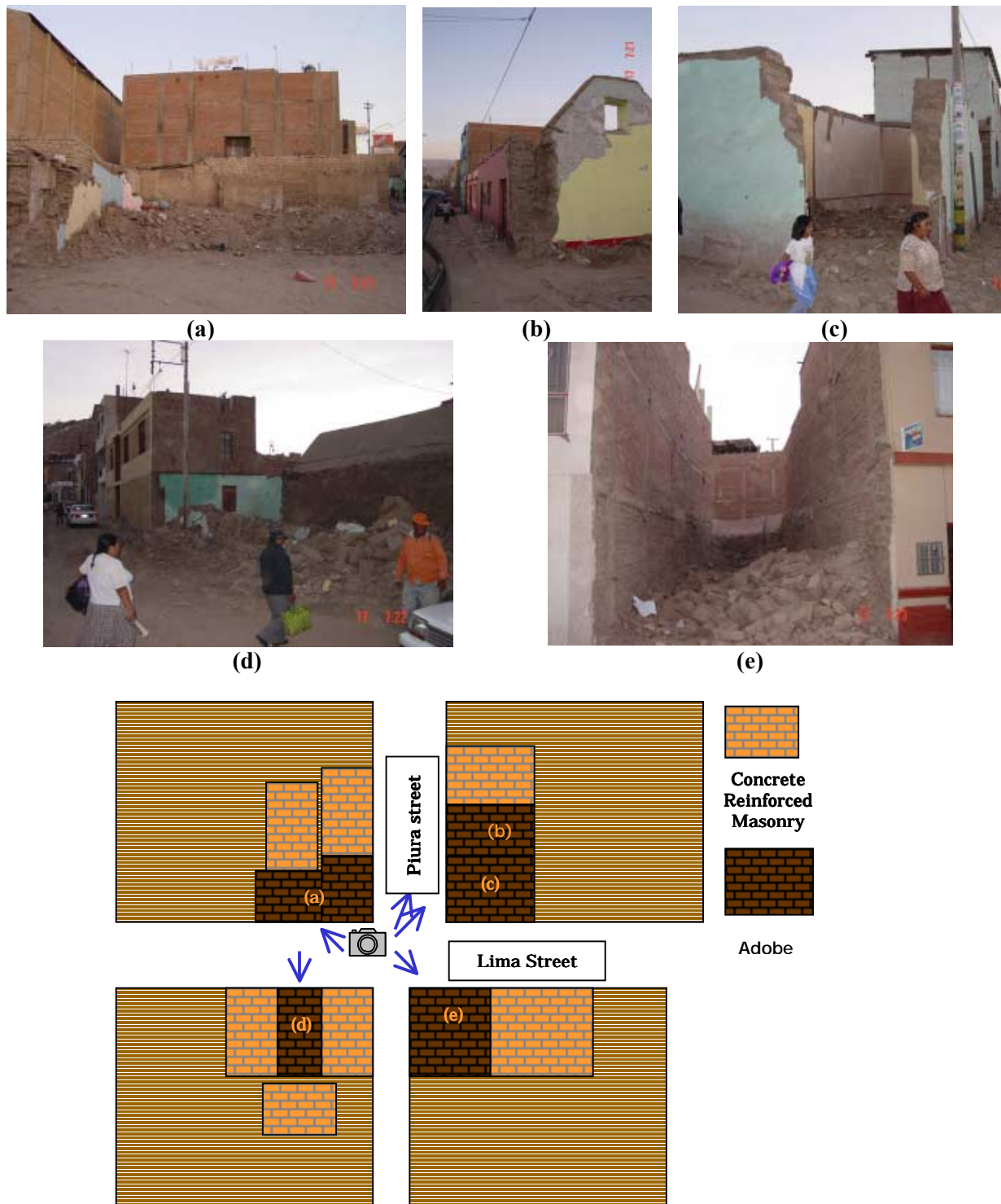


Figure 10. Sketch showing location of **Points (a)-(e)**.

In **Figure 11** and **12** an adobe wall with side support still stands after the shake while the brick wall next to it fell over. This type of side support could be a simple but effective strengthening technique for adobe houses (**Figure 13**).



Figure 11: Standing adobe wall and fallen masonry wall.

Figure 12: Close up of side support

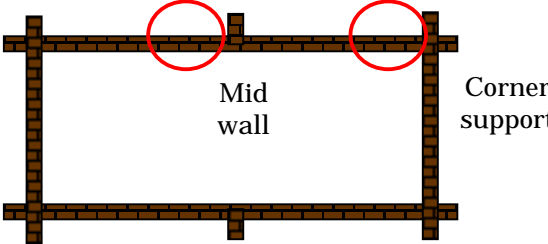


Figure 13: Plan view of overlapping adobe walls with mid wall side support.

Geotechnical issues

(1) Flexible Gabion Wall (Jörgen JOHANSSON)

Figure 14 shows a gabion wall that even after undergoing around 44 % (2.2/5) shear strain in the vertical plane still has not ruptured. This is good example of the ductility of Mechanically Stabilized Earth structures. (Photo taken at the masonry factory in Moquegua, below the hotel El Mirador).

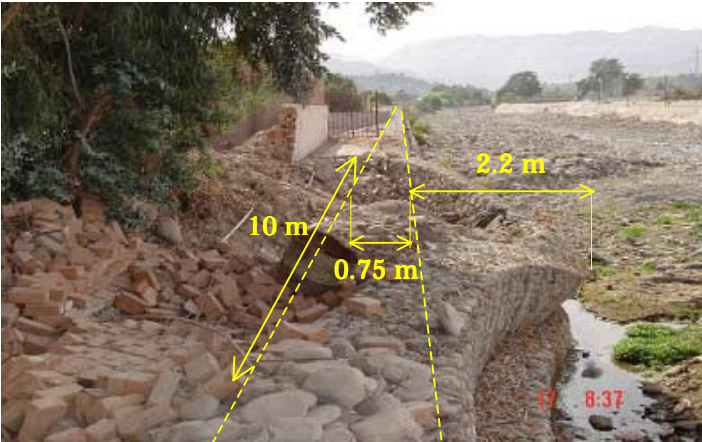


Figure 14. Deformed Gabion wall

(2) Sewage treatment facility (Junichi KOSEKI)

Figure 15 shows a plan of two oxidation ponds for sewage treatment in Moquegua. The upper and lower ponds have a capacity of 21000 and 13000 m³, respectively, and have been cleaned every ten years. Their bottom is sealed with clay layer.

By the earthquake, the embankment on the downstream side of the lower pond suffered cracking in its crest (**Figure 16, left**). The total opening width of the cracks amounted up to 46 cm at maximum (**Figure 16, right**), and the residual settlement at the embankment shoulder was about 10 to 20 cm. In addition, the embankment between the upper and lower ponds became partly wet (**Figure 17**), suggesting a sign of piping. This location corresponds to a boundary between the original embankment constructed 40 years ago and the newer embankment re-constructed 6 years ago.

After the earthquake, in order to avoid instability of these embankments, the water level in both ponds were lowered by about 1 m. In order to cope with the current influent flow rate of 120 liters per second, which exceeds the design flow rate of 38 liters per second, the oxidation period had to be reduced down to 5 hours from the design value of 10 hours. These operations resulted into poor quality of treated water, which was used for irrigation purposes. Because the pipes to distribute the treated water were also damaged by the earthquake, it leaked into the adjacent Osmore River, affecting the quality of the river water.

It is reported that this sewage treatment facility will be closed after constructing a new facility on the downstream side, which would cover all the demand from the residential areas.

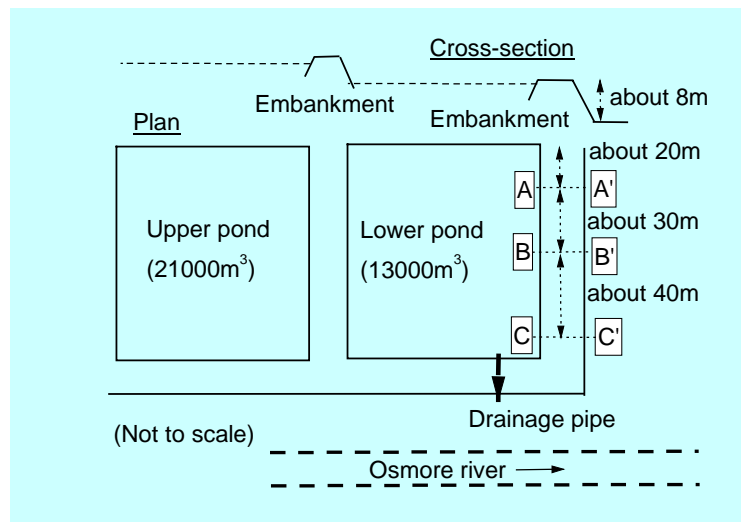


Figure 15. Plan of two oxidation ponds for sewage treatment

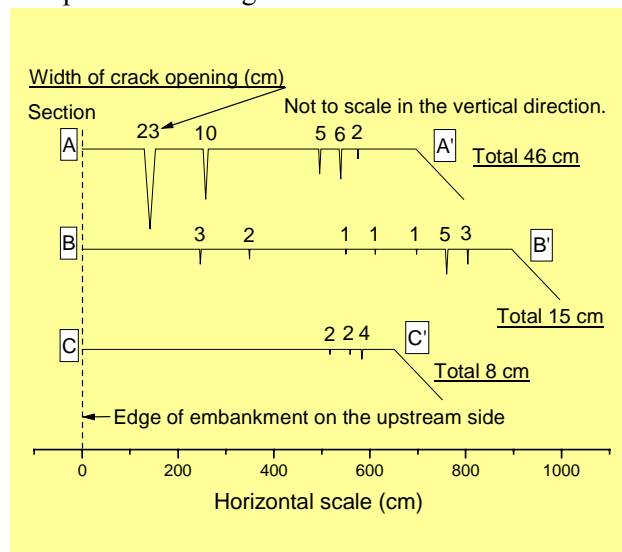


Figure 16. Longitudinal cracks



Figure 17. Embankment between the upper and lower ponds

(3) Expansive soils (Junichi KOSEKI)

At San Antonio in Moquegua, one school constructed on expansive soil layers suffered extensive cracks in the walls and floors (**Figure 18**). They had been formed before the earthquake, which were not worsened by the earthquake. Similar damage to adjacent houses was also observed. It is reported that the expansive soil layers were activated by water leaking from sewage pipes installed in the affected area.

In Moquegua, a plan of developing a new residential area for those who lost their houses in the severely damaged area (San Francisco, **Figures 6 and 7**) is under way. In order to avoid any damage in the newly developed area due to the expansive soils, it is required to establish procedures for detecting the existence of expansive soil layers and for evaluating their effects on buildings and underground pipes.



Figure 18. School constructed on expansive soil layers

LA PUNTA, CAMANA (Hiroshi SATO and Kazuo KONAGAI)

The earthquake also generated a tsunami, which struck the south central portion of Peruvian coastline stretching from the town of Atico in the north, to Matarani in the south. Camana and its vicinity including La Punta located directly in the center of the affected coastline was the hardest hit zone. La Punta is a summer resort located along a narrow strip of beach with Los Cerrillos Hill rising behind. 26 people were reportedly killed by the tsunami, with roughly 70 still missing. Though tragic, this death toll was fairly light considering the location of the resort, because the tsunami occurred during the southern hemisphere winter.

The orange colored zone in **Figure 19** is considered to have been inundated with water. The surges destroyed a great number of dwellings, hotels and restaurants there (**Figures 20** and **21**). The inundated zone was covered thin with wet fine silty soils suggesting that the water surged over the zone was stopped there for a while as is shown in **Figure 22(c)**. From a number of RC columns pushed down (**Figure 22(a)**), possible directions of tsunami surges were estimated (**Figure 22 (b)**).

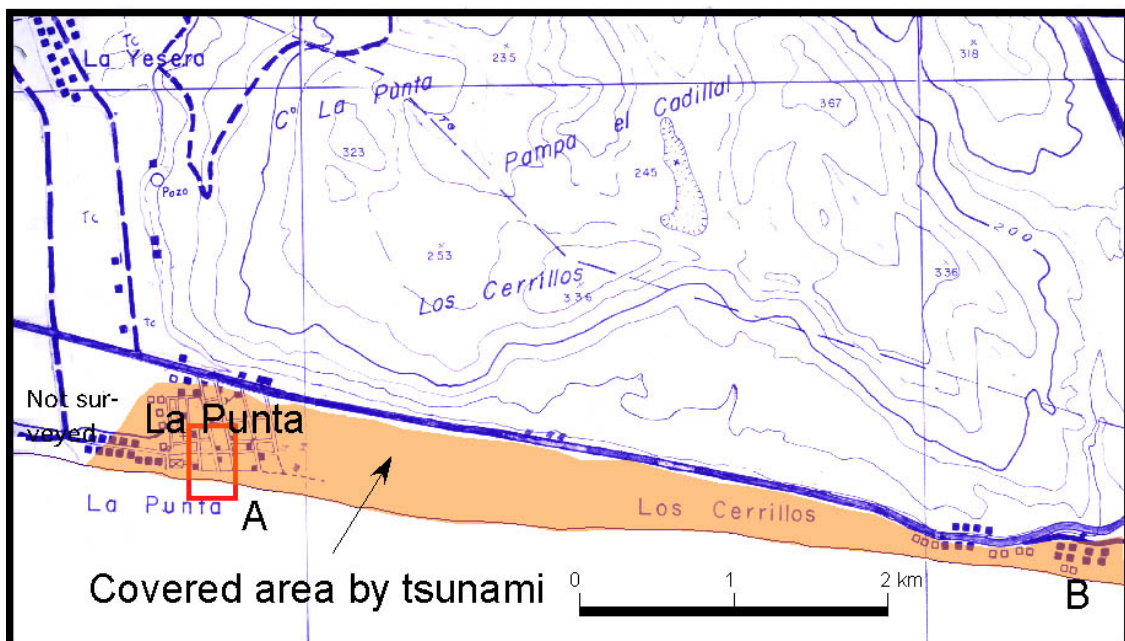


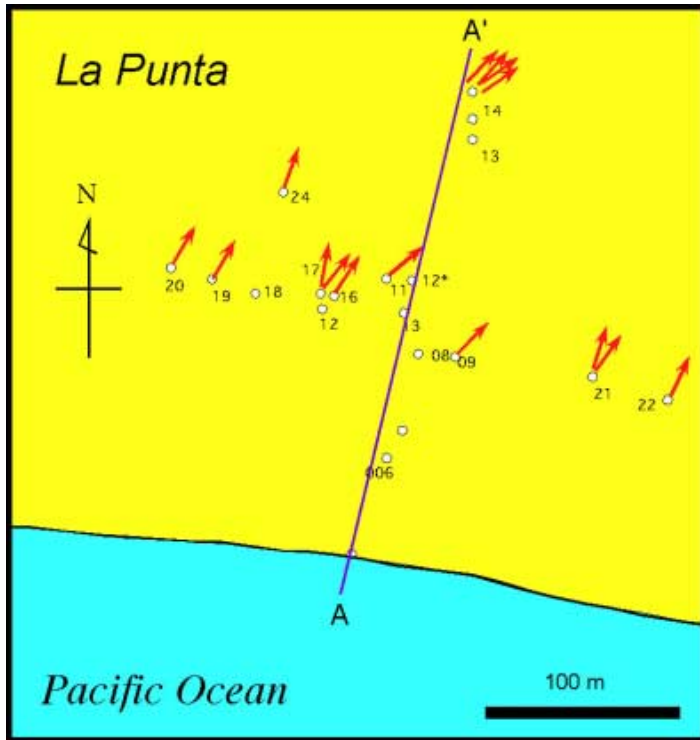
Figure 19. Inundated zone, La Punta:



Figure 20. Destroyed dwellings by tsunami



Figure 21. A car caught in soft silty soils

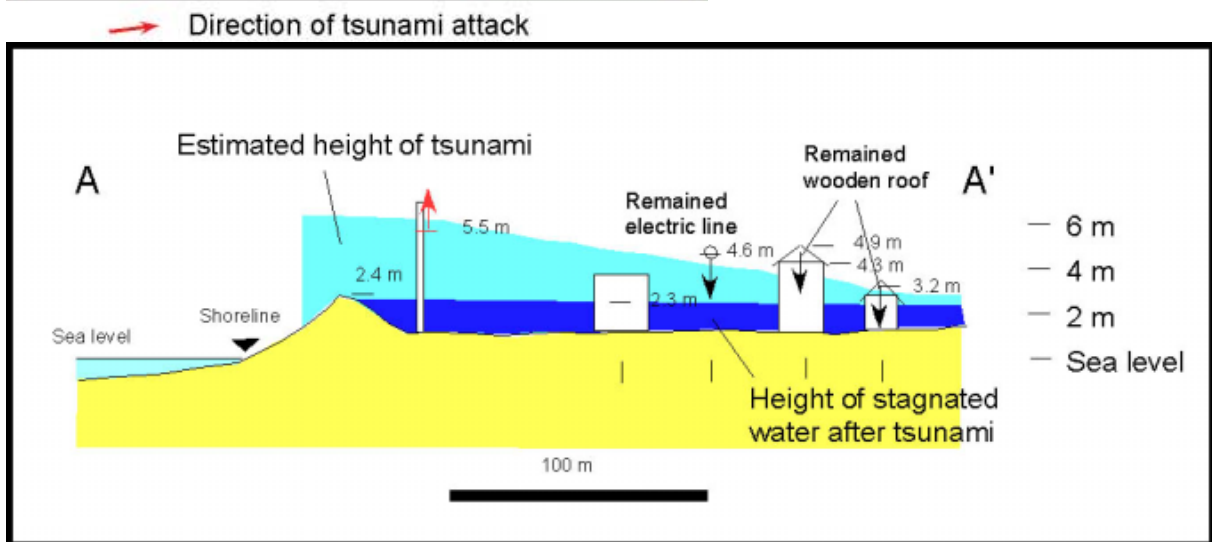


↑ (a) reinforcing bars bent by tsunami

← (b) Possible directions of tsunami surge

↓ (c) Variation of estimated tsunami height along AA' line.

Figure 22. Possible directions of tsunami surge and estimated tsunami height



Direction of the surge was also estimated from spalled utility poles (**Figure 23**). Two lines of utility poles along the coast were examined. Most poles on the front were still standing almost upright while those about 100m inland were more or less tilted because their foot soils were scoured by the surge. Probably for this reason, spalled poles were mostly found on the front. Lateral hair cracks were found on some poles, which seemingly suggest that the poles have experienced lateral shake before the area was inundated. The red arrows show inferred directions of strong ground motion, which seem to have been intense in about EW direction.

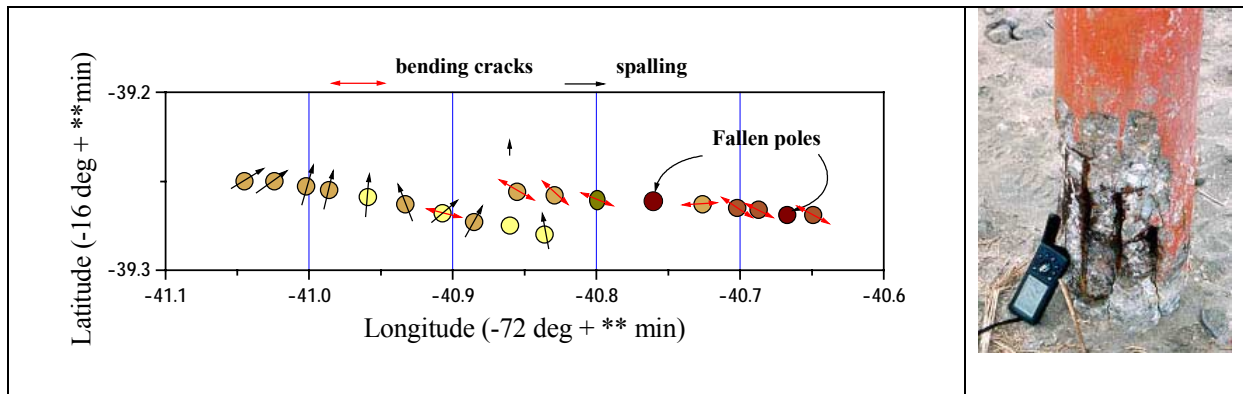


Figure 23. Spalled and cracked utility poles

AREQUIPA

Geotechnical issues (Junichi KOSEKI)

Liquefaction occurred in a lowland of Arequipa (at Lara, Socabaya district; latitude of $S16^{\circ}27.271'$, longitude of $W71^{\circ}32.148'$, and elevation of 2288 m). It induced lateral spreading of ground as typically shown in **Figures 24a** and **24b**. The plan of the affected area is shown in **Figure 25**. The lateral spreading caused collapse of brick walls (**Figure 26a**) and closing of drainage channels that had an original opening width of about 50 cm (**Figure 26b**). Several cracks were also formed in almost level ground at a horizontal distance of about 25 m from the closed drainage channel (**Figure 26c**). It should be noted that there was no damage to concrete pipes with a diameter of about 50 cm used for the drainage channel to under-pass an unpaved road (**Figure 25**).

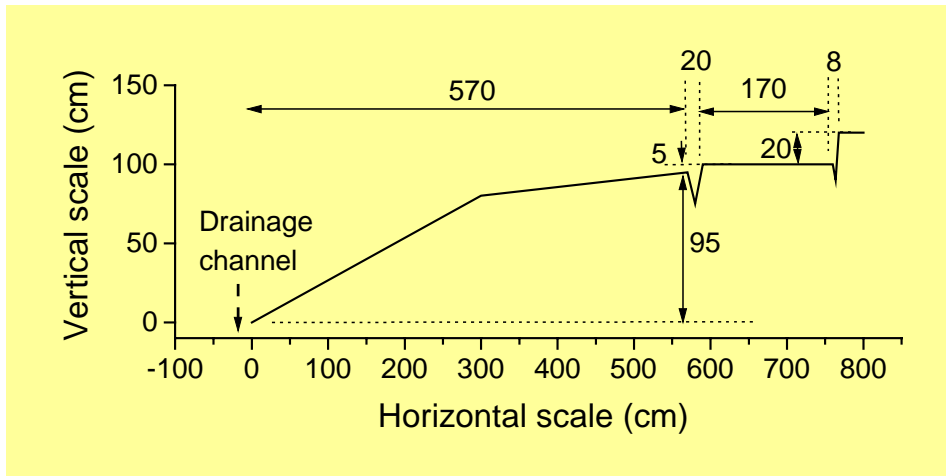
In the affected area, one house suffered uplift of sewage catch basin by about 20 cm (**Figure 26e**) and heaving of house floor due to sand boils (**Figure 26f**). The boiled sand was black under wet state and white under dry state, possibly containing some volcanic or organic components, which also contained coarser particles having a maximum diameter of about 5 mm. It is reported that the heaving took place during the earthquake shaking. It was accompanied by additional ejection of water that lasted for about 1 day, which may have been affected by the re-excavation work of the closed drainage channel.

It should be noted that a sewage manhole with a diameter of about 60 cm and a depth of *** cm below the ground surface (Mr. Carlos Huaman Egoavil at CISMID is going to get this information) located near the undamaged concrete pipe (**Figure 26**) did not suffer any damage or uplift. In contrast to this, the uplifted sewage catch basin had a diameter of about 40 cm and an original depth of about 50 cm below the ground surface, suggesting that its bottom was located above the ground water table even before the earthquake. In addition, it is reported that extensive sand boiling took place around the uplifted catch basin. This uplift damage was, therefore, estimated to have been caused by the upward forces exerted by the boiling sands, not by the loss of stability against uplift due to generation of excess pore water pressures in the liquefied soils.

Detailed investigation is required on the soil conditions at this site, which will provide useful information on liquefaction susceptibility in lowland areas in Arequipa.



(a) Lateral spreading toward drainage channel



(b) Cross-section of lateral spreading

Figure 24. Liquefaction-induced lateral spreading (Lara, Socabaya District, Arequipa)

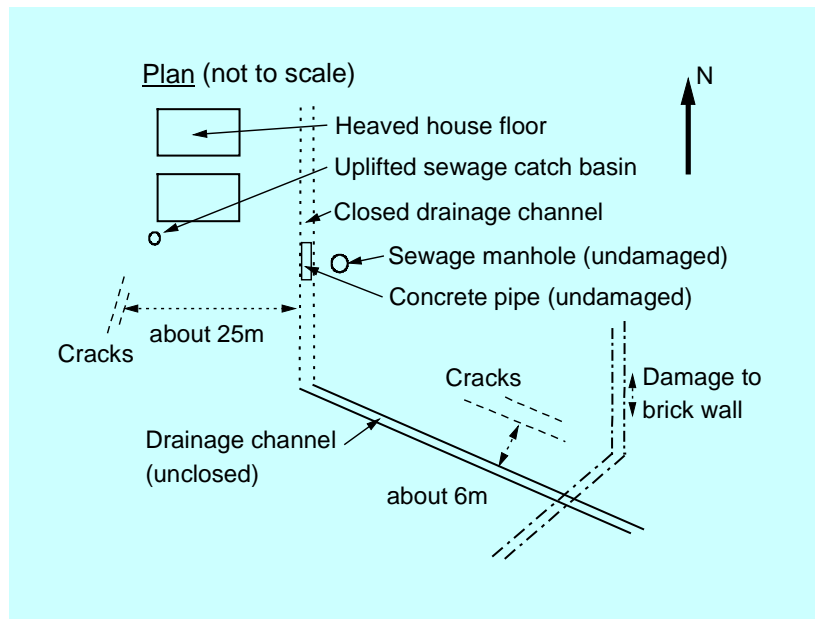


Figure 25. Plan of affected area (Lara, Socabaya District, Arequipa)



(a) Collapsed brick wall due to lateral spreading



(b) Re-excavated drainage channel that was clogged with spread soil



(c) Cracking in ground surface located at a horizontal distance of about 25 m from drainage channel



(d) Uplift of sewage catch basin located near drainage channel



(e) Heave of house floor due to sand boil

Figure 26. Liquefaction-related damage (Lara, Socabaya District, Arequipa)

Pan American Highway Road and Bridge Damage

At the 1213 km of the Pan American Highway the ground shaking damaged the pavement so much that it had to be removed to allow the traffic to pass (**Figure 27**) and heavy traffic was redirected to another route. The white rail side guard along the road buckled severely due to the large soil deformations as seen on the right side of **Figure 28**. The large ground deformations may have been a combination of a basin effect and soft soil layers since the damaged part of the road is situated in an alluvial valley. Similar road damage was observed at other alluvial valleys along the part of the Pan American highway between Tacna and Moquegua.



Figure 27. Pan American Highway Pavement removed after damaged due the earthquake (looking in southbound direction).



Figure 28. Buckled side guard (looking in northbound direction).



Figure 29. Settlement of bridge approach and cracking of road. Only one lane is open for traffic (looking in southbound direction).

