Provisional Report of the June 23, 2001 Atico Earthquake, Peru[1]

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1. INTRODUCTION

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 ERS (Earthquake Resistant Structure Research Center, Institute of Industrial Science, University of Tokyo) and CISMID (Japan-Peru Center for Earthquake Engineering and Disaster Mitigation) were organizing an EQTAP[5] workshop at Lima for a possible collaboration on researches for earthquake disaster mitigation. To discuss this issue on the spot, ERS 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 (ERI, University of Tokyo, member of NOAA at that time, *Tsunami*), the JSCE/EQTAP team was finally organized.

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 report outlines the findings obtained through the reconnaissance survey and some comments by some individuals

2. 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.

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[1], The greater part of the report was taken from the authors' provisional report put up on http://www.jsce.or.jp/e/index.html

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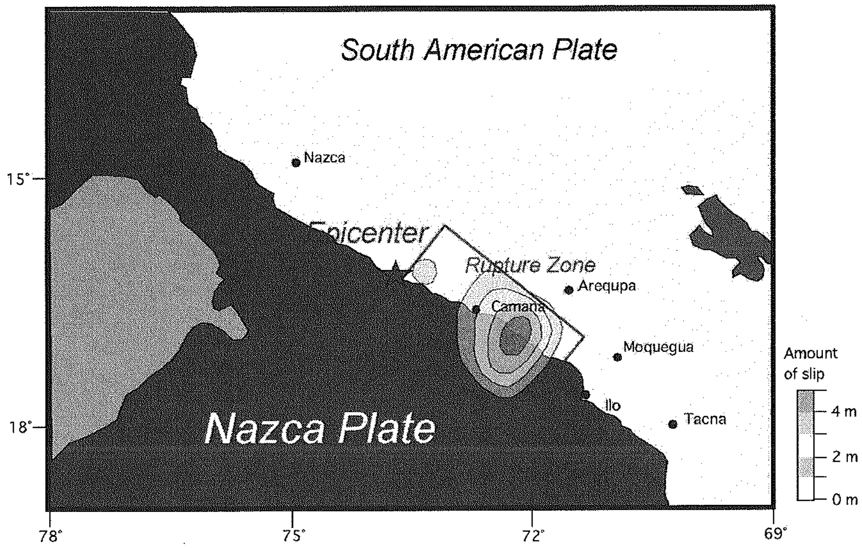
[5] EQTAP: "EarthQuake and Tsunami disaster mitigation in the Asia and Pacific region" project, Ministry of Education, Culture, Science and Technology.



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).

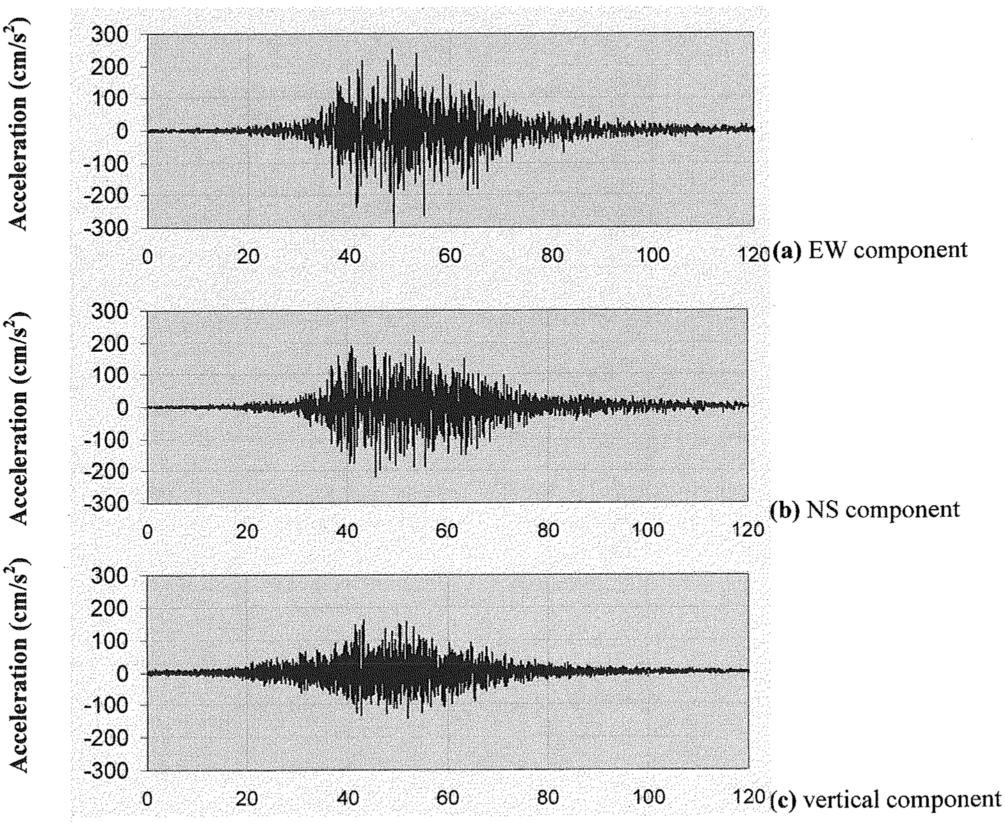
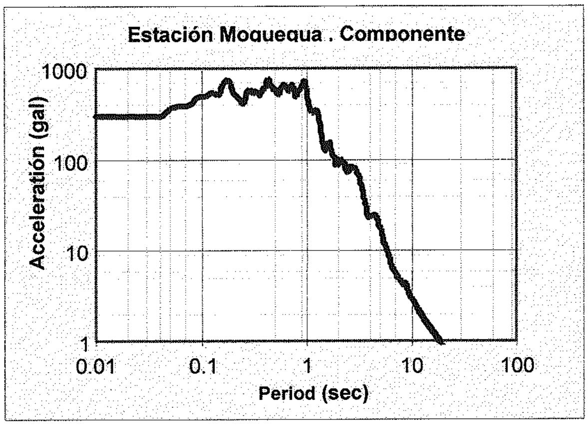
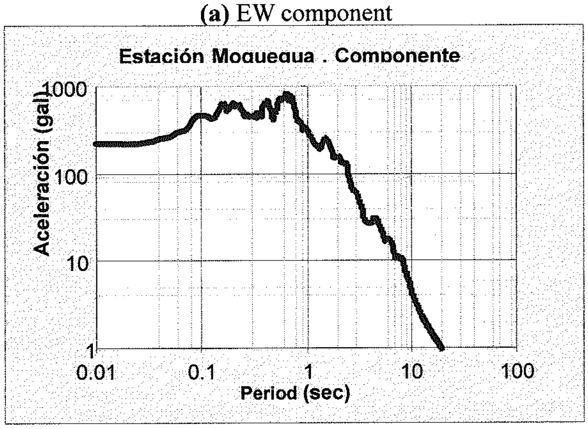


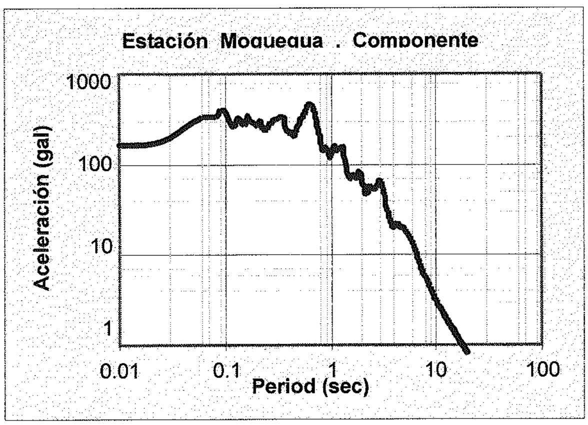
Figure 2. Acceleration time histories at Moquegua



(a) EW component



(b) NS component



(c) UD component

Figure 3. Acceleration time histories at Moquegua

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.

3. OBSERVED SITE EFFECT AND MICROTREMOR MEASUREMENT

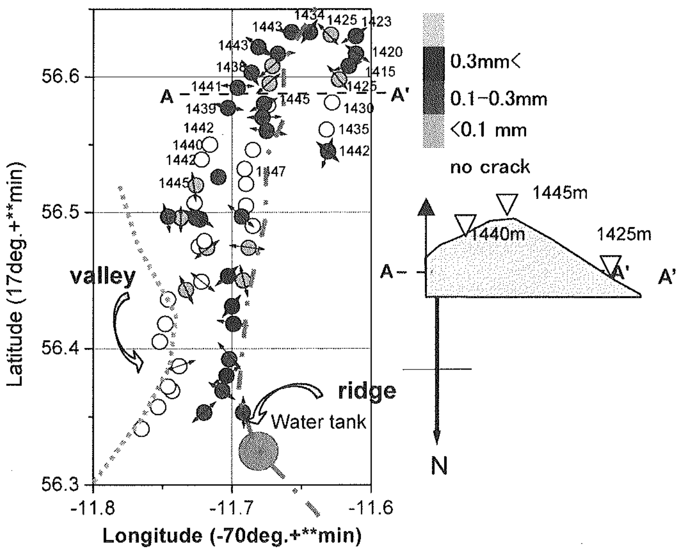
San Francisco area, Moquega

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 4**).

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 4 View of the terrace next to San Francisco hill



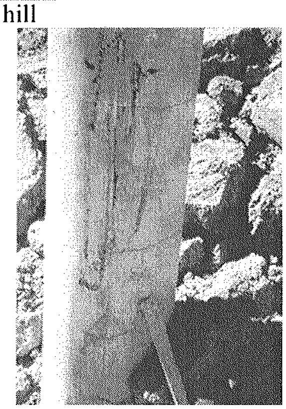


Figure 5. Distribution of cracked utility poles in San Francisco area, Moquega: Numbers put by circles show elevations of utility poles measured by using a GPS receiver.

Figure 5 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 wile those around the highest peak of the ridge near a water tank 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.

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 6**). 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** 7. Since EW direction is about normal to the ridge, this fact is consistent with the finding from the investigation of cracked utility poles.

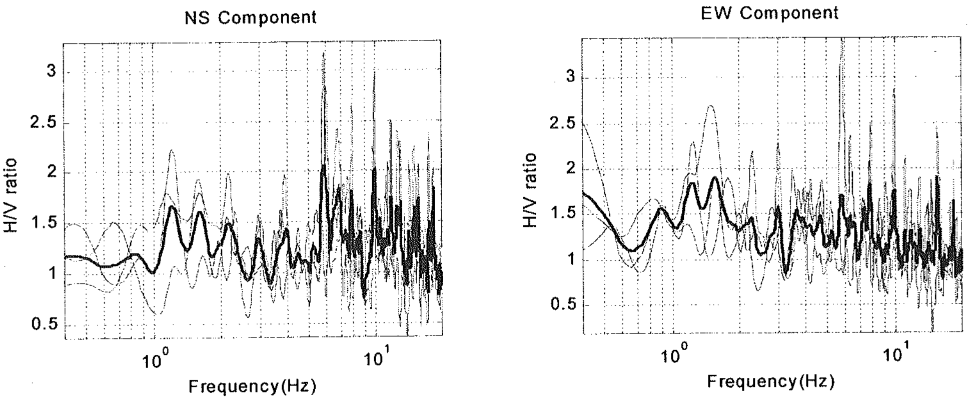


Figure 6. H/V ratio at the toe

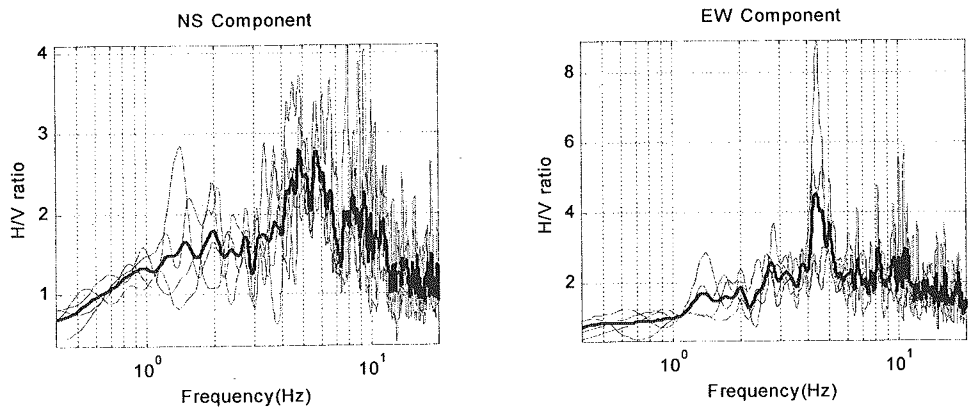


Figure 7. H/V ratio at the top

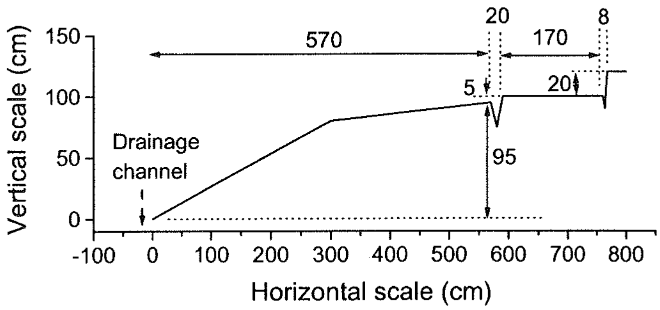
4. GEOTECHNICAL HAZARDS

The plateau, on which such affected cities as Tacna, Moquega and Arequipa are located, is for the most part barren, and therefore surface soils are mostly dried up and cemented stiff excluding those found at some oases scattering along some rivers. Therefore, geotechnical hazards were found limited in those wet areas.

Liquefaction

Liquefaction occurred in a lowland of Arequipa (at Lara, Socabaya district; latitude of S16°27.271', longitude of W71°32.148', and elevation of 2288 m). It induced lateral spreading of ground as typically shown in **Figure 8**. The plan of the affected area is shown in **Figure 9**. The lateral spreading caused collapse of brick walls (**Figure 10**a) and clogging of drainage channels that had an original opening width of about 50 cm (**Figure 10b**). Several cracks were also formed in almost level ground at a horizontal distance of about 25 m from the closed drainage channel (Figure 3.3c). 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 9**).

(a) Lateral spreading toward drainage channel



(b) Cross-section of lateral spreading at line A-A' in Figure 3.2

Figure 8 Liquefaction-induced lateral spreading (Lara, Socabaya District, Arequipa)

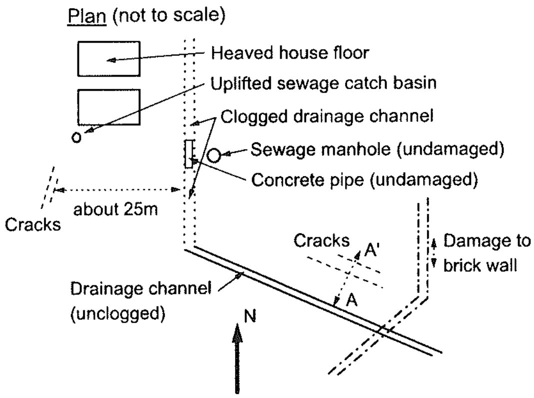
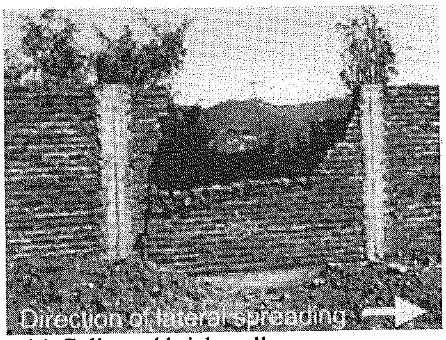
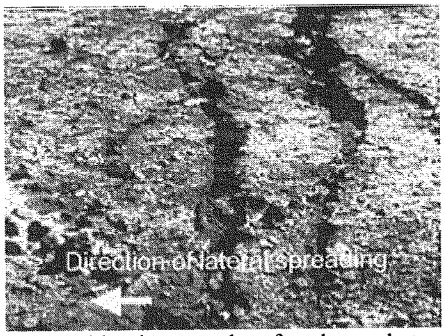


Figure 9 Plan of affected area (Lara, Socabaya District, Arequipa)



(a) Collapsed brick wall

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

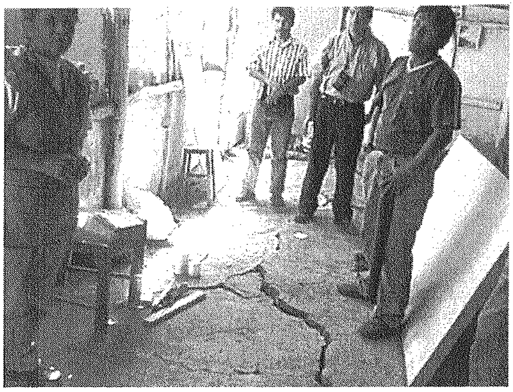


(c) Cracking in ground surface located at horizontal distance of about 25 m from drainage channel

(d) Uplift of sewage catch basin

Figure 10 Liquefaction-related damage (Lara, Socabaya District, Arequipa)

In the affected area, one house suffered uplift of sewage catch basin by about 20 cm (**Figure 10d**) and heaving of house floor due to sand boils (**Figure 10e**, next page). 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.



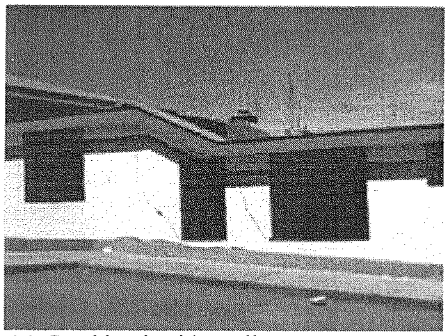
(e) Heave of house floor due to sand boil
Figure 10 Liquefaction-related damage (continued)

It should be noted that a sewage manhole with a diameter of about 60 cm located near the undamaged concrete pipe (**Figure 9**) did not suffer any damage or uplift. In contrast to this, the uplifted sewage catch basin (**Figure 10d**) 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.

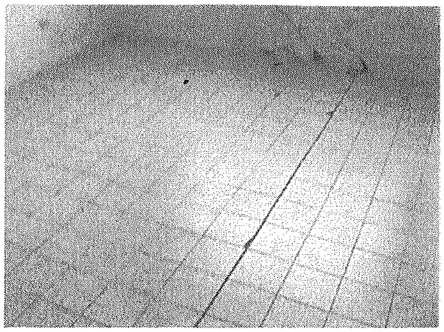
Detailed investigation is required on the soil conditions at this site, which will provide useful information on liquefaction susceptibility in lowland areas in Arequipa.

Expansive soils

At San Antonio in Moquegua, one health center constructed on expansive soil layers suffered extensive cracks in the walls and floors (**Figure 11**). 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.



(a) Cracking in side wall



(b) Cracking in floor

Figure 11 Damage to health center constructed on expansive soil layers (San Antonio, Moquegua)

In Moquegua, a plan of developing a new residential area for those who lost their houses in the severely damaged area (San Francisco) 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.

Flexible gabion wall

Figure 12 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 Stabilzed Earth structures. (Photo taken at the masonry factory in Moquegua, below the hotel El Mirador).

Figure 12. Deformed Gabion wall

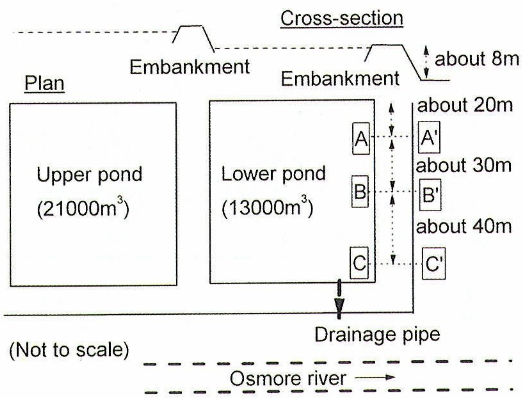


Figure 13. Plan of two oxidation ponds for sewage treatment

Sewage treatment facility

Figure 13 shows a plan of two oxidation ponds for sewage treatment in Moquegua. The upper and lower ponds have a capacity of 21000 and 13000 m^3, 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 14, left**). The total opening width of the cracks amounted up to 46 cm at maximum (**Figure 14, 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 15**), 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.

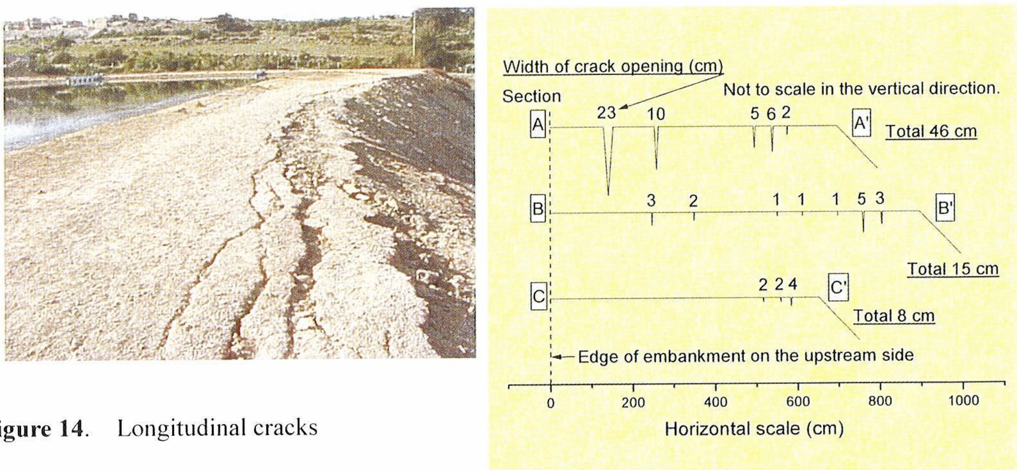


Figure 14. Longitudinal cracks

Figure 15. Embankment between the upper and lower ponds

Pan American Highway Road and Bridge Damage

At the time of the survey, conducted about 25 days after the earthquake, there was no interruption along the Pan American Highway.

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 16**) 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 17**. The large ground deformations may have been a combination of a basin effect and soft soil layers. The damaged part of the road is situated in an alluvial valley and similar road damage was observed in other alluvial valleys along the Pan American highway between Tacna and Moquegua.

Figure 16: Pan American Highway Pavement removed after damaged due the earthquake (looking in Southbound direction).

Figure 17: Buckled side guard (looking in Northbound direction).

Figure 18: Settlement of bridge approach and cracking of road. Only one lane is open for traffic (looking in southbound direction).

Some road embankments along the Pan American Highway between Moquegua and Tacna, and between Arequipa and Moquegua were damaged. The embankment shown in **Figure 19** had a height of about 30 m, which suffered residual settlement of about 5 cm over a length of 72 m with cracking in the pavement having a maximum width of about 30 cm.

(a) Settlement of embankment crest

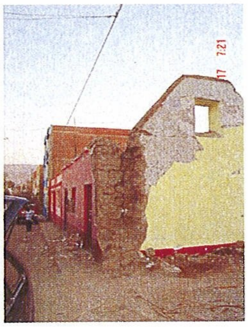
(b) Side view of embankment

Figure 19 Damage to road embankment (Pan American Highway between Moquegua and Tacna)

5. PERFORMANCE OF REINFORCED MASONRY VS ADOBE

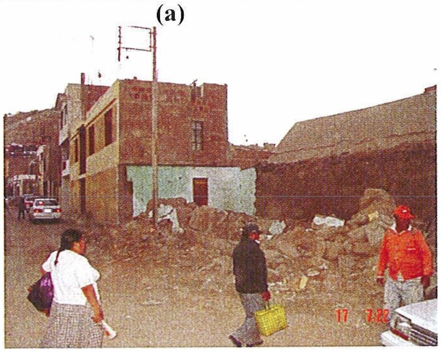
Structures of adobe performed in general badly as observed in many other earthquakes. Below follows a sketch and some figures showing collapsed adobe structures whereas neighboring reinforced masonry structures suffered on only minor damage (**Figure 20**). **Points (b)** and **(c)** show that a corner of an adobe structure is a weak point.

(a)

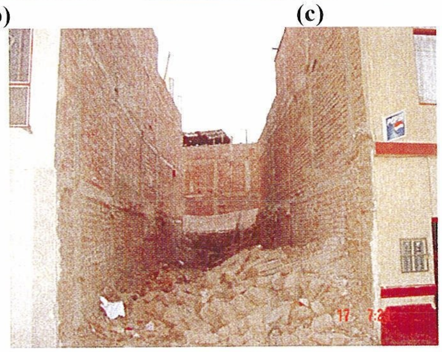


(b)

(c)



(d)



(e)

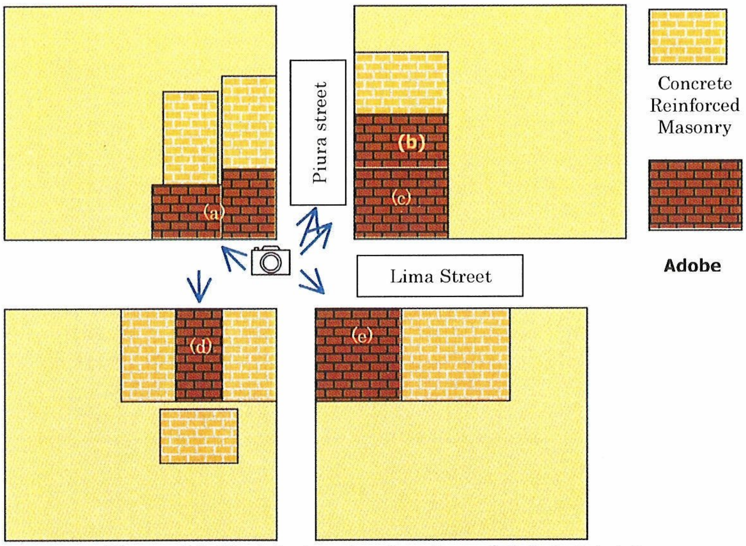


Figure 20. Sketch showing location of **Points (a)-(e)**.

In **Figure 21** and **22**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 23**).

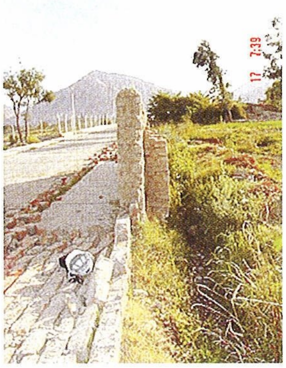


Figure 21: Standing adobe wall and fallen masonry wall.

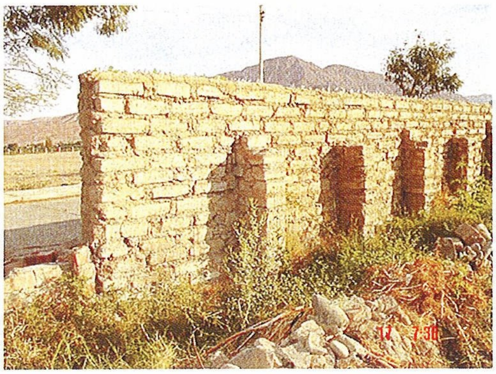


Figure 22: Close up of side support

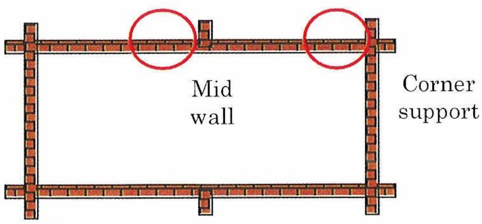


Figure 23: Plan view of overlapping adobe walls with mid wall side support.

6. TSUNAMI

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 dark colored zone in **Figure 24** is considered to have been inundated with water. The surges destroyed a great number of dwellings, hotels and restaurants there (**Figures 25** and **26**). 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 27(c)**. From a number of RC columns pushed down (**Figure 27(a)**), possible directions of tsunami surges were estimated (**Figure 27 (b)**).

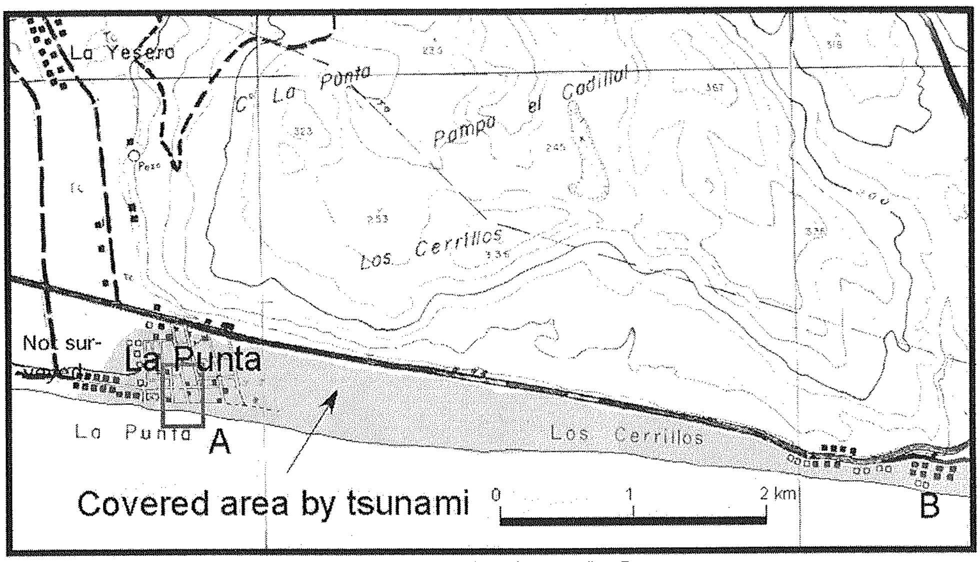


Figure 24. Inundated zone, La Punta:

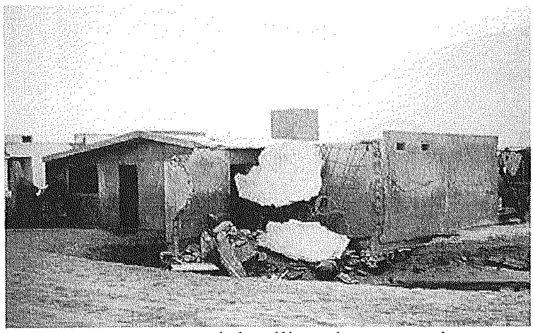
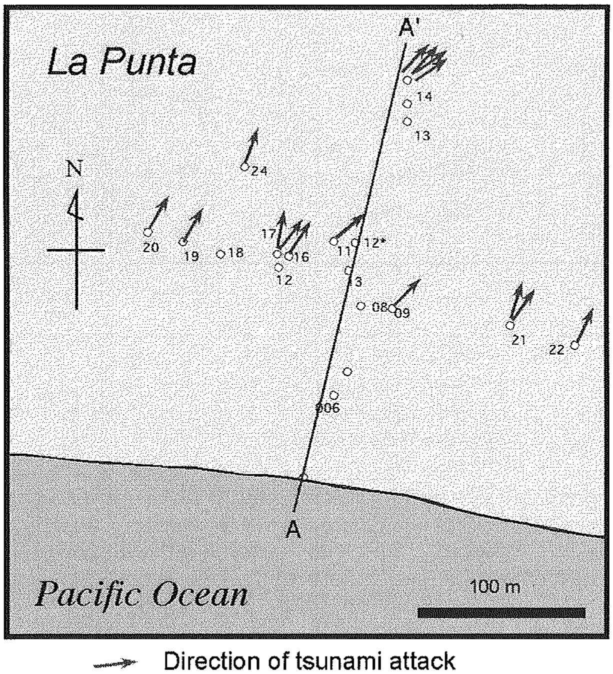
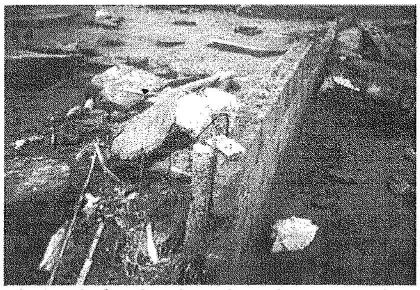


Figure 25. Destroyed dwellings by tsunami

Figure 26. A car caught in soft silty soils



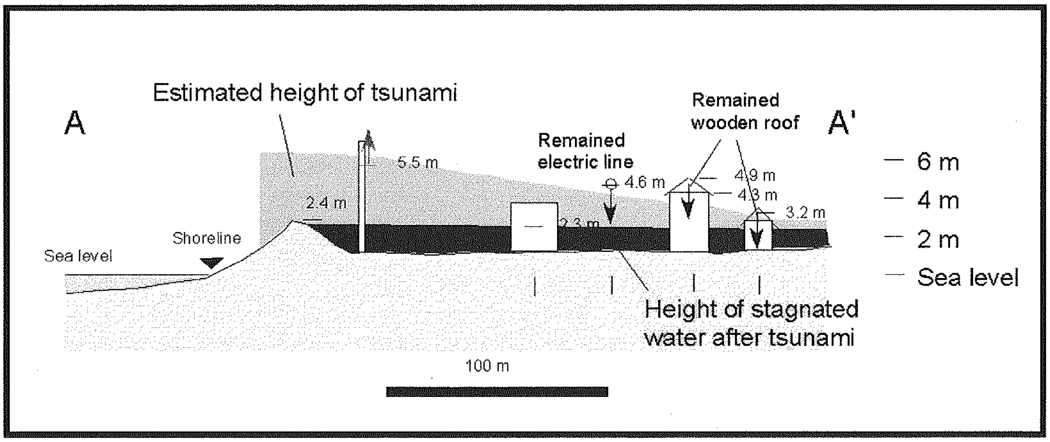


↑ **(a)** reinforcing bars bent by tsunami

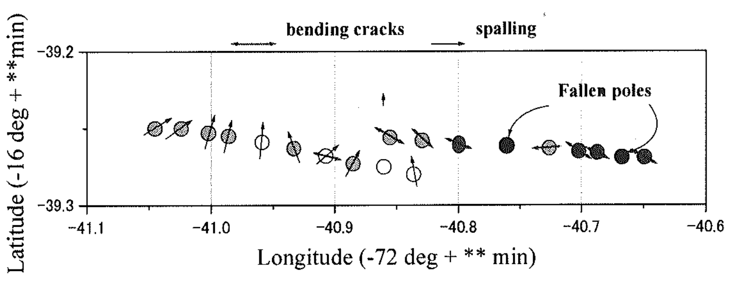
← **(b)** Possible directions of tsunami surge

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

Figure 27. Possible directions of tsunami surge and estimated tsunami height



Direction of the surge was also estimated from spalled utility poles (**Figure 28**). 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 (one-head arrows). Lateral hair cracks were found on some poles, which seemingly suggest that the poles have experienced lateral shake before the area was inundated. The two-heads arrows show inferred directions of strong ground motion, which seem to have been intense in about EW direction.



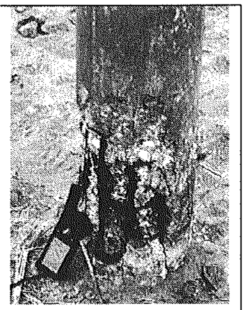


Figure 28. Spalled and cracked utility poles

7. SUMMARY

The influence of local geologic and soil conditions on the intensity of ground shaking was recognized through this reconnaissance, and the amplified tremors flattened some local areas, where the dwellings were mostly made out of mud bricks. In the Atico earthquake, total 41,394 dwellings were reportedly destroyed or heavily damaged. In urban areas, more than 80% of the housing infrastructures are made of masonry and adobe/tapial while in rural areas almost 70% of the dwellings are made of the latter [INEI, 1993]. As for RC buildings, the Peruvian Seismic Design Code covers all necessary aspects of their designs, and it is mandatory for a licensed contractor to submit a set of design drawings for revision and approval. It is, however, often reported that buildings do not fulfill its requirements probably because in-situ inspections are not mandatory. Moreover, many people, without being licensed, have been constructing their dwellings, and damaged RC structures are mostly found in them. In general, adobe structures performed badly as observed in many other earthquakes except those with welded wire reinforcement meshes provided to their walls[6], the fact proving the efficiency of strengthening existing dwellings in this simple manner.

Red Cross's documents say that approximately 2,700 people were injured and the death toll of 70 to 100 was reached in this earthquake. The death tall was fairly light considering the serious magnitude of the damage to dwellings. Many refugees, being interviewed, said that they were luckily out of their dwellings shopping or working etc. As was described in Chapter 6, the tsunami was also the cause of serious destructions in La Punta, Camana etc. Though tragic, only 26 people were reportedly killed by the tsunami, with roughly 70 still missing, because the tsunami occurred during the southern hemisphere winter and washed the summer resort. However, over 210,000 people lost their houses and were forced to live in tents or in the open. Although Peru lies just south of the equator, only the Amazon region, east of the Andes, has the year-round heat associated with the tropics. In the mountains, temperature drops with elevation, The most seriously affected cities such as Tacna, Moquega and Arequipa are located on a plateau with an elevation of about 1400m or more. The plateau is for the most part barren, and thus temperatures can drop from 20℃ in daytime to sub-zero in nighttime. The alleviation of both physical and mental pains of the people was thus getting more and more pressing matter as the time went on. In making a steady recovery, these issues should draw due attentions.

[6] Zegarra et al (2000) proposed a technique for strengthening of existing adobe structures by providing welded wire reinforcement mesh to the adobe walls. As part of the study, 19 adobe houses at different locations in Peru were reinforced.

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Lastly, All members of the 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.

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