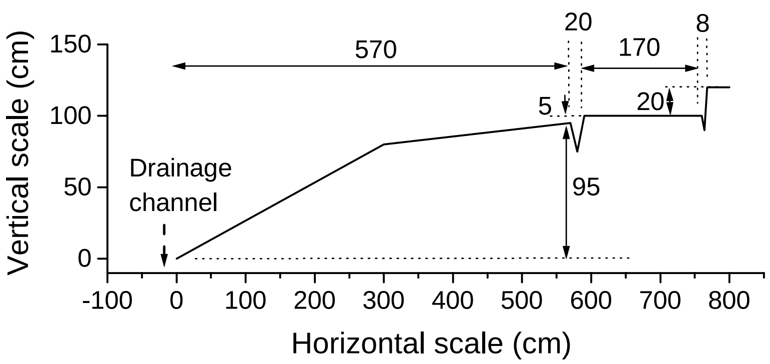
3. GEOTECHNICAL HAZARDS

As was briefly shown in Section 2.4, 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.

3.1 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 3.1**. The plan of the affected area is shown in **Figure 3.2**. The lateral spreading caused collapse of brick walls (**Figure 3.3**a) and clogging of drainage channels that had an original opening width of about 50 cm (**Figure 3.3b**). 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 3.2**).

(a) Lateral spreading toward drainage channel



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

Figure 3.1 Liquefaction-induced lateral spreading (Lara, Socabaya District, Arequipa)

In the affected area, one house suffered uplift of sewage catch basin by about 20 cm (Figure 3.3d) and heaving of house floor due to sand boils (**Figure 3.3e**). 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.

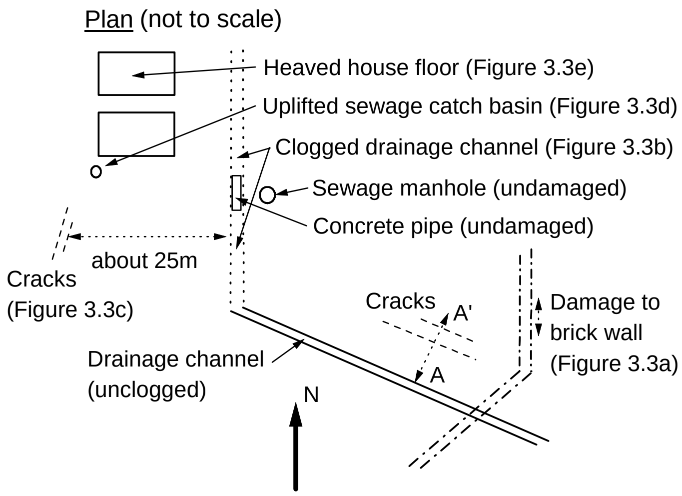


Figure 3.2 Plan of affected area (Lara, Socabaya District, Arequipa)

(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

(b) Uplift of sewage catch basin

Figure 3.3 Liquefaction-related damage (Lara, Socabaya District, Arequipa)

(e) Heave of house floor due to sand boil
Figure 3.3 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 3.2**) did not suffer any damage or uplift. In contrast to this, the uplifted sewage catch basin (**Figure 3.3d**) 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.

3.2 EXPANSIVE SOILS

At San Antonio in Moquegua, one health center constructed on expansive soil layers suffered extensive cracks in the walls and floors (**Figure 3.4**). 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.

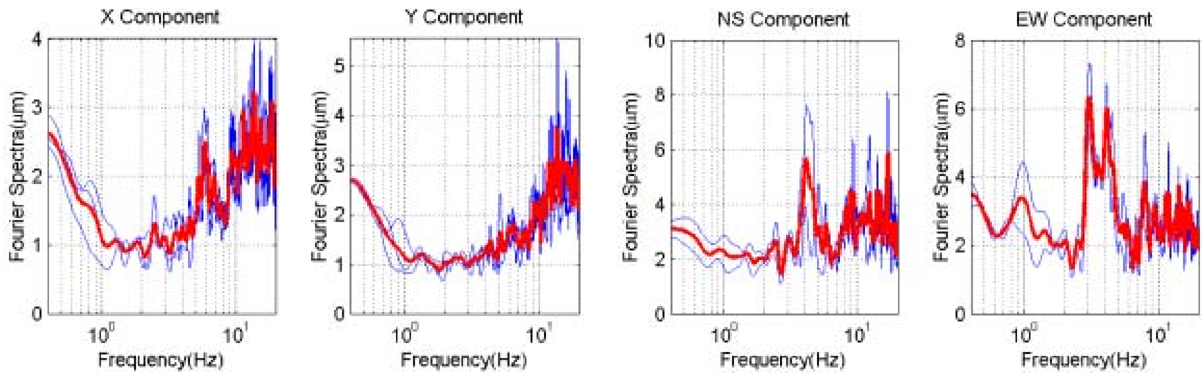
(a) Cracking in side wall

(b) Cracking in floor

Figure 3.4 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.

Microtremors were measured at San Antonio where expansive soils have been identified. The corresponding Fourier spectra are shown in **Figure 3.5.** Although both locations correspond to expansive soils, very different shapes are observed. When comparing the H/V ratio (Nakamura, 2000), differences are also observed (refer to **Figure 2.13**, **chapter 2.3**).



(a) ENACE Residential Buildings **(b)** Health Center

Figure 3.5 Microtremor Fourier Spectra at San Antonio, Moquegua

Upon request of the Peruvian counterpart, microtremors were measured at Chechen, Moquegua. Although this area has been chosen to relocate the people affected by the earthquake, there are serious concerns that the soil at this location is expansive. Although microtremors cannot identify whether a soil deposit is expansive or not, it was expected that by finding some similarities between the frequency contents of microtremors at other locations where expansive soil presence is confirmed could give some indication of the presence of such type of soils at Chechen. A total of 10 sites were measured and the H/V ratio as wells as the Fourier Spectra of the NS and EW components are shown in **Figures 3.6 to 3.8**.

Unfortunately, neither the Fourier Spectra nor the H/V ratio within the frequency range 0.4 to 20Hz showed a clear pattern. The only common feature observed at eight (8) of the observed sites, was the predominance of low frequency components in the Fourier Spectrum such as the one observed at the ENACE Residential Buildings. Both horizontal and vertical components showed this characteristic. Low frequency components involve thicker soil strata and therefore this common feature might evidence the presence of a deep common structure.

In general, ground microtremor observations are used to identify soil dynamic properties such as the site predominant period, which depends on the soil column thickness, shear wave velocity, and mass density. Therefore, by estimating the predominant period and knowing some of the previously mentioned properties, it could be possible to indirectly estimate soil stiffness or density and then compare it to the ranges expected for expansive soils. Another possibility is to perform measurements before and after moistening the soil to detect variations in the soil properties that resemble those expected for expansive soils. By using microtremor measurements only, it is impossible to detect conclusively the presence of expansive soils.

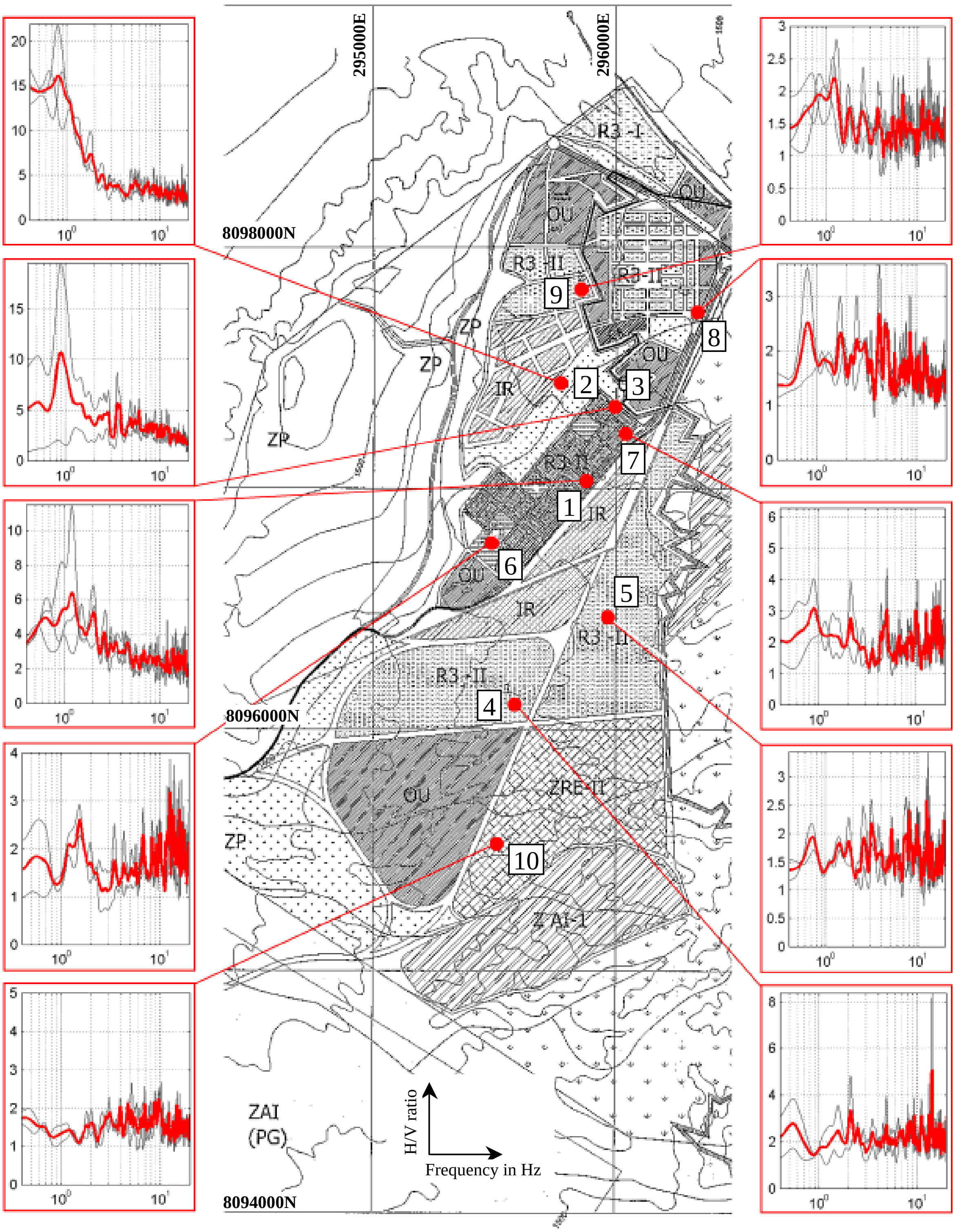


Figure 3.6 Microtremor measurements at Chechen – H/V ratio

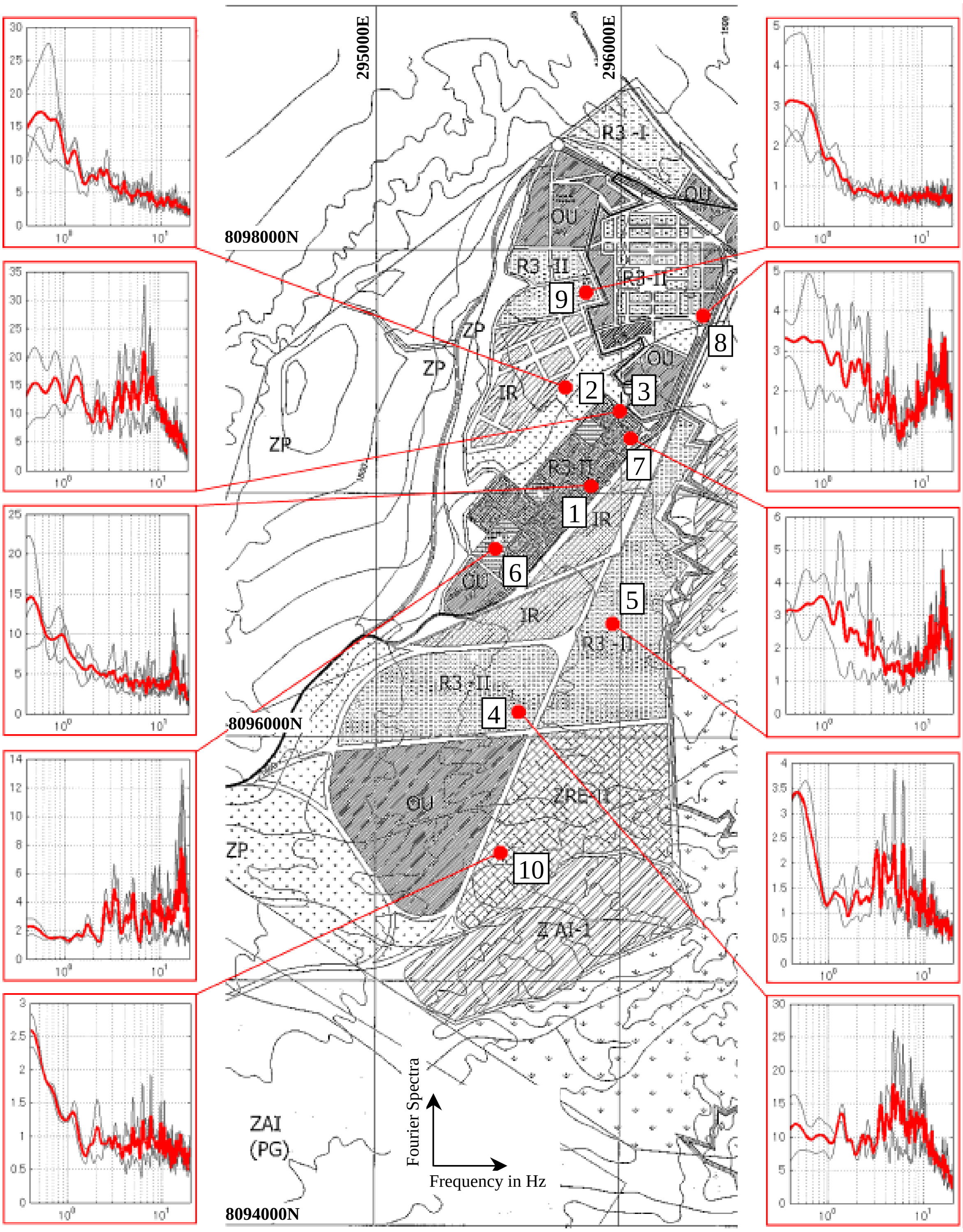


Figure 3.7 Microtremor measurements at Chechen – NS Component Fourier Spectra

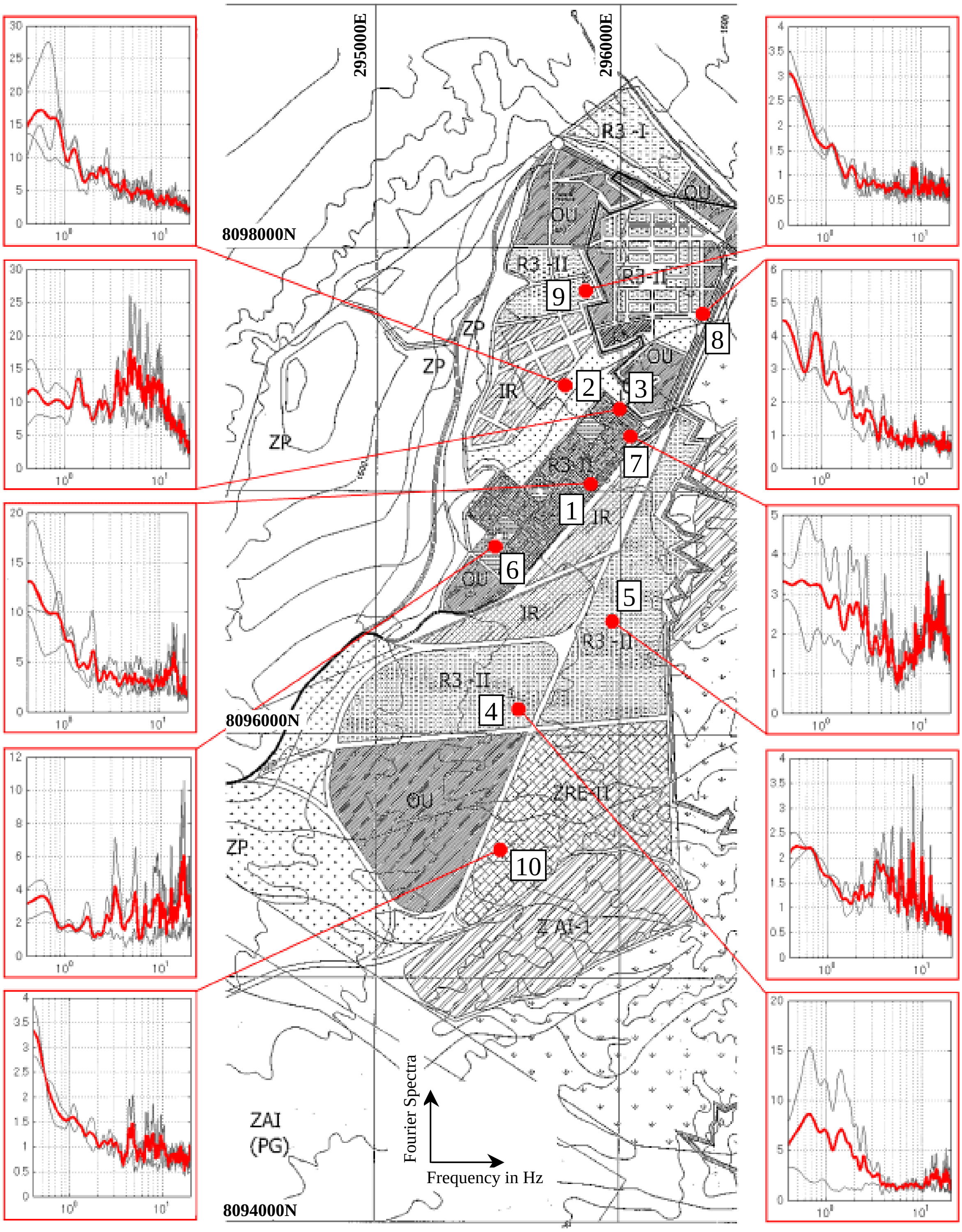


Figure 3.8 Microtremor measurements at Chechen – EW Component Fourier Spectra

3.3 Flexible Gabion Wall

Figure 3.9 below shows a gabion wall that did not rupture even after undergoing a shear strain over 40 % (2.2/5) in the vertical plane. 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).

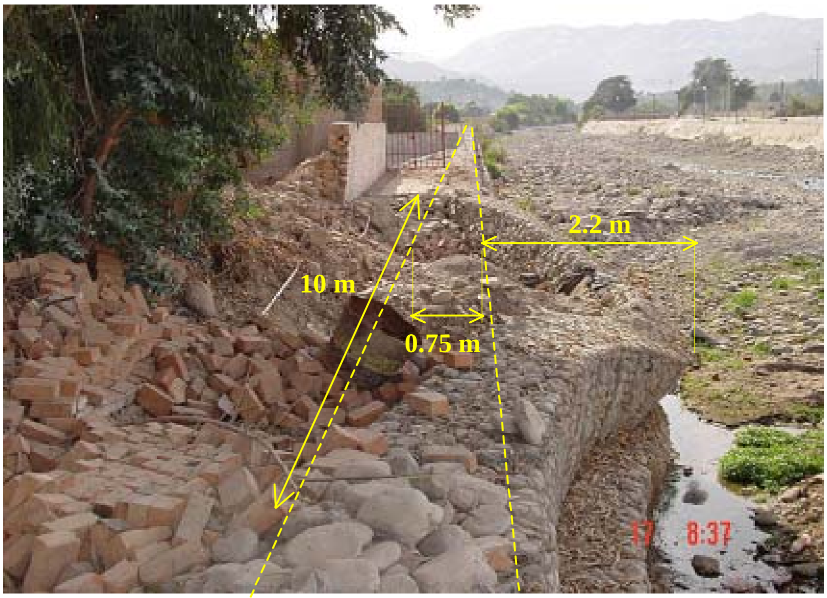


Figure 3.9 Flexible gabion wall.

3.4 DAMAGE TO PAN AMERICAN HIGHWAY

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

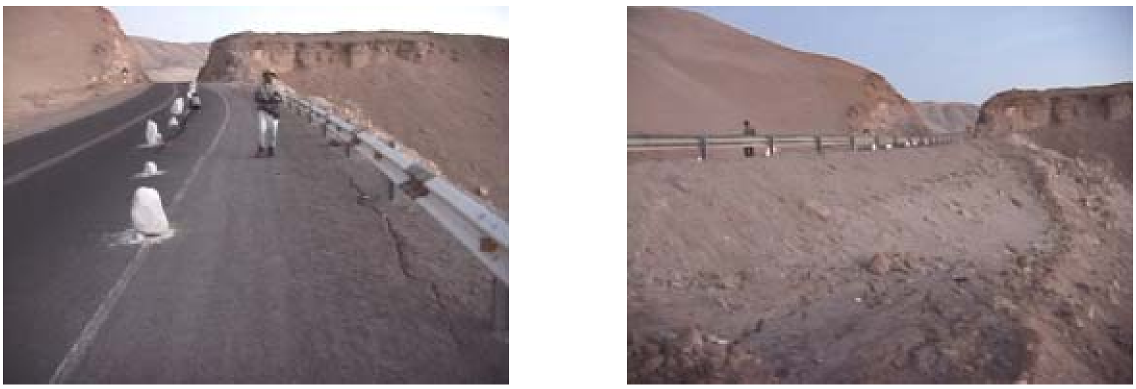
At the 1213 km of the Pan American Highway the ground shaking damaged the pavement so much that it had to be removed to allow the traffic to pass (**Figure 3.10**) and heavy traffic was redirected to another route. The white rail side guard along the road buckled severely due to the large soil deformations as seen on the right side of **Figure 3.11**. 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 3.10: Pan American Highway Pavement removed after damaged due the earthquake (looking in Southbound direction).

Figure 3.11: Buckled side guard (looking in Northbound direction).

Figure 3.12: 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 3.13** 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 3.13 Damage to road embankment (Pan American Highway between Moquegua and Tacna)

3.5 SUMMARY

The survey results on geotechnical issues can be summarized as follows.

1) Liquefaction in a lowland area in Arequipa induced lateral spreading, causing collapse of brick walls and closing of drainage channels. Sand boils heaved a house floor, which possibly caused uplift of a sewage catch basin as well. On the contrary, a sewage manhole and a buried concrete pipe could survive in the affected area.
2) One health center constructed on expansive soil layers in Moquegua suffered extensive cracking without the earthquake effects, which was not worsened by the earthquake. Micro tremors were measured in an attempt to identify the presence of expansive soils. However, no regular pattern of Fourier Spectra or H/V ratio that could lead to such conclusions was found.
3) Road embankments along Pan American Highway suffered residual settlement and partial failure. Road stretches crossing alluvial valleys were suffered more damage probably due to softer soils in the alluvial valleys and basin effects.
4) Future investigations are required on liquefaction susceptibility in lowland areas and on survey procedures to evaluate the existence and effects of expansive soil layers.

(**3.1, 3.2, 3.4, 3.5**/ *Junichi KOSEKI*, IIS, University of Tokyo)
(**3.2/** *Kimiro MEGURO and Paola MAYORCA,* IIS, University of Tokyo)
(**3.3, 3.4**/ *Jörgen JOHANSSON*, IIS, University of Tokyo)

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