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SEISMIC MICROZONATION OF MOQUEGUA CITY, PERU

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SUMMARY

After the June 23, 2001 Southern Peru Earthquake that caused severe damage in Moquegua city, the local government planned to relocate the homeless in a new expansion zone, located behind the hills. To help implementing this plan, the Japan Peru Center for Earthquake Engineering Research and Disaster Mitigation, of the National University of Engineering, CISMID-FIC-UNI, carried out the seismic microzonation study. A large number of geotechnical and geophysical exploration tests, such as microtremor measurements, and seismic refraction tests, were performed, which allowed to define four different zones according to the mechanical and dynamical characteristics of the foundation soils. Two main problems were identified, the first one is the presence of high potential expansive soils, associated to the sedimentary clays from the Tertiary Moquegua Formation, that outcrops in the south western hills, and the second one is the high dynamic amplification factor that show the zones located in deep cohesionless coarse materials, and those located over the hills. GIS based hazard and vulnerability maps were generated, which were calibrated with the observed damage in this city. Recommendations for the foundation design, and the seismic design parameters in each zone are proposed as a result of this study, which were included by the Local Authorities in the Expansion Plan Regulation.

INTRODUCTION

On June 23, 2001, at 15:33 local time, a strong earthquake struck southern Peru. According to the USGS a revised magnitude of Mw 8.4 was computed for this event. The earthquake occurred along the south west coast of Peru, at the boundary between the Nazca and South American plates. The epicenter was located at the shore, 82 km NW from Ocoña City, Arequipa. The affected area include cities as far as Arica and Iquique in northern Chile, being the cities of Ocoña, Camana, Arequipa, Moquegua, Ilo and Tacna severely damaged. The damage intensity in the epicentral area reached VIII degrees in the Modified Mercalli Intensity, Tavera [1].

A strong motion record of the mainshock obtained by CISMID-FIC-UNI accelerographic network at the Downtown Moquegua Station shows a peak acceleration of 0.30 g, with a total time length of the record

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of 200 seconds, where, the duration of the intense phase of the motion lasts for about 35 seconds, Aguilar [2].

Damage to buildings, bridges and roads varied across the affected region, being in some places directly correlated to local soil conditions. The damage to buildings was mainly nonstructural, with the majority of the structural damage occurring in self constructed adobe and unreinforced masonry buildings. The most affected city was Moquegua, where a great number of old adobe structures collapsed. According to Civil Defense, the dead toll reach 104, and about 4000 persons were injured. In the affected region a total of 59,000 houses were affected or destroyed by this earthquake, Moreno [3].

After the quake, the local authorities planned to relocate the homeless in the only available expansion area, behind the city surrounding hills, however there were evidences that near this new expansion area highly expansive soils has caused severe damage to structures, as it is showed in the pictures of Figure 1. This figure shows two representative structures in San Antonio Area that were severely damaged by the swelling of the expansive soil, the first one are ten blocks four-story apartment buildings that were built in 1996, and are still unoccupied due to the cracks in their walls and swelling of the floor. The second one is a one story masonry structure health center that was built in 1999, and soon after it was finished wide cracks appeared in its walls due to swelling of the foundation. At the present this center was evacuated and is waiting for retrofitting.

With this precedent, and in order to help with the reconstruction activities, the CISMID-FID-UNI carried out a damage evaluation study of the affected area and developed the seismic microzonation study for Moquegua city, putting special efforts in the geotechnical characterization of the new expansion zone. The results of this study, that is presented in this paper, has been implemented in the Regulation of the Urban Expansion Plan of Moquegua City.

(a)

(b)

Figure 1: Structures Damaged due to swelling of expansive soils in San Antonio Area, Moquegua City. (a) Lopez Albujar Building, built in 1996, and (b) San Antonio Health Center, built in 1999.

GEOTECHNICAL CHARACTERISTICS OF MOQUEGUA CITY

Moquegua city is located on a narrow alluvial valley of the Moquegua River, at the foot of the western Andes Mountains. The city has an average altitude of 1,400 meters above sea level, and is surrounded by steep hills, with altitudes ranging from 1400 to 1800 m.a.s.l. The lower part of the city is settled on the alluvial soil deposit of Moquegua River, constituted by a thick layer of sandy gravels containing a large amount of boulders, while the hills are composed by sedimentary soil deposits of the Terciary Lower Moquegua Formation, which in some areas are covered by a layer of coarse granular soil and tuffs of the Upper Moquegua Formation.

In order to determine the mechanical and dynamical characteristics of the foundation soils all over the city, a large exploration program has been carried out, specially in the selected area for the new expansion zone of the city. A total of 77 four-meter deep manhole pits where excavated, and a large amount of soil samples were taken for analyzing their characteristics in the geotechnical laboratory. Where thick deposits of tuffs and softer conglomerates were found, several plate load tests on saturated soils were performed to evaluate the collapsibility potential of soils, however the results show low percentage of collapsibility . Furthermore, a large number of expansive soil samples were also taken and laboratory testing were performed to determine their expansion potential and their uplift expansion loads. Results show that the free expansion potential of the soils reach up to 18%, and uplift expansion loads as large as 4.5 kg/cm^2 were obtained.

To complement the geotechnical exploration program and determine the dynamic behavior of the foundation soils, geophysical testing consisting in seismic refraction tests and microtremor measurements were also intensely carried out all over the city. Results of this geotechnical exploration have allowed to identifying four zones with different soil mechanic and dynamic characteristics. Figure 2 shows a Map of this Earthquake Geotechnical Microzonation, whose main characteristics are described following, Salas [4]:

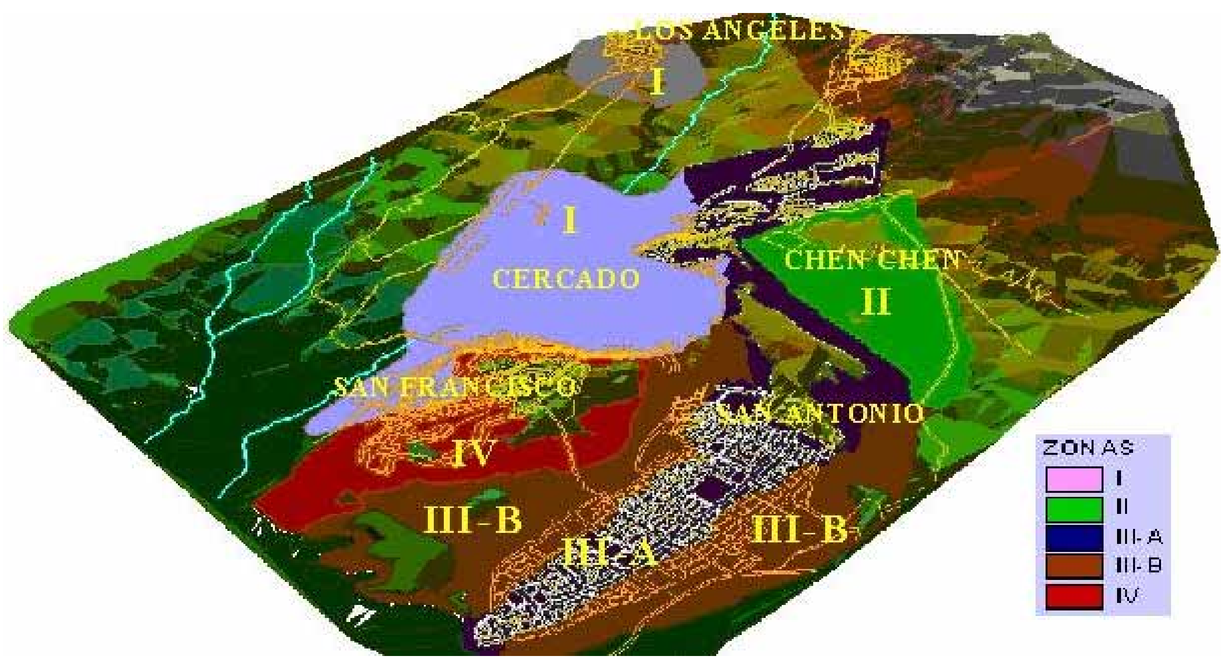


Figure 2: Earthquake Geotechnical Microzonation Map of Moquegua City

Zone I
This zone includes the alluvial valley of Moquegua River where the well consolidated part of the city, namely the downtown, is settled, and Los Angeles district. The soil is composed by a very stiff sandy gravel with competent mechanical characteristics; which is found at relatively shallow depth, however the predominant period values determined by microtremor measurement range from 0.10 to 0.40 s. The Downtown Moquegua Station, where the mainshock record of the 2001 June 23 earthquake was obtained, is also located in this zone, and as it could be observed in the acceleration response spectra, showed in Figure 3, large amplifications factor are expected up to a period of 0.8 s. Therefore, this zone was classified as a Type 2 soil from the Peruvian Seismic Code.

Zone II
This zone includes the new expansion area of Moquegua City, named Chen Chen, that was chose to relocate people from the San Francisco District, which was the most affected area by the earthquake. In this zone an intensive geothecnical exploration program was performed. The soil profile is composed by a layer of deep silty gravel from colluvium-alluvial origin. The mechanical characteristics of this material are adequately competent, however it shows a peculiar dynamic characteristics, since the predominant period values determined by microtremor measurements range from 1.00 to 1.50 s with large amplification factors at this period rage. To verify this findings, a strong motion accelerographic station was installed in this zone. The analysis of earthquake records obtained simultaneously at both the Downtown and Chen Chen Stations confirmed the large amplification of this zone respect to Zone I. Due to this behavior, this zone was classified as a Type 3 soil from the Peruvian Seismic Code.

Zone III
This zone includes two areas that are mainly composed by expansive soils, where the San Antonio and San Francisco Districts settles, and the area of El Siglo district, located on a very steep hill that present topographical effect. The first area, identified as Zone III A, is covered by a layer of loose granular soil, 4.0 to 5.0 m in thickness in San Antonio District, where the predominant period values determined by microtremor measurements range from 0.50 to 0.80 s, and is a very steep hill in El Siglo district, where topographical effect is expected. The second are, identified as Zone III B, is composed by outcropping expansive soil and the predominant period values range from 0.20 to 0.40 s. Severe mechanical problems have been observed in this zone due to the high expansion potential of the soil, where well built houses were severely damaged by the volumetric change of the foundation soils. Special consideration for foundation design must be taken in order to resist the uplift expansion loads. Due to this behavior, this zone was classified as a Type 3 soil from the Peruvian Seismic Code.

Zone IV
This zone is restricted to the area of San Francisco District, which was extensively damaged during the June 23, 2001 earthquake. The soil profile in this area is composed by a shallow layer of two meter thick loose colluvial silty gravel, that covers the expansive clays of the Lower Moquegua Formation. The topography of this area is very abrupt conformed by a steep hill, with an average slope of 70°. Predominant period values range from 0.20 to 0.40 s, which evidence the stiffness of the soil foundation, however during the earthquake mainshock topographic amplification effects has been observed. Besides the fact that homeless of this area were relocated in the new expansion zone of Chen Chen, many people continue living there, and some of then have reconstructed their houses using self construction procedures, a practice that is not recommended in this zone. Therefore, in order to issue a regulation, this zone was classified as a Type 3 soil from the Peruvian Seismic Code, where it is recommended that only well designed housing could be constructed in the flat area, leaving the steep slopes of the hill as green areas.

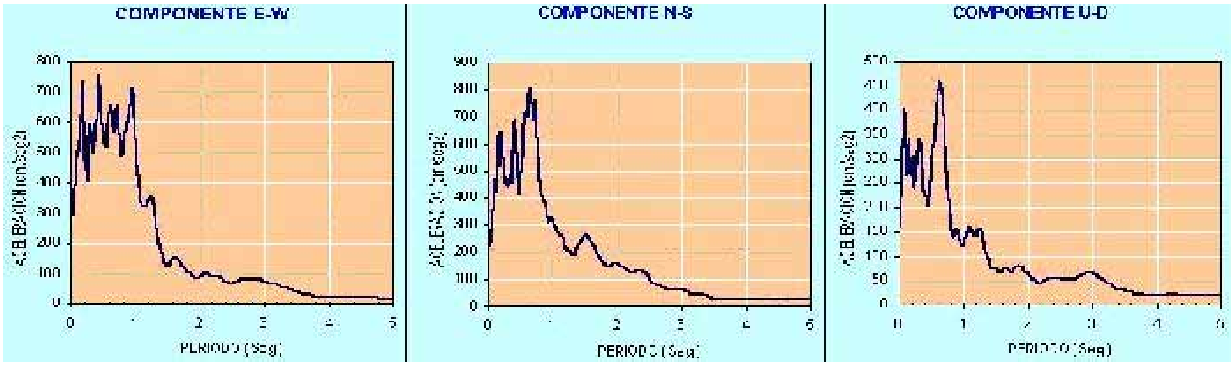


Figure 3 Acceleration Response Spectra of the June 23, 2001 Southern Peru Earthquake, obtained at Downtown Moquegua City.

Site Conditions and Amplification Factors

According to the geotechnical characteristics of the foundation soils found at the four zones the only dynamic effect that could increase the seismic load is the seismic amplification due to the dynamic behavior of the deep cohesionless soil deposits and the topographic effect of the steep hills that surrounds the city, Moreno [3]. No liquefaction phenomenon was observed in the Moquegua valley area.

Since no borehole data was available to model a soil profile in order to perform a seismic amplification analysis, the Nakamura H/V ratio of microtremor measurements were used to determine the predominant period and estimate the amplification factor in the different zones of the city. Figure 4 shows the isoperiod map at the new expansion zone of Chen Chen, where period values as large as 1.5 s are observed, Salas [4]. This values are similar to those obtained in this area by Sato [5] and Lermo [6] in different microtremor measurement campaigns.

Based on these results and small magnitude earthquake ground motion records obtained at both Downtown Moquegua and Chen Chen stations, the short period (less than 0.4 s) amplification factor for each one of the four zones was estimated. Figure 5 shows the proposed Amplification Factors Map for Moquegua City, which was used to estimate the damage that was observed on the June 23, 2001 earthquake in this city.

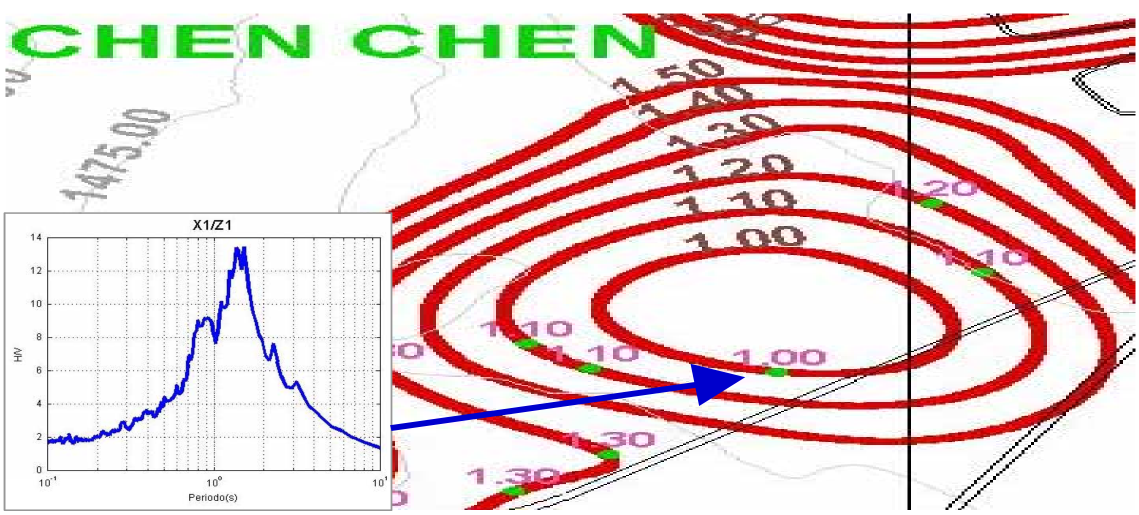


Figure 4: Isoperiod Map of the new expansion zone of Chen Chen, in Moquegua City

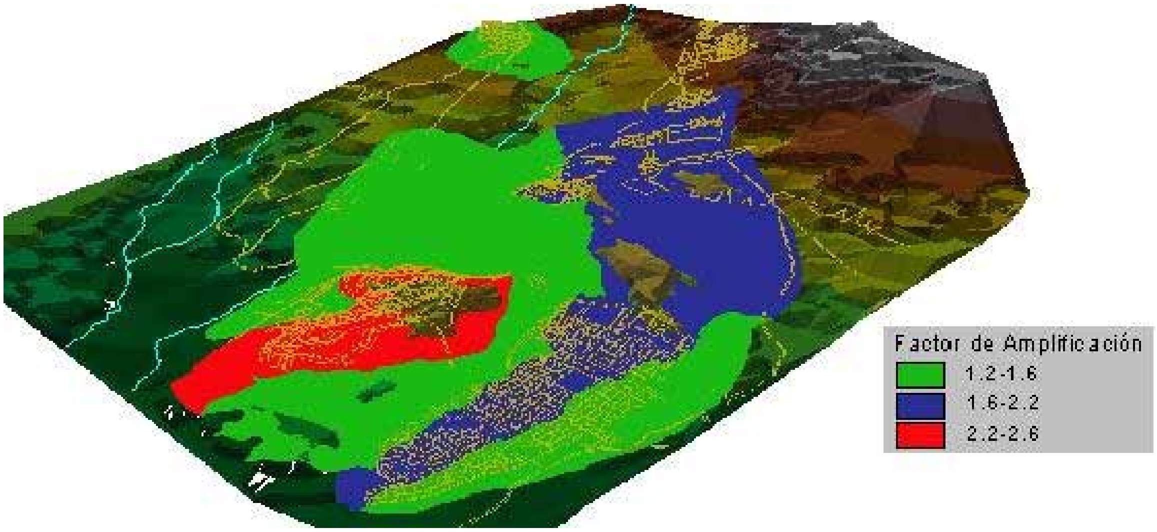


Figure 5: Estimated Dynamic Amplification Factors in Moquegua City

VULNERABILITY AND SEISMIC RISK ANALYSIS OF MOQUEGUA CITY

Damage Distribution in Moquegua City

The evaluation of damage distribution based on building damage observation on a large area of the city was performed by a team of the San Agustín de Arequipa National University, Kosaka [7]. Another team of CISMID of the National University of Engineering, surveyed the most affected area of Downtown Moquegua and San Francisco Hill, and proposed a damage distribution map. These information has been used in this research to calibrate three structural vulnerability matrices, namely: Utah-1994, proposed by the ATC36 [8], Costa Rica-1978, proposed by Sauter, and Antofagasta-2000, proposed by Tapia [9]

Several ranges of damage factors were assigned to the qualitative damage levels used during the evaluation, in order to quantify the damage percentage that represent each damage level used. Once the appropriate range was defined, the damage matrix for an intensity of VIII MMI in Moquegua City was drawn. Table 1 shows the results of the three damage matrices compared with the observed damage matrix, and considering only a VIII MMI intensity.

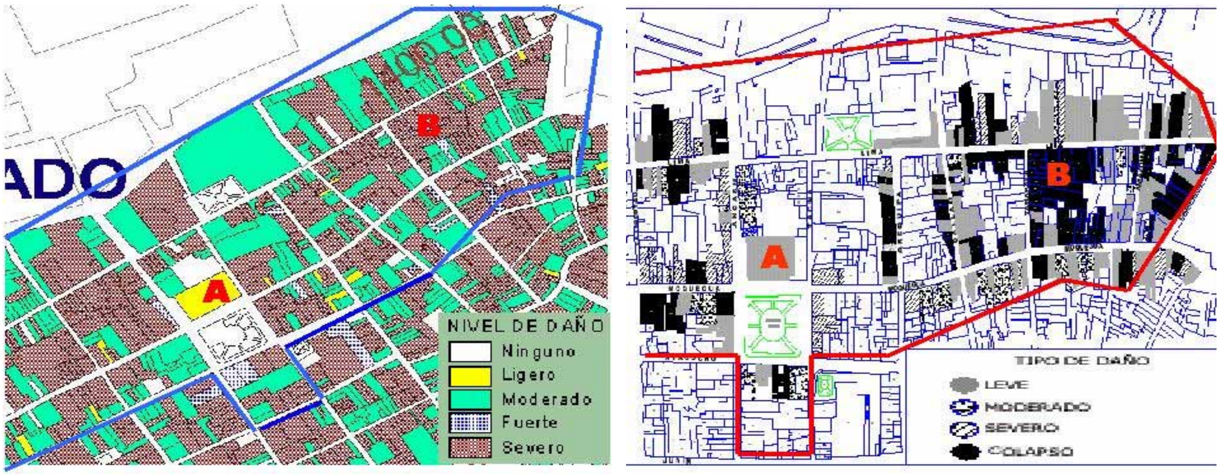
Table 1. Vulnerability Matrices for an Intensity of VIII MMI, compared with observed damage at Moquegua City

Vulnerability Matrix	RM lr	RM mr	ADOBE	URM	Self-CONS
Antofagasta	21.00	5.00	58.00	38.00	48.00
Moquegua	24.56	21.11	51.47	33.66	43.00
Costa Rica	16.00	5.70	50.00	43.00	44.00
Utah	-	5.97	-	39.53	-

Given the fact that structures in Antofagasta City, located in the norther part of Chile, have more similarities to the Peruvian ones, this vulnerability matrix was chose to estimate the damage distribution all over Moquegua City using the proposed amplification factors map.

Damage Evaluation in Moquegua City

The procedure proposed by King [10], was used to estimate the damage to structures in Moquegua City. The structural inventory of buildings existing before the June 23, 2001 disaster, that has been provided by the Municipality of Moquegua was implemented under a GIS environment using ArcView GIS, ESRI[11], and was overlapped to the hazard map. Figure 6 shows the Damage Distribution Map, that was calculated with the Antofagasta vulnerability matrix for the June 23, 2001 earthquake scenario, compared to the Damage Distribution Map developed by CISMID team.



(a) **(b)**

Figure 6: Damage Distribution Maps of Downtown Moquegua for the June 23, 2001, (a) Calculated with the Antofagasta Vulnerability Matrix and, (b) Evaluated by CISMID team.

There is an adequate correspondence among the different damage levels in these two maps, unfortunately the comparison could not be complete since the evaluation performed by CISMID team include only the buildings comprised between the two main streets. Similar correspondence in damage levels was observed in San Francisco Area, where damage evaluation was also carried out by CISMID members. Furthermore, in order to more accurately validate the damage distribution predicted by the Antofagasta vulnerability matrix, a recognizance trip was organized few month after the earthquake. A good agreement between the predicted and the observed damaged level in all the inspected areas was found, therefore, this vulnerability matrix was proved to be adequate to predict the damage level and the direct economic loss generated by this event.

Seismic Risk Assessment

The seismic risk of Moquegua city for the June 23, 2001 earthquake scenario was evaluated in terms of direct economic loss, using the following relations:

E[loss] = E[DF] x (buildings' unit cost)

Where: E[loss] is the expected loss for a building type
E[DF] is the expected damage factor for the building type.

The buildings unit cost was obtained from the property tax database of the Land Registry Office, which has registered about the 80% of the buildings of Moquegua City. This information was overlapped with the damage distribution map for the June 23, 2001 earthquake scenario, to obtain the Direct Economic Loss Distribution Map, shown in Figure 7. The total direct economic loss estimated for this event, considering only the 80% of the buildings in Moquegua City, rises up to 48.11 million soles (approximately 14 million American dollars).

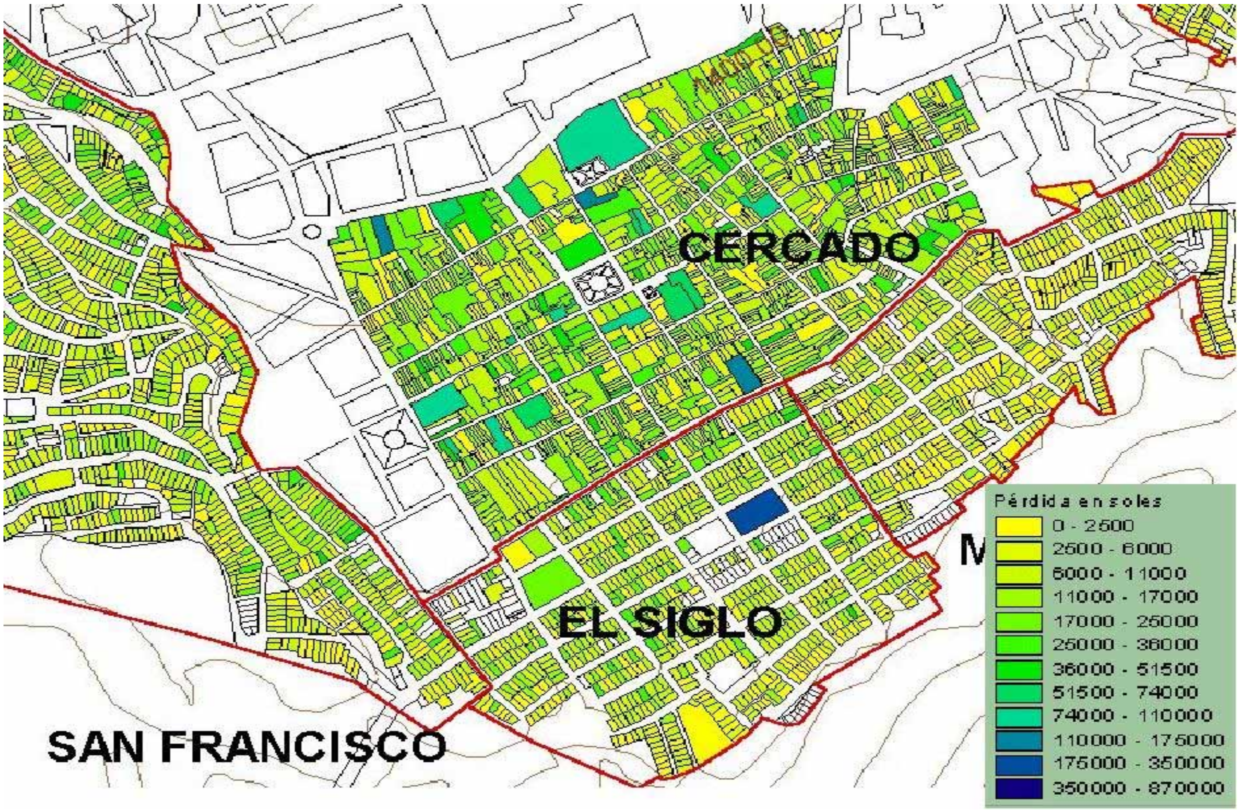


Figure 7: Direct Economic Loss Distribution Map of Moquegua City for the June 23, 2001 Earthquake Scenario.

CONCLUSIONS

a. The earthquake geotechnical microzonation of Moquegua city was developed based on a broad geotechnical exploration program. The main concern was to identify if the expansive soils deposits outcrops in the new expansion area of the city, where was planed to relocate the homeless of the June 23, 2001 earthquake disaster.

b. Microtremor measurements were carried out to characterize the dynamic behavior of soils in the different areas of the city. No other site effect than dynamic and topographic amplifications, that could increase the ground motion intensity, were identified.

c. Four geotechnical zones were defined according to the soils mechanical and dynamical characteristics. The main problems identified are the presence of expansive soils, that outcrops in Zone III and have caused severe damage to masonry housing due to volumetric change of the foundation soils. Also large dynamic amplification factors were estimated in the deep cohesionless coarse soil deposits of the Zone II, and due to topographic effects in the hills of the Zone IV.

d. Several workshops including stakeholders, engineers and local residents were carried out to discuss the results of this study. A long term disaster prevention plan was implemented by the NGO PREDES, taking the outputs of this research as a basis.

e. Recommendation for foundation design in each of these zones were proposed, considering the mechanical and dynamical characteristics of the foundation soils. The conclusions and recommendation of this study were included by the local authority in the urban regulation plan of Moquegua city.

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