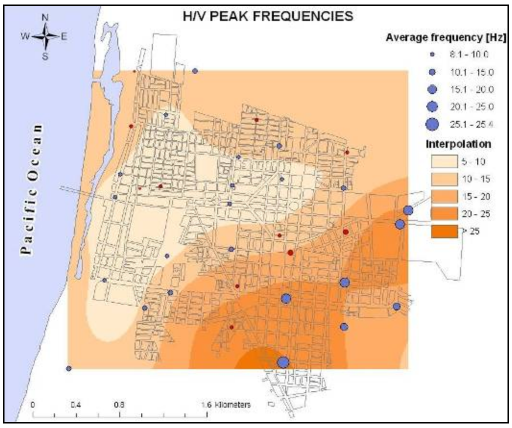
A RECONNAISANCE REPORT

ON

THE PISCO, PERU EARTHQUAKE OF AUGUST 15, 2007



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2007 Pisco, Peru Earthquake Reconnaissance Team

by

Japan Society of Civil Engineers (JSCE),

Japan Association for Earthquake Engineering (JAEE)

and

University of Tokyo

With the collaboration of

CISMID, National University Engineering
(For ambient vibration observations in Pisco)

October 2007

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Preface

On August 15, 2007 a large earthquake hit the central part of Peru's coast, some 150 km south of Lima. The earthquake tragically resulted in 519 deaths, 1291 injured, and more than 650,000 affected people. Totally some 80,000 dwellings and buildings were damaged or completely destroyed in the regions of Ica, Lima, Huancavelica, Ayacucho and Junín. We would like to extend our sincere condolences to all the people of Peru.

Due to the large magnitude (Mw=8.0) and the heavy damage, Japan Society of Civil Engineers (JSCE) and Japan Association of Earthquake Engineering (JAEE) decided to support the dispatch of a joint team together with the Institute of Industrial Science at the University of Tokyo. The objectives of the mission were to investigate damages to dwellings and buildings, considering both structural and geotechnical aspects, and applying the findings to disaster mitigation and reconstruction strategies.

Our team consisted of four Spanish speaking persons (two researchers and two students) who spent up to three weeks in Peru. During a 10-day long field survey several locations close to the epicenter, such as Pisco, Tambo de Mora, and Guadalupe, and locations further away from it such as Huaytara, Lunahuana, and Pacaran, were visited. We also collaborated with CISMID (Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres) of the National University of Engineering, Lima, to perform microtremor measurements in Pisco. Another 10 days were used for meetings with several authorities and other organizations in Lima and for gathering indispensable information such as topographical and geological maps.

During our visit we received help from many local and international organizations and persons. We would like to extend our warm thanks to all them and we hope to continue our fruitful collaborations. We would also like to thank JSCE and JAEE for their financial support.

We hope that this report will contribute to continued efforts for improving disaster mitigation in Peru and worldwide.

Jörgen Johansson, October 29, 2007
On behalf of the JSCE/JAEE/UT investigation team

Executive Summary

At 18:41, August 15, 2007 a large earthquake hit the central part of Peru's coast, some 150 km south of Lima. The earthquake tragically resulted in 519 deaths, 1291 injured, and more than 650,000 affected peopled. Totally some 80,000 dwellings and buildings were damaged or completely destroyed in the regions of Ica, Lima, Huancavelica, Ayacucho and Junín. Despite the large number of building damage the death toll was relatively low most likely due to the earthquake occurrence time. Pisco and Chincha cities were the hardest hit. The Peruvian government preliminarily estimated that public infrastructure recovery will cost at least US$220 million. Although the Internal Gross Product of the Ica Region is estimated to fall 6%, the expected National Internal Gross Product Growth for 2007 will only be reduced with 0.38 percentage points.

Japan Society of Civil Engineers (JSCE), Japan Association of Earthquake Engineering (JAEE), and the Institute of Industrial Science at the University of Tokyo dispatched an investigation team three weeks after the earthquake with the objectives of investigating damages to dwellings and buildings, considering both structural and geotechnical aspects, and applying the findings to disaster mitigation and reconstruction strategies.

This earthquake had a very long duration of almost three minutes. Two of the four seismographs closest to the epicenter did not work. While several independent organizations have seismograph networks, there is no common base for exchanging information. A clearinghouse with a public website to quickly disclose information, e.g computed intensities, based on all networks, would be very useful for disaster response.

Ground failure, particularly liquefaction, caused extensive damage to buildings and infrastructure. Large soil cracks and displacements were observed at Tambo de Mora and Pisco. Hazard maps for such ground failures already existed before the earthquake. Expensive foundations can resist such soil deformations. However, for houses, it is cheaper to avoid hazardous locations.

To contribute to existing and ongoing hazard evaluations we measured small ambient ground vibrations (so called microtremors) in Pisco, Tambo de Mora, and in other locations to evaluate dynamic characteristics of the ground. Measurements at Pisco were done in collaboration with CISMID (Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres). Dynamic in-situ properties of reinforced adobe houses were also evaluated. This type of data is still scarce.

Twenty percent of the houses in the affected areas, roughly 50,000 units sheltering more than 200,000 people, collapsed completely. A tremendous response effort is needed to assist these people. The predominant building types in the area are adobe (52%) and confined masonry (39%) combined with light roofs made of either straw mat or light gage steel plates. These light roofs may also have contributed to the relatively low death toll.

Structures designed and built according to the construction codes performed well. Peruvian building codes are regularly updated and cover a wide range of construction

systems. However, in practice they are not enforced. Design and construction deficiencies due to lack of control, caused most of the observed structural damage. This is valid not only for houses but also for public facilities, including schools, hospitals, churches, and hotels. The collapse of one church in Pisco caused 30% of the total casualties. The main hospital of Pisco was heavily damaged as well as large part of the school infrastructure. Retrofitting or new construction of public buildings is necessary. A few reinforced and retrofitted adobe houses in the affected area performed well, demonstrating that *adobe can be made earthquake safe*.

In many locations we observed moist adobe walls due to the lack of foundation preventing ground moisture from entering the walls. In addition to reducing the earthquake resistance of an already earthquake vulnerable building type, the moisture also constitute a general health problem.

Road damage extended over a wide area with the south Pan-American Highway being the most affected. It was restored to restricted traffic some hours after the earthquake and to full traffic in 48 hours. Only the reparation of the Huamani Bridge, along this Highway, took two months. The rapid recovery of the Pan-American Highway was very important for the disaster response activities. Regional and rural roads were affected mainly by rock falls and landslides.

Despite the efforts by the organizations in charge of disaster response, the extent of the damage has overwhelmed them resulting in slow debris removal, few temporary houses and tents, and poor conditions at the refugee camps. Implementing disaster mitigation countermeasures and promoting disaster awareness are key to reduce damage and are recommended.

A reconstruction fund, FORSUR, was created two weeks after the earthquake to coordinate the reconstruction efforts. Although reconstruction planning seems to have progressed, no government sponsored reconstruction works have started yet. One of the main reasons is that at least half of the people who have lost their houses did not have a property title. Without this, they cannot apply for any governmental support.

The delay of an orchestrated reconstruction effort is creating unrest among the population who have already started reconstruction by themselves with the same poor construction practices, the same low quality materials and the same bad locations. To address this, training courses for masons have started, however not for constructing with adobe.

The 2007 Pisco Earthquake has been a reminder for the Peruvian authorities and general public of the urgent need for disaster mitigation. Of particular concern is the possibility that a large magnitude earthquake hits the capital city, Lima. It is our hope that lessons from this tragedy are learned and help create a more disaster resilient country.

1. INTRODUCTION

On August 15, 2007 at 18:41, a large earthquake (Magnitude, M_W=8.0) hit the central part of Peru's coast, some 150 km south of Lima. The Peru Geophysics Institute (IGP) estimates Modified Mercalli Intensities of VII-VIII in Pisco, Chincha, and Ica. The earthquake tragically resulted in 519 deaths, 1,291 injured, and more than 650,000 affected people. Totally, some 80,000 dwellings and buildings were damaged or completely destroyed in the regions of Ica, Lima, Huancavelica, Ayacucho and Junín.

Due to the event large magnitude and the heavy damage, Japan Society of Civil Engineers (JSCE) and Japan Association of Earthquake Engineering (JAEE) decided to support the dispatch of a joint team with the Institute of Industrial Science at the University of Tokyo. The objectives of the mission were to investigate damages to dwellings and buildings, considering both structural and geotechnical aspects, and applying the findings to disaster mitigation and reconstruction strategies.

The reconnaissance team consisted of four Spanish speaking persons (two researchers and two students) who spent up to 3 weeks in Peru(Table 1.1). During a 10-day long field survey, several heavily damaged locations, such as Pisco, Tambo de Mora, and Guadalupe, and less damaged locations further away from the epicenter such as Huaytara, Lunahuana, and Pacaran, were visited. Fig. 1.1 and Table 1.2 present further details. The team collaborated with CISMID (Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres) of the National University of Engineering, Lima, to perform microtremor measurements in Pisco.

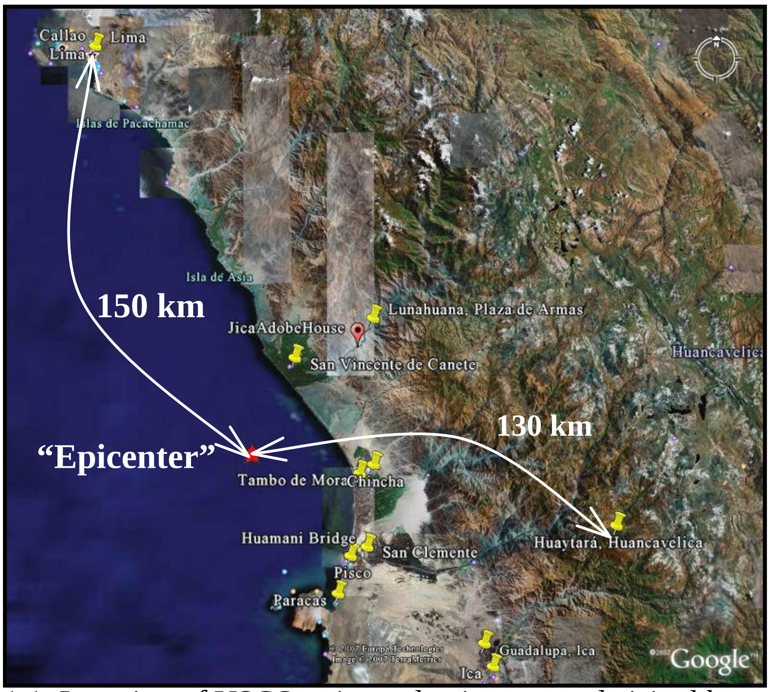

Fig. 1.1. Location of USGS estimated epicenter and visited locations.

In addition to the field activities another 10 days were spent for meetings with several authorities and other organizations in Lima and also for gathering indispensable information such as topographical and geological maps.

The team benefited from discussions with many people, who in spite of their busy schedule in the aftermath of the disaster, spared time and provided us with all available materials and information at their disposal to help us with our activities. Table 1.3 shows a list of the people that we met and to whom we would like to extend our sincere gratitude.

Table 1.1 List of JSCE/JAEE/UT team members

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Table 1.2 Activities carried out by the JSCE/JAEE/UT Mission in Peru

Date	**Activity**
Sept. 4, 2007	Mission (1st group) arrives in Peru
Sept. 5, 2007	Topographical and geological map collection at National Geographic Institute (IGN) and Geology, Mining and Metallurgy Institute (INGEMMET) Interview with Eng. Arellano who was in charge of the design of the rehabilitation of the Huamani Bridge
Sept. 6, 2007	Briefing at the Pontifical Catholic University of Peru (PUCP) Briefing at the Japan-Peru Center for Seismic Investigation and Disaster Mitigation (CISMID)
Sept. 7, 2007	Briefing at the Faculty of Civil Engineering, University of Engineering (FICS) Digital map collection
Sept. 8, 2007	Field survey (Huamani bridge)
Sept. 9, 2007	Logistic arrangements (car rental, hotel)
Sept. 10, 2007	Field survey (San Luis, Nuevo Monterrico, Tambo de Mora)
Sept. 11, 2007	Field survey (Los Libertadores Highway, Huaytara, Huancano, Humay, San Clemente)
Sept. 12, 2007	Field survey (Pisco)
Sept. 13, 2007	Field survey (Pisco, Lunahuana, Canete-Yauyos Highway) Mission (2nd group) arrives to Peru
Sept. 14, 2007	Meeting at FICS for discussing microtremor measurements in Pisco Data preparation for the detailed field survey
Sept. 15, 2007	Field survey (Pantanos de Villa, Playa Totoritas, and microtremor measurements in Pisco) with CISMID
Sept. 16, 2007	Microtremor measurements in Pisco with CISMID
Sept. 17, 2007	Field survey (Guadalupe, Ica, Parcona, Tinguina, Los Molinos) Microtremor measurements (Guadalupe)
Sept. 18, 2007	Field survey (Ica, Tambo de Mora), Microtremor measurements (Ica, Tambo de Mora)
Sept. 19, 2007	Field survey (Lunahuana, Pacaran, Tambo de Mora, Canete-Yauyos Highway) Microtremor measurement (Lunahuana, Pacaran, Tambo de Mora)
Sept. 20, 2007	Briefing at CISMID to exchange information and report survey findings
Sept. 21, 2007	Meeting at INGEMMET and the Peru Geophysics Institute (IGP) to report survey findings and exchange information
Sept. 22, 2007	Meeting with Prof. Kuroiwa, Eng. Jack Lopez and Eng. Jack Lopez-Lara together with the ASCE/TLCEE Team. Briefing with the ASCE/TLCEE Team
Sept. 23, 2007	Field survey (Lima)
Sept. 24, 2007	Meeting at the Ministry of Transportations and Communications (MTC) together with the ASCE/TLCEE Team Briefing at the Japanese Embassy in Lima and SENCICO to report survey findings and exchange information
Sept. 25, 2007	Meeting at INDECI and the Ministry of Economy and Finances to report survey findings and exchange information
Sept. 26, 2007	Meeting at the IGN to collect information Meeting at the Swedish Consulate toe report survey findings and exchange information Fly back to Japan
Sept. 28, 2007	Arrive to Japan

Table 1.3. List of people interviewed during the JSCE/JAEE/UT survey

Agency	**People met**
Ministry of Economy and Finance (MEF) Direction of the Public Sector Multi-Annual Programming	Eng. Miguel Priale Ugas (Director General) Eng. Jorge Escurra Cabrera (Consultant-Coordinator of the Program for Prevention and Rehabilitation of the Regions affected by Natural and Human Induced Disasters) Mr. Mitsuo Sakamoto (JICA Advisor on ODA Loans) Mr. Jose Garcia Pisco Mr. Adhemir Ramirez Rivera
Ministry of Transportation and Communications (MTC) (unfortunately it was not possible to obtain the list of all the participants from the MTC side)	Dr. Carlos R. Valdez Velasquez Lopez (Director General, Comunications Secretaria) Mr. Juan Carlos Paz Cardenas (Director General of Aquatic Transportation)
Municipality of Pisco (Urban Development Office)	Eng. Hugo Suarez Eng. Raul Doroteo Eng. Nestor Lopez del Mar Eng. Jose Uribe
Municipality of Huaytara	Ms. Lidia Sedano Quintanilla
Municipality of Parcona	Eng. Cesar E. Guillen Vasquez
Municipality of Lunahuana	Ms. Cesarían Vera Gonzalez del Valle Ms. Nancy Villanueva Ms. Elia Luyo
National Institute of Civil Defense (INDECI)	Retired Colonel Ciro Mosqueira (Sub-director) Eng. Alfredo Perez Arch. Alfredo Zerga
National Service for Training for the Construction Industry (SENCICO)	Eng. Carmen Kuroiwa Horiuchi (Head of the Standardization and Research Department) Eng. Gabriela Esparza Requejo
Geology, Mining and Metallurgy Institute (INGEMMET)	Eng. Lionel Fidel Smoll Dr. Jose Machare Ordonez Geologist Carlos Lenin Benavente Escobar Ms. Yanet Antayhua Vera
National Geographic Institute (IGN)	Colonel Cesar Nicolas Alva Baltazar
Peru Geophysics Institute (IGP) (unfortunately it was not possible to obtain the list of all the participants from the IGP side)	Dr. Hernan Montes Ugarte Dr. Hernan Tavera Dr. Laurence Audin-Hourton
CISMID National University of Engineering Faculty of Civil Engineering (FICS)	Dr. Jorge Alva (Dean of FICS) Dr. Carlos Zavala (CISMID Director) Dr. Miguel Estrada Eng. Fernando Lazares Dr. Zenon Aguilar

Agency	People met
Pontifical University Catholic of Peru	Dr. Marcial Blondet (Dean of the Graduate School) Eng. Angel San Bartolome Eng. Walter Silva Eng. Gladys Villagarcia
San Luis Gonzaga National University	Eng. Rene Oswaldo Canchasi Vega (Chief of the Soil Mechanics Laboratory)
COVIPERU	Eng. Julio Mujica (telephonic communication)
Individuals	Prof. Julio Kuroiwa (INDECI Senior Advisor) Eng. Francisco Arellano (Consultant) Eng. Jack Lopez (Consultant) Eng. Jack Lopez-Jara (Consultant) Ms. Shizuko Matsuzaki (EVAA NPO)
Ica Association of Civil Engineers	Ing. Luis Ordonez
San Juan de Dios Hospital (Pisco, Ica)	Dr. Ricardo Cabrera
San Juan Bautista School (Huaytara, Huancavelica)	Mr. Gil Josué Huaroto Arango (Interim Director)
Beatita de Humay 22451 (Humay, Ica)	Mr. Fidencio Diaz Condori (President of the Students Association)
San Luis Gonzaga School (Ica)	Mr. Pedro Eduardo Falcon Guerra (Director) Ms. Mili Alvaro Lopez (Subdirector)
Japanese Embassy in Lima	Eng. Akihiko Tasaka (1st Secretary) Arch. M. Sato
Swedish Consulate	Mr. Stefan E. Sandberg (Consul) Rev. Nicklas Fahlgren

1.1 Affected area

Peru is divided into 25 administrative regions (formerly departments). Each region has number of provinces, and each province consist of districts. In this report, the term affected areas refer to the most heavily damaged areas, i.e Pisco, Chincha, and Ica Provinces in the Ica Region, Canete and Yauyos in the Lima Region, and Huaytara and Castrovirreyna Provinces, in the Huancavelica Region.

1.2 Economic impacts

It is still early to estimate the economic impacts of the 2007 Pisco Earthquake, especially the indirect losses. However, the Ministry of Economy and Finance (MEF) has already made a preliminary estimation of the public infrastructure reconstruction costs which is shown in Table 1.4. In the table, the item Housing refers to the S/.6 000 (roughly US$2 000) that the government has promised to give the people who lost their houses. Note that the estimation does not include all the affected provinces.

Table 1.4. Estimation of public infrastructure reconstruction cost (after MEF [1])

Sector	Million US$
Housing	30.61
Sanitation[1]	49.64
Power supply[2]	23.25
Transportation	33.00
Health[3]	15.19
Education	68.99
Total	220.68

[1] Only water supply and sewage of Pisco, Canete, Ica and Chincha
[2] Power supply system of Pisco, Ica, and Chincha
[3] Only Canete Province and Ica Department

MEF also estimated that the earthquake will cause the Ica Departmnent Gross Internal Product to fall 6% in 2007.

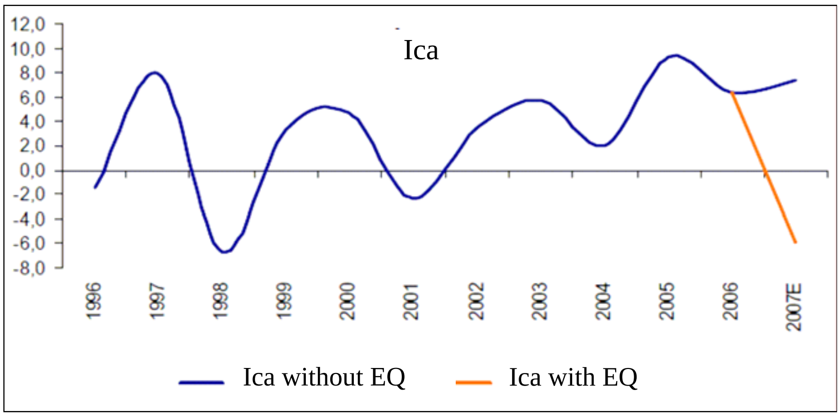

Fig. 1.2 Variations of the Gross Internal Product in Ica Department (after MEF [1])

In the last years, Ica has represented 2.4% of the National Gross Internal Product, which will grow 0.38 percent units less than forecasted for 2007, due to the event.

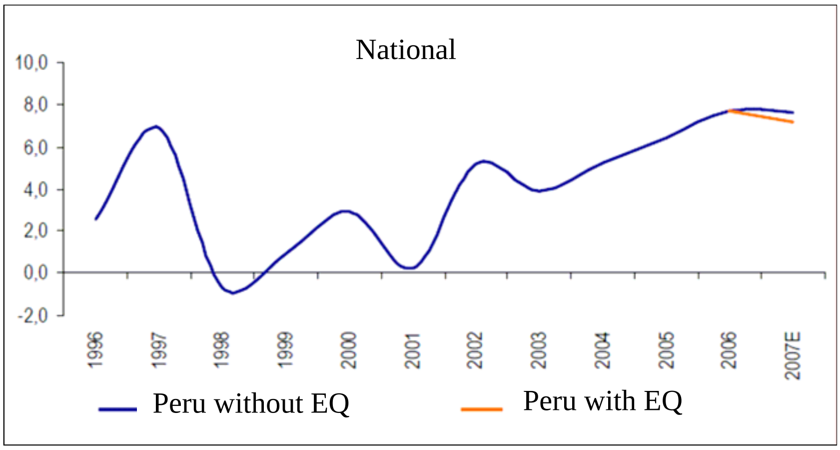

Fig. 1.3 Variations of the National Gross Internal Product (after MEF [1])

REFERENCES

[1] Multi-Annual Macroeconomic Framework 2008-2010 (updated in August 2007), Ministry of Economy and Finance, approved in the Minister's Council Session on August 28, 2007.

2. SEISMOLOGICAL ASPECTS

2.1. Tectonic and Seismological background

The Pisco Peru earthquake was caused by the subduction of the Nazca plate beneath the South American Plate (see Fig. 2.1. after Degg and Chester [1], who give a nice overview of Seismic and Volcanic hazards in Peru). The amount of movement is approximately 7-8 cm/ year. Several large magnitude earthquakes have occurred in the historical period (see Fig. 2.2), most recently in 2001 in the southern part of Peru (see e.g. [14]). Tavera et. al. have estimated a "seismic gap" in the subduction zone at the height of Pisco and Ica (see red mark in Fig. 2.2.)

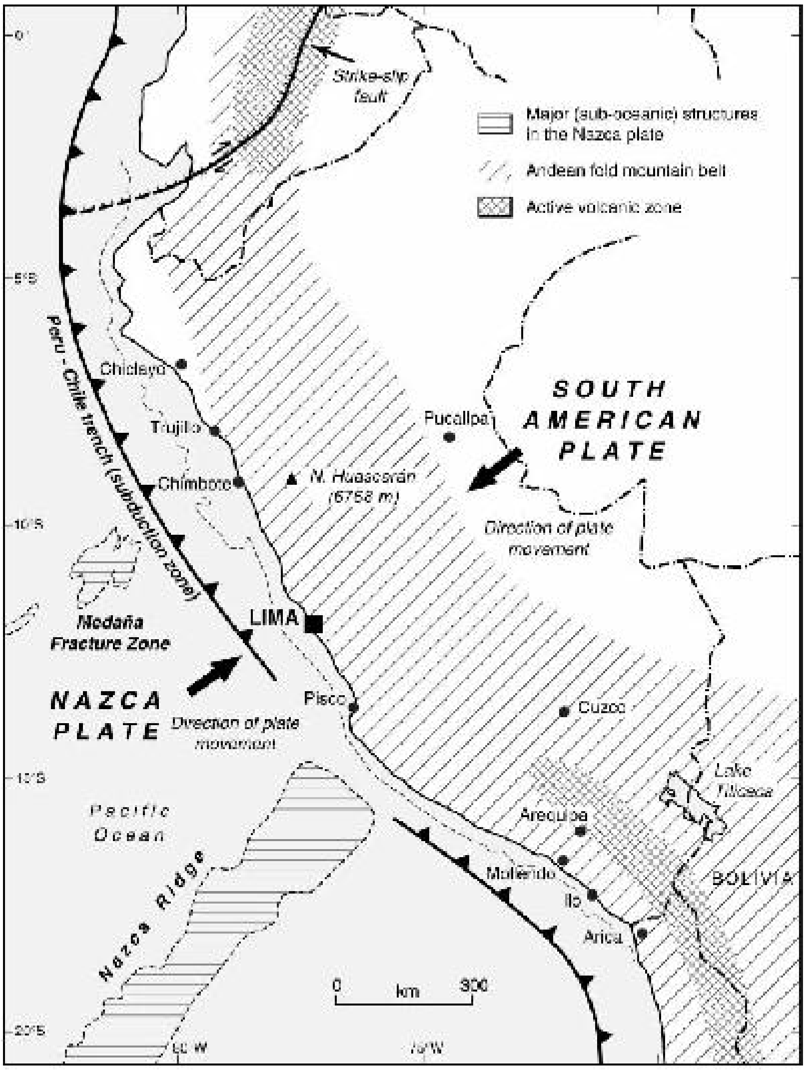

Fig. 2.1. Tectonic map. (after Degg and Chester, 2005, [1]

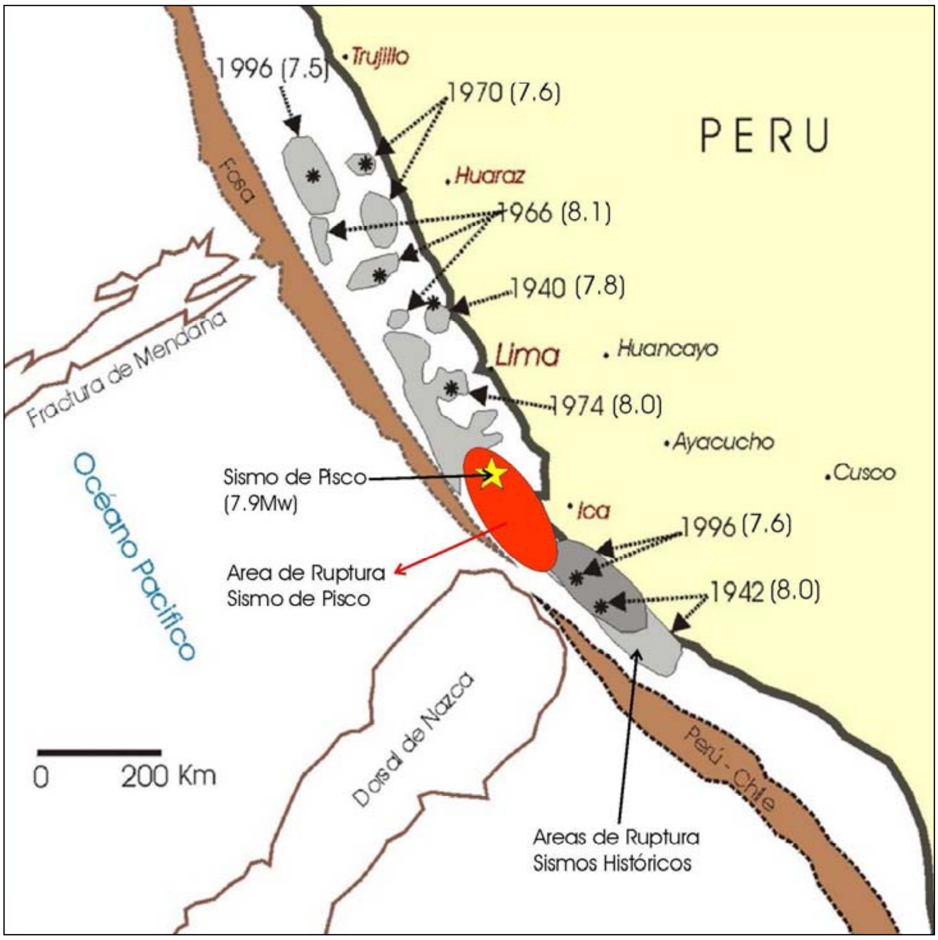

Fig. 2.2. The Pisco Peru earthquake ruptured an identified seismic gap. (after Tavera et. al. 2007, [3].)

2.2. The August 15 earthquake

August 15 18:41 local time a magnitude 8 (Mw=moment magnitude) class earthquake occurred of the middle part off Peru's coast, close to the cities of Chincha, and Pisco. The duration of the earthquake was very long with over 2 minutes of strong ground shaking at Ica (see Fig. 2.5). The local/Richter magnitude computed by IGP was 7.0 (M_L). (The use of different magnitude by seismologists caused confusion since laymen take them for the same thing, which they are not. This confusion was amplified by a rumor that reconstruction financial support would depend on the magnitude). The epicenter location from Institute of Geophysics of Peru (IGP), University of Harvard, and USGS/NEIC differs by some 10 to 20 kilometers as can bee seen in Fig. 2.3. Its depth was reported as 39km (USGS), 33.3 km (Harvard), and 26 km (IGP).

2.2.1. Intensities

Intensities were estimated by both USGS and IGP based on interviews and according to the Modified Mercalli scale. The IGP estimates MM VII-VIII in Pisco, Chincha, and Ica [4]. An intensity map is shown in Fig. 2.4 (after [1]). Intensities have been further discussed in [7] from which

Table 2.1 was adapted. In [7] a logarithmic function is fitted to graph with intensities versus hypocentral distance. This type of fitting can allow for evaluating points with intensities deviating from the fitted curves. Such deviations could be due to effects of soil amplification, directivity, fling, which warrant further scientific and engineering studies.

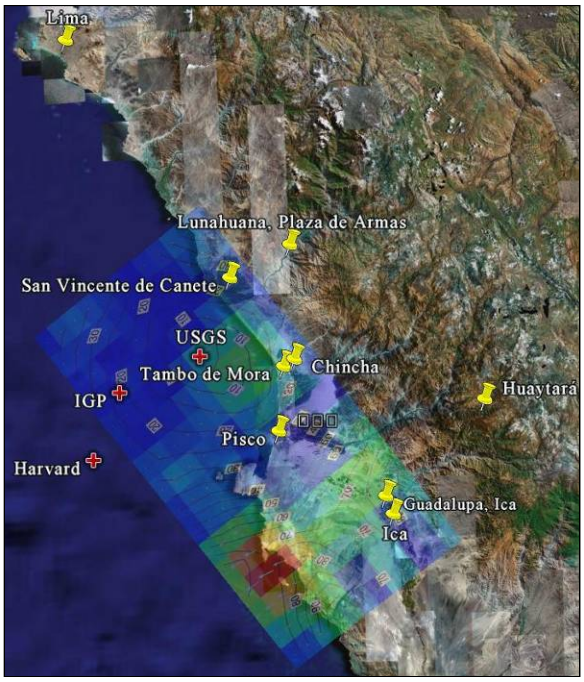

Fig. 2.3. The epicenter location from Institute of Geophysics of Peru, University of Harvard (CMT), and USGS/NEIC differs by some 10 to 20 kilometers. (Google Earth map).

Fig. 2.4. Modified Mercalli intensities according to the Institute of Geophysics of Peru. [1].

Table 2.1. Table of intensities (after [7])

Town		Region	Province	Intensity	Hypocentral Distance [km]
1	Lurín	Lima	Lima	5.5	160
2	Pucusama	Lima	Cañete	5.5	138
3	Chilca	Lima	Cañete	6	133
4	Mala	Lima	Cañete	6.5	121
5	Asia	Lima	Cañete	6.5	108
6	Coayllo	Lima	Cañete	7	116
7	Lunahuana	Lima	Cañete	7	111
8	Cerro Azul	Lima	Cañete	6.5	87
9	Pauyo	Lima	Cañete	6	103
10	San Vicente de Cañete	Lima	Cañete	7	86
11	Chincha Alta	Ica	Chincha	7.5	82
12	Tambo de Mora	Ica	Chincha	7	76
13	Chincha Baja	Ica	Chincha	7.5	79
14	San Clemente	Ica	Pisco	7.5	77
15	Pisco	Ica	Pisco	8	71
16	San Andrés	Ica	Pisco	7.5	70
17	Paracas	Ica	Pisco	7.5	70
18	Pozo Santo	Ica	Pisco	7.5	87
19	Guadalupe	Ica	Ica	7.5	119
20	Ica	Ica	Ica	7	127
21	Tate de la Capilla	Ica	Ica	6.5	132
22	Santiago	Ica	Ica	7	133
23	Ocucaje	Ica	Ica	6	146
24	Palpa	Ica	Palpa	5	199
25	Nazca	Ica	Nazca	5	238
26	San Juan	Ica	Nazca	5	259
27	Talara	Piura	Talara	2	1123
28	Chiclayo	Lambayeque	Chiclayo	2	837
29	Cajamarca	Cajamarca	Cajamarca	3	749
30	Chachapoyas	Amazonas	Chachapoyas	2	838
31	Moyobamba	San Martin	Moyobamba	2	848
32	Trujillo	La Libertad	Trujillo	3	666
33	Chimbote	Ancash	Santa	4	549
34	Huaraz	Ancash	Huaraz	4	469
35	Huanuco	Huanuco	Huanuco	4	423
36	Cotobamba	Loreto	Ucayali	3	730
37	Pucallpa	Ucayali	Coronel Portillo	3	636
38	Barranca	Lima	Barranca	5	345
39	La Merced	Junin	Chanchamayo	4	333
40	Canta	Lima	Canta	5	249
41	Matucana	Lima	Huarochiri	5	210
42	Lima	Lima	Lima	5	187
43	Huancayo	Junin	Huancayo	4	247
44	Huancavelica	Huancavelica	Huancavelica	5	221
45	Calango	Lima	Cañete	6	135
46	Ayacucho	Ayacucho	Huamanga	4	283
47	Puquio	Ayacucho	Lucanas	4	309
48	Chala	Arequipa	Caraveli	4	367
49	Abancay	Apurimac	Abancay	3	421
50	Cusco	Cusco	Cusco	3	519
51	Cotahuasi	Arequipa	La Union	3	454
52	Camana	Arequipa	Camana	3	548
53	Arequipa	Arequipa	Arequipa	2	642
54	Mollendo	Arequipa	Islay	3	635

2.3. Seismic network[JJ1]

2.3.1. Number of organizations and stations

Five organizations (to our knowledge) have accelerometers installed in different locations in Peru. The Institute of geophysics of Peru (IGP) and CISMID have both their independent national networks of some 15 stations each; CERESIS, SEDAPAL and Pontific Catholic University of Peru (PCUP) also have their own accelerometers. Some of the organizations mentioned above have records available on their websites (see Table below.)

Table 2.2. Organization with downloadable acceleration data.

Organization	URL
CISMID	http://www.cismid-uni.org/descargas/acelerogramas.zip
CERESIS	http://www.ceresis.org/informacion/acelerogramas_ica20070815/index.php
PCUP	Included in the CERESIS website

2.3.2. Earthquake Records and Strong Ground Motion amplification

Peak ground accelerations (PGA) from the different seismic networks are given in *Table 2.3* (compiled from [5] and [6].) The maximum acceleration observed was 488 gals in Parcona (IGP station), to the east of Ica and 334 gals at the University of Ica (CISMID station, see also Fig. 2.5). The other accelerometers shown in *Table 2.3* are located in Lima, further away from the fault and the maximum accelerations here are 115 gals that were observed in the district of La Molina (Rinconada, CERESIS station.). The ground motion recorded at Callao is shown in see Fig. 2.5. The accelerometer in Guadalupe, closest to the epicenter, did unfortunately not work properly so the two accelerometers in Parcona and at the university of Ica are the ones closest to the fault.

The earthquake records in Lima show how the soil conditions affect the ground motions with rock sites having PGAs of 20 gals, while PGAs of over 100 gals soft soil sites like the port of Callao and La Molina, i.e. an amplification of 5 times. Similar amplification of ground motion is also likely to have occurred in Tambo de Mora, Chincha, Pisco, Guadalupe, etc, all located upon alluvial and marine deposits. An evaluation of possible amplification levels in Pisco is discussed in Chapter 3.

Table 2.3. Accelerometer locations and Peak ground accelerations. The first two locations are outside Lima closer to the epicenter, the rest are in Lima some 150-200 km from the epicenter.

Station	Location	PGA cm/s^2
PCN	Parcona	488.0
Ica2	Uni. of Ica	334.1
RIN (Rinconada)	La Molina	115.0
CAL (Callao)	Callao	101.0
ANR (A. Nac. R)	S. de Surco	85.3
MOL (Molina)	La Molina	78.7
CSM (Cismid)	Rímac	73.9
PUCP (U. Católica)	San Miguel	67.0
MAY (Mayorazgo)	Ate Vitarte	59.7
CLD-CIP	San Isidro	58.8
CER (Ceresis)	San Borja	58.7
ANC (Ancón)	Ancón	58.4
E1 (Estanque-1)	Santa Anita	54.8
LMO (La Molina)	La Molina	25.3
NNA (Ñaña)	Ñaña	22.1
E2 (Estanque-2)	Santa Anita	20.6

Interestingly all records have two parts with large accelerations, separated by some 50 to 70 seconds as seen in Fig. 2.5. Furthermore for the records closer to the epicentral area (Parcona, University of Ica) the 1st part is bigger than the 2nd, but for all records in Lima the 2nd part have larger accelerations than the 1st part. The time difference between the two pulses is some 50 seconds in Ica and 70 seconds at Callao, Lima. This suggests that the second pulse is due to a rupture of an asperity on the southern part of the fault, further away from Lima, and closer to Ica, which corresponds to Yagi's [8] finite fault solution. Fig. 2.6 shows the response spectra for the Ica 2 and Callao, Lima stations. The peak response occurs at a period of 0.49 seconds at Ica 2 and 0.65 seconds at Callao. More about the two pulses in the records and Peak ground accelerations dependency on the soil conditions have been investigated in [5] and [6].

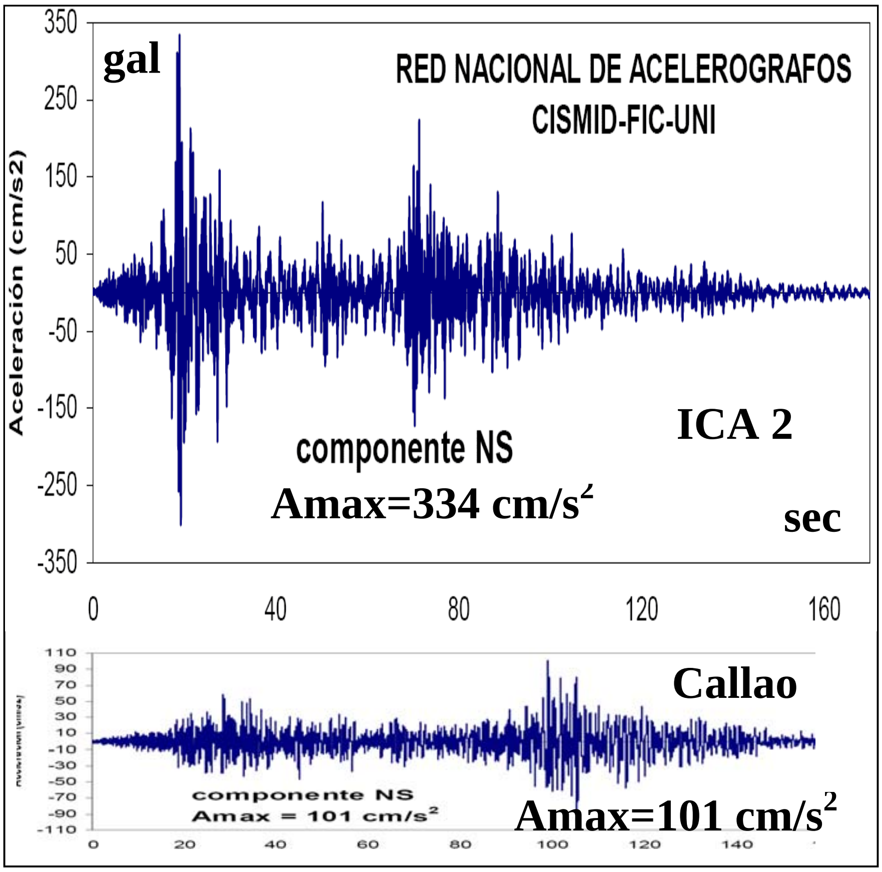

Fig. 2.5. Acceleration records at ICA2 in Ica, and at Callao (port of Lima). [15]

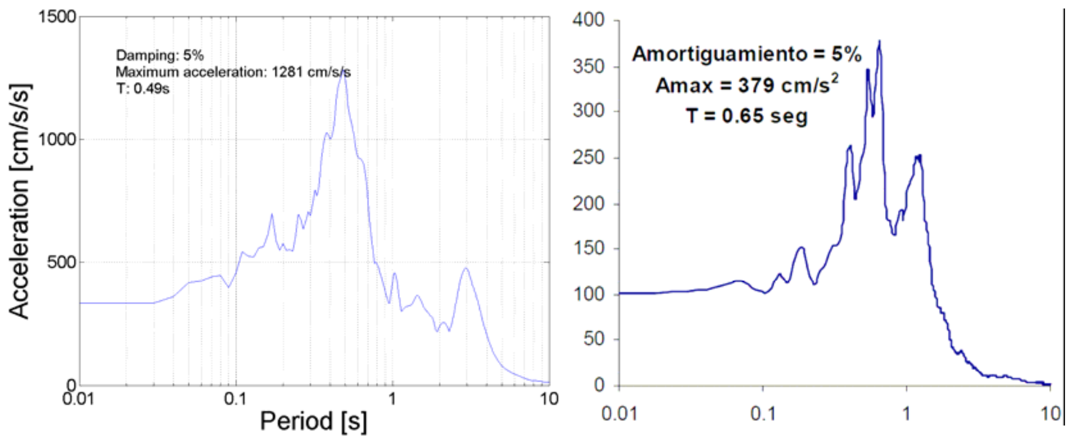

Fig. 2.6. Response Spectra for acceleration records at ICA2 in Ica, and at Callao (port of Lima). (Callao record after [15])

2.4. Finite Fault solutions

We are aware of five different researchers finite fault solutions [8]-[12]. While there are differences in the maximum slip in the solutions as seen in Fig. 2.7, there is a general trend in all solutions of two major areas of slip (asperities), one located close to the epicenter in near Chincha, and the other further south, beneath and to the west of Ica. Perfettini [13] compares and discusses the results obtained by Yagi [8], Konca [11], and

Vallée [12], and suggests that the model by Yagi [8] corresponds well to several types of field observations.

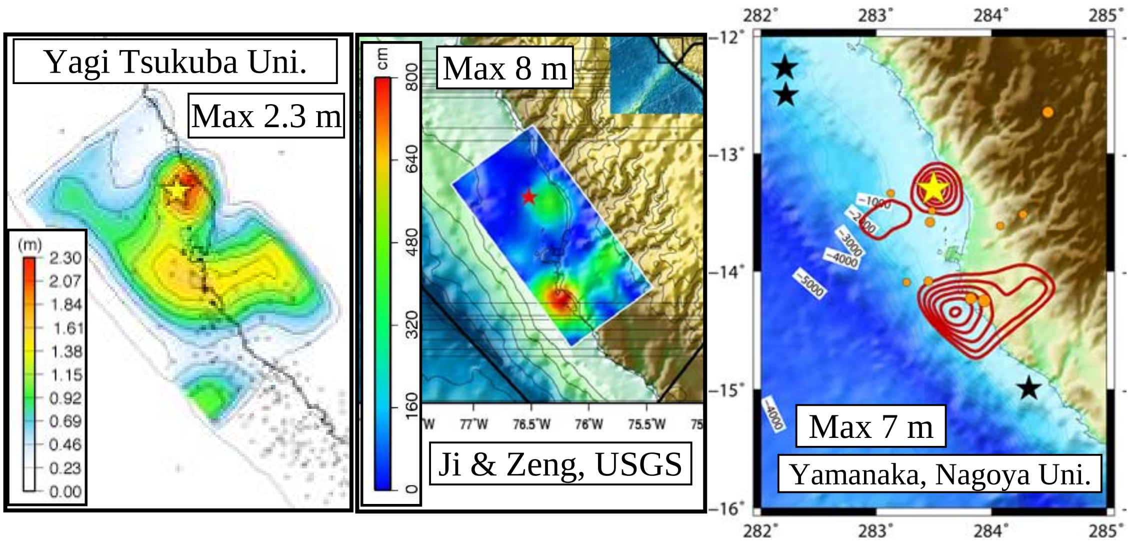

Fig. 2.7. Finite fault solutions after Yagi [8], Ji and Zeng [9], and Yamanaka [10].

2.5. Recommendations

Strengthen the system for sharing strong ground motion recorded information, through, for instance a common Internet platform from where the information of all relevant institutions can be downloaded as soon as it is available. E.g. instrumental intensity maps based on all records could be provided.

Adding more seismographs to the networks, especially to the bigger cities, and converting analog instruments to digital, would e.g. allow for quicker estimation of affected areas.

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3. GEOTECHNICAL ASPECTS

3.1. Introduction

The most spectacular geotechnical aspect of the 2007 Peru Pisco earthquake was the damage caused by the liquefaction and accompanying lateral spreading, not only in Tambo de Mora (section 3.4), but also in the parts of Pisco closest to the ocean (section 3.5). In the northern part of the affected area, close to Canete, several large ground cracks were observed and they are described in the next section. A common and important problem in this earthquake is the lack of foundation reinforcement in important public buildings or complete lack of foundations for adobe houses, both reducing considerably the earthquake resistance. Furthermore, due to the lack of foundation, many adobe houses have very humid walls, which is health problem in itself. The slope failures and landslide we visited caused damages to roads and are therefore described in the road damage chapter.

3.2. Large soil cracks in San Luis

In the San Luis annex Nuevo Monte Rico, several large and long ground cracks were observed in an area of $1km^2$ size. Fig. 3.1 shows view from Google earth of the location of the ground cracks and Fig. 3.2 shows geology the same area. Nuevo Monterrico is located on an alluvial plain, shown as green areas in Fig. 3.1, and as whitish color with open circles in Fig. 3.2, are spreading between granitic formation in the North at San Francisco (in Fig. 3.1) and a tertiary sandstone formation (Paracas Formation) in the south. The ground cracks cause by damage to buildings, agriculture, and also, according to the local people, 3 wells went dry in the area. We do not know presently if the cracks were caused by liquefaction induced lateral spreading, or if large scale tectonics might have created extension in this area. Such extension often occurs on the continental plates in subduction zones. This needs to be investigated further. Below follows a more detailed description of the cracks and related damages

Fig. 3.1. Google earth view of San Luis Annex Nuevo Monte Rico. GPS coordinates next to right yellow point shows location of large cracks.

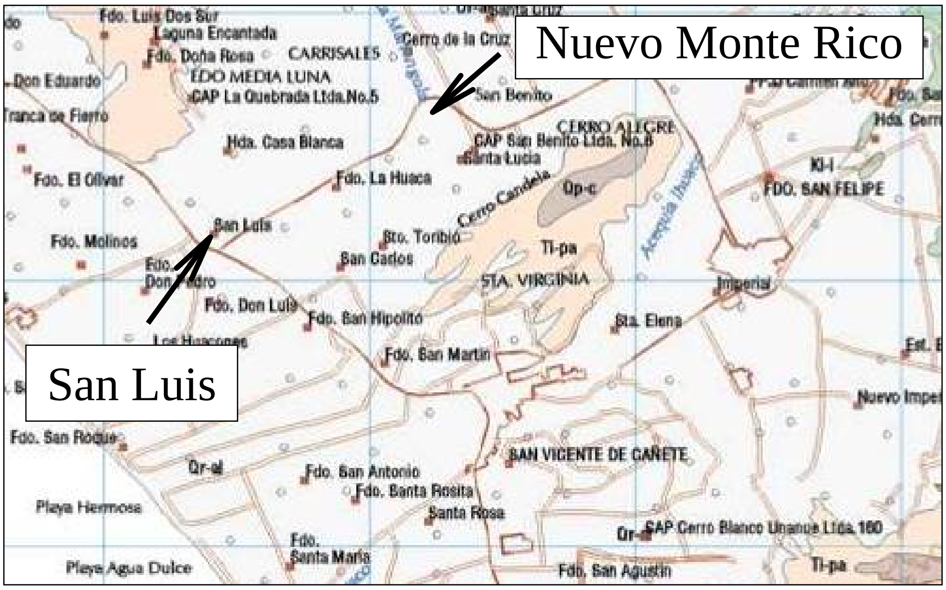

Fig. 3.2. Geological map (INGEMMET) view of San Luis Annex Nuevo Monte Rico.

There are 3 clusters of cracks in Fig. 3.3. The first cluster of points 37 to 40 indicated smaller lateral spreading failures along the dirt road (road 746) leading from the Pan-American Highway to Nuevo Monte Rico. There was drainage ditch on the north side of the road towards which lateral spreading occurred over a length of over 200 meters. On the south side of the dirt road there was a sewage pipe, leading from Nuevo Monterrico towards the ocean, which broke, likely due to the lateral spreading, and related soil displacement induced a lot of cracks in the cotton field next to the road (see Fig. 3.4). These cracks cause a lot of trouble for the farmers to irrigate their fields, since the water went into ground through the cracks, instead of being distributed through small irrigation canals to the whole field.

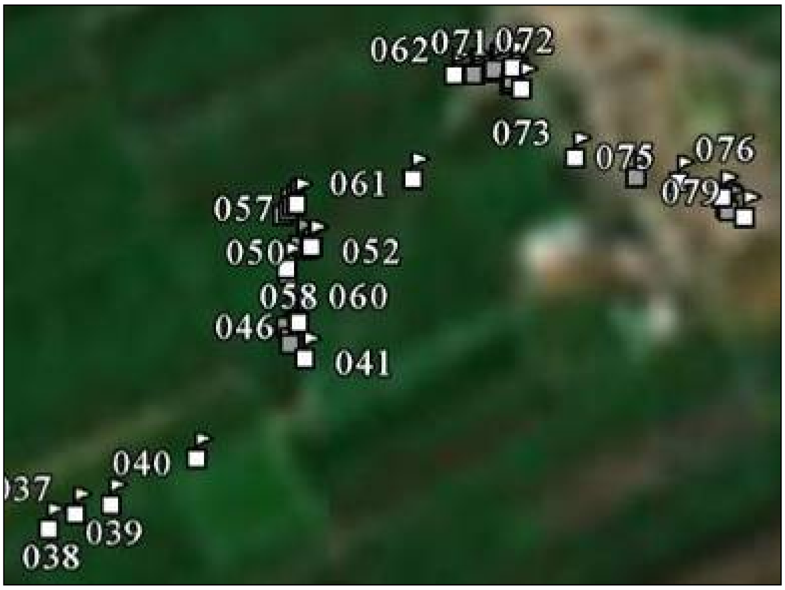

Fig. 3.3. Google earth view of San Luis Annex Nuevo Monterrico with GPS points.

Fig. 3.4. Cracks in cotton field causing trouble for the farmers to irrigate their fields.

At the cluster of points 40-44 in Fig. 3.5, an approximately 70 meter long crack were found. A close up is shown in the map in Fig. 3.6 and photo in Fig. 3.7. Another shorter crack was also found nearby, at point 46 in Fig. 3.5, with large vertical offsets of up to 40 cm (see Fig. 3.8). There were some indications of liquefaction since soil seemed to have been fluidized and finer grains settled on the top, but we saw no clear sand boils in the area. These "liquefaction traces" might have rather been due to irrigation of field in the weeks after the earthquake. Some of the fields in this area had already been plowed so many cracks had been erased. This shows how important it is to get into the field directly after the earthquake hit.
Another farmer had also irrigation problems in an apple plantation at GPS point 57 in Fig. 3.5. due to large cracks (see Fig. 3.9)

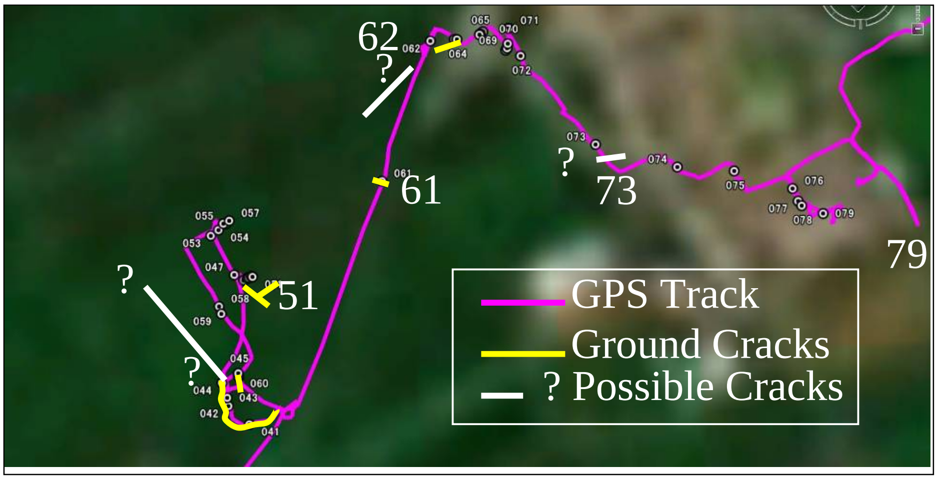

Fig. 3.5. Google earth view of San Luis Annex Nuevo Monterrico with GPS tracks in purple. Yellow shows location of large cracks. White shows location of cracks reported by local people. White colored crack located close to point 62 we observed from the road only.

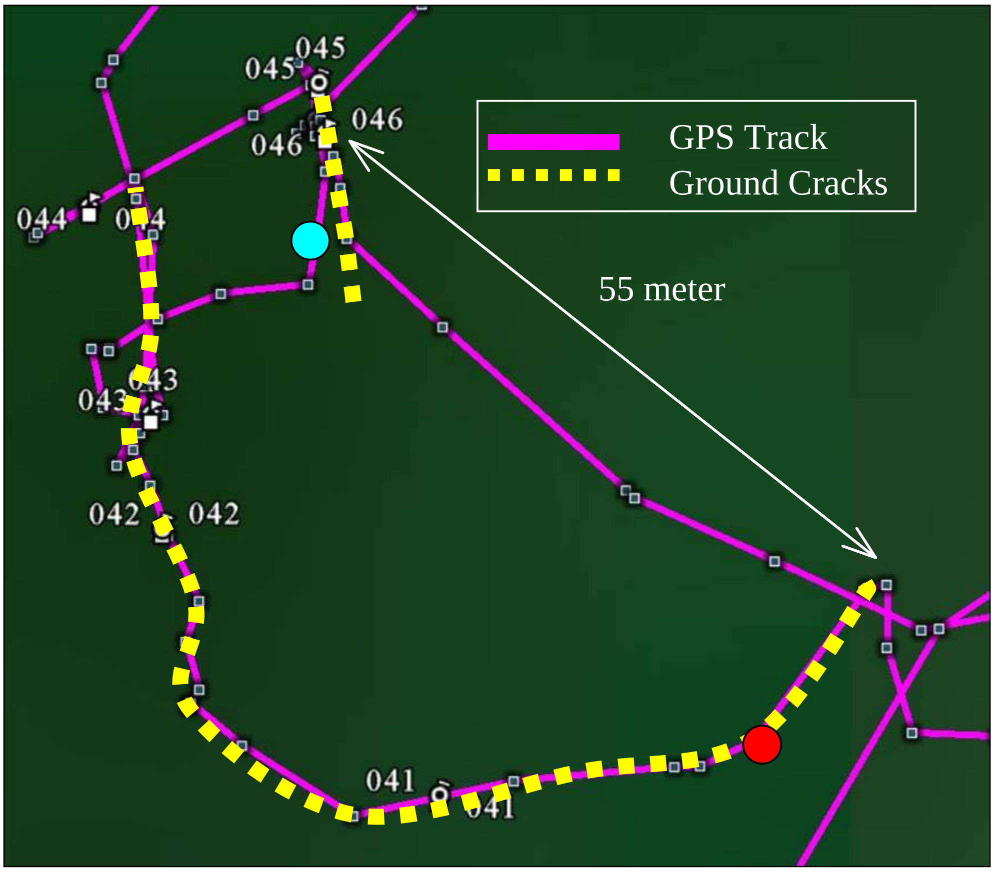

Fig. 3.6. Close up of ground cracks and GPS tracks at point 41-46. Photos taken at light blue dot and red dot are shown in Fig. 3.7 and Fig. 3.8. Cracks were some 70 meters long.

Fig. 3.7. Photo of large ground cracks at GPS points 41-46 in Nuevo Monterrico agriculture field. (Photo taken at red dot in Fig. 3.6.)

Fig. 3.8. 40 cm offsets of ground cracks in Nuevo Monte Rico agriculture field. (Photo taken at blue dot in Fig. 3.6.)

Fig. 3.9. Apple plantation ground cracks in Nuevo Monterrico. (Photo taken at point 51 in Fig. 3.5.)

More ground cracks were scattered further NNW, at point 61 there were cracks in the road and also at point 62 where the cracks damaged some houses (see Fig. 3.10). At our visit in this area many ground cracks were already gone and we relied upon local people stories and our own judgment. Fig. 3.11 shows a collapsed adobe house possibly due to large ground cracks; A local construction company person told us the crack crossed the street and reach the adobe house. Noting that the adobe wall to the left was not damaged it is possible that the damage of the right part was due to the crack and less due to shaking. However this needs to be confirmed.

Fig. 3.10. Large ground cracks in Nuevo Monterrico crossing road at point 61 with destroyed houses in the back ground.

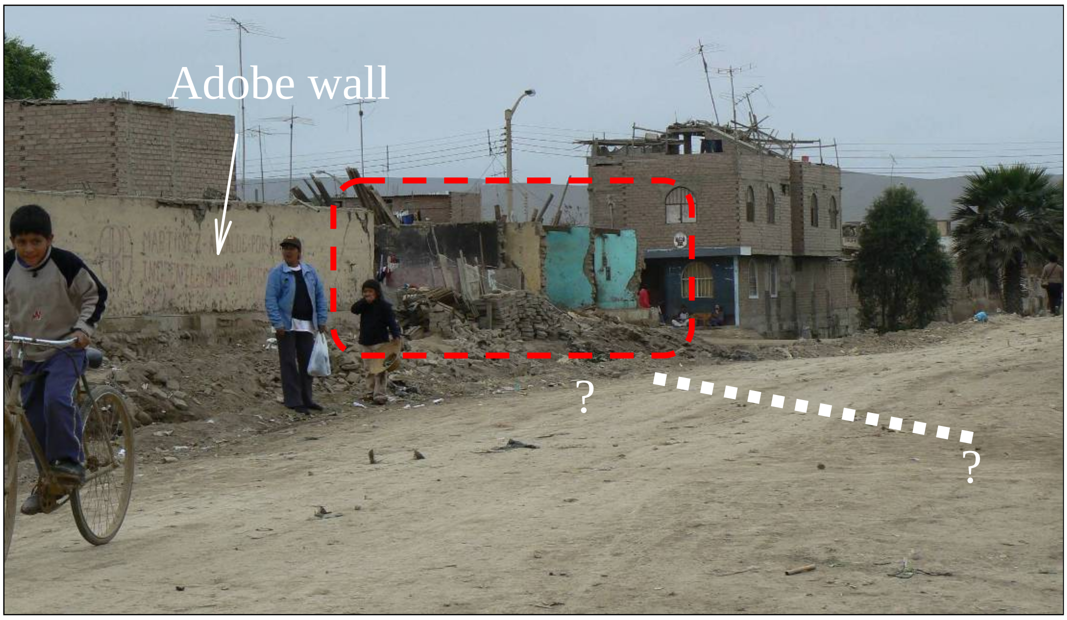

Fig. 3.11. Collapsed adobe house due to large ground cracks in Nuevo Monterrico. The local people told us the crack crossed the street. The adobe wall to the left did not collapse.

Fig. 3.12. Damage house located at point 79 in Fig. 3.6.

3.3. Foundation aspects

3.3.1. Health center in Huaytara

Huaytara is located some 130 km away from the epicenter, high up in the mountains. Here the ground shaking was not so severe and mainly vertical cracks in adobe walls were observed. One of the church towers suffered damage as well. A damaged school building is described in Chapter 4.

The health center in Huaytara suffered cracking of walls due to a foundation problem. At the construction there was a sewage canal, which is not in use any more, and on top of which an unreinforced foundation slab was placed. Due to the earthquake there was some soil movement around the canal and there was uneven settlement of the slab, causing it to crack as seen in Fig. 3.14.

Fig. 3.13 Health center in Huaytara with cracks in walls due to foundation differential settlement.

The health center was built on a slope, which likely exaggerated the soil movements and their effects on the slab foundation.

Fig. 3.14. Huaytara health center foundation slab with 1cm wide crack due to differential settlement.

3.3.2. Adobe foundations and ground humidity an example from Guadalupe

Guadalupe is located on kilometer 290 of the Pan-American Highway. There was a lot of damage to adobe house in this area ranging from completely collapsed house to houses with cracked walls. There was greater amount of damaged houses on the east side of the Pan-American Highway, possibly related to higher moisture content of the soils weakening the adobe walls. The adobe walls absorb the moisture from the surrounding ground, which thereby softens the mud bricks. This problem is wide spread in many locations in Peru and likely in other countries as well. The moisture absorption was evident inside one house as shown in Fig. 3.15.

Fig. 3.15. Foundation problems in Guadalupe: Miscoloring due to moisture absorption by adobe wall. The moisture weakens the structural properties of the wall, thereby the earthquake resistance of the house, and it also constitutes general health threat.

A typical foundation method for the adobe houses consists excavating a narrow trench and putting the adobe blocks inside trench, right on top of the soil. With time the buried part of the adobe wall absorbs moisture becomes soil again, i.e. the wall is virtually placed on the ground. It is questionable if it is of any help to excavate the trench in the first place. An example of such a wall is shown in Fig. 3.16. The moisture also accelerates decomposition of organic materials within the adobe blocks, further reducing the strength of the blocks, since the organic materials function as sort of "fiber reinforcement". In addition to reducing the earthquake resistance of an already earthquake vulnerable building type, the moisture also constitute a general health problem. With the above in mind it is necessary to convey the message of proper foundations preventing moisture to be absorbed in the walls. The adobe moisture absorption is a big problem in the "Barrios Altos" area in Lima and the vulnerability of these houses will show itself in the next big earthquake in Lima.

In the northern part of Ica a drainage dike was constructed to drain the soil in the area (according to local engineer), but due to the suspended material entering, the dike clogged up and the drainage capacity was reduced drastically. Proper maintenance of these civil infrastructure is thus important.

Fig. 3.16. Temporary self-built house. The original house collapsed in the earthquake. The dashed box shows how the lower part of the wall is darker due to moisture absorption.

3.3.3. Good performance by two liquefaction resistant buildings in Pisco

We found two buildings with good performance even though damage to buildings around them was severe. The location is indicated in Fig. 3.17. This area was severely damage by liquefaction as seen in the ground cracks in Fig. 3.18. Lateral spreading caused the soil to displace towards the ocean and the creating some 10-15 cm wide cracks in the soil. The crack probably continues in front of and/or beneath the blue building and then up through the confined masonry wall as marked by the black arrow in Fig. 3.18. The soil settled some 10-15 cm next to the blue house as shown in Fig. 3.19.

Settlements and cracks like these caused by the liquefaction damage in many houses in this and other areas of Pisco.

Fig. 3.17. Google earth satellite view of location of buildings with pile foundation (blue mark) and strong foundations slab (green mark).

Fig. 3.18. Soil displacement crack next to old building. (blue mark in Fig. 3.17). The crack probably continues in front of and/or beneath the building and then up through the confined masonry wall as marked by the black arrow. (The curvature of the building top is due image distortion, it should be a straight line.)

Fig. 3.19. 10-15 cm soil settlement around blue building on pile (?) foundation. Blue mark in Fig. 3.17

The old building was hybrid structure with confined masonry to the right and left as seen from the ocean side in Fig. 3.20. The central part is made of wood and stands on an elevated pile foundation. The small stair to the left in Fig. 3.20 came partially off the building due to the lateral displacement, but otherwise the building performed seemingly well.

Fig. 3.20. Old building located close to the ocean in Pisco that performed well even large liquefaction displacement was observed. In the central part a pile foundation is visible.

Fig. 3.21 shows a close up of pile foundation with corroded reinforcement bars. The age of building foundation is unknown, but many of the buildings in here were constructed 50 to 100 years ago, in connection with the establishment of the fishing industry here.

Fig. 3.21. Close up of pile foundation showing corroded reinforcement bars. The age of building foundation is unknown, but many of the buildings in these area were up to 100 years old.

On the opposite side of the street away from the ocean there was a recently completed hotel that was about to open. It suffered only minor damages due to that its strong reinforced foundation could resist the liquefaction effects. A close up of hotel damage is shown in Fig. 3.23. Relative ground movement, due to liquefaction, between the columns of the exterior roof structure and the building, caused the cracks. In general well engineered structure like this one suffered only minor or no damage.

Fig. 3.22. New hotel which suffered only minor damages. A close-up of the part inside the red dashed box is shown in Fig. 3.23

Fig. 3.23. Close up of hotel damage. Relative ground movement, due to liquefaction, between the columns of the exterior roof structure and the building, caused the cracks.

3.4. Tambo de Mora

Tambo de Mora district, part of Chincha province in the Ica region, has a population of 5348 [4]. The city is located some 38 km from the USGS estimated epicenter, and 175 km south of the capital Lima. Buildings, industrial and public facilities in Tambo de Mora were severely damaged due to liquefaction induced ground failure and lateral spreading. To evaluate ground conditions we performed microtremor measurements at 8 locations.

Under the program of Sustainable Cities, INDECI in association with the National University of Ica [15] present the Seismic Hazard of Chincha city (see Fig. 3.24). According to the hazard zoning map, Tambo de Mora (Zone 1) has the highest risk in the area.

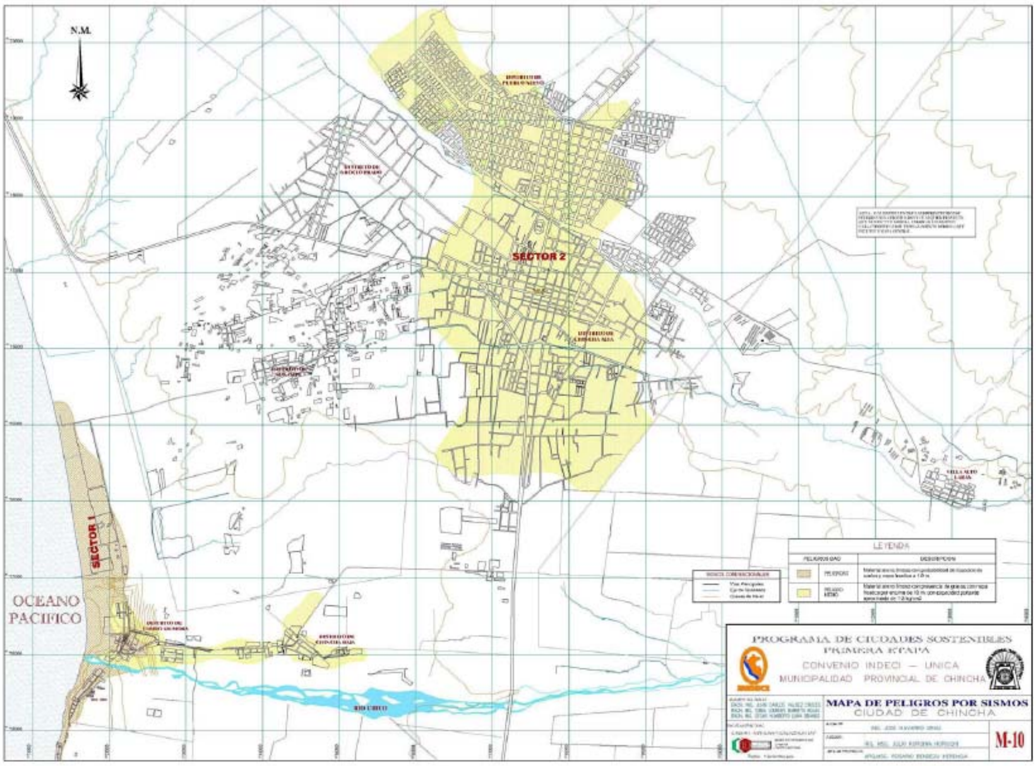

Fig. 3.24. Seismic Hazard Areas City of Chincha. INDECI [1]. Brown colored area next to the ocean indicates “dangerous”s area.

3.4.1. Damage

Severe settlement of buildings and foundation damage, due to liquefaction induced ground failure and lateral spreading, caused the collapse of adobe houses and severe cracking of walls of confined masonry buildings. The damage resulted in the death of 5 persons; Out of 1447 dwellings, 465 houses were completely destroyed, 308 were severely affected, another 467 were affected, and 121 were lightly affected [4]. This left only 121 unaffected houses.

Fig. 3.25. Settlement of 0.7 m of building in front of palm tree.

At Canchamana in the northern part of Tambo de Mora (0.5 km north of microtremor point 1.), a masonry community building (see Fig. 3.26) was severely damaged by lateral spreading and an adobe school building was partially collapsed, while a newer school building with proper foundation behaved well (Fig. 3.27.)

Fig. 3.26. Severely damaged community building in Canchamana, with liquefaction traces in the foreground.

Fig. 3.27. Severely damaged community building in Canchamana, with liquefaction traces in the foreground and well behaved red school building in the background.

Fig. 3.28. Foundation pushed up due settlement the building.

Fig. 3.29. Liquefaction splashed all the way to the top of Prison building door.

It is worthy to mention that Chincha Prison, located in the North of Tambo de Mora, suffered extensive damage due to liquefaction. The surrounding wall collapsed (see Fig. 3.30) and the prison cells exhibited large settlements (see prFig. 3.31). Due to the risk of additional damages, the local government decided to set free the prisoners. This fact suggests that location of this public building deserve further review as long as the social consequences of its failure were also considerable.

Fig. 3.30. Collapsed wall at Chincha prison due to large ground deformation

prFig. 3.31. Sand inside prison cell. (Courtesy of Julio Kuroiwa)

3.4.2. Geology and liquefaction

Tambo de Mora is located on an alluvial deposit in the south and a marine deposit in the north (see Fig. 3.32) and to the east of the marine deposit lies the Pleistocene Canete formation consisting of alternating layers of sand and silt stones [1]. Ground water level is very shallow in the marine deposit, surfacing at some locations. South of the river Chico, we found one well, close to microtremor point 8, where the water level was at approximately 2.5 meter.

Fig. 3.32. Google earth image of microtremor measurement locations and results.

In the northern part (close to Microtremor point 1) a lot of over 20 meter long cracks with grayish sand ejecta were observed. Cracks and up to 3 meter differential settlements (see Fig. 3.33) where seen closer to the Canete formation. Here light brown/beige seemingly liquefied soil covered parts of some of the vertical scarps. The liquefied area extends from the central park (Plaza de Armas) of Tambo de Mora all the way to Pan-American highway in the north, which is distance of more than 7 km. A large block moved seemingly had moved downwards from the Canete formation and this movement downward continued as marked by the dashed lines as seen in Fig. 3.34. However there was vegetation between the block and the slope so this movement did not happen in the 2007 earthquake.

Fig. 3.33. On the border between the Canete formation and the marine deposit, there is a 3 meter differential vertical offset.

Fig. 3.34. Block moved seemingly moved down and towards ocean some 5 meters, however there was vegetation between the block and the slope, so this did not happen in the 2007 earthquake.

3.4.3. Microtremor measurements

We measured microtremors in the afternoons of the September 18 and 19 at 8 locations from Canchamana in the North to San Pablo in the south (see Fig. 3.32). We used a Geodas-10 system with a velocity meter CR4.5-2SV, frequency range 0.5-20

Hz. The Sampling frequency was 100Hz, record length 2x3min or more and the software Geopsy [2] was used for data processing.

The result indicates that fundamental frequency increases from 3 Hz in the south to 5 Hz at “Plaza de Armas” and at point 8, south of the river, the frequency was approximately 12 Hz.

The microtremor results seem to be related to the geological conditions in that the lower fundamental frequencies are observed in the area of the marine deposit at location where water level is very close to or at the surface, and when moving south towards the stiffer alluvial deposit the frequencies increases to 5 Hz. The observed damage, in Tambo de Mora and other locations with marine deposits, such as Villa Swamps, port of Pisco and the port of Paracas, indicates that liquefaction resistant foundations, such as stiff reinforced foundations are necessary to avoid damages under similar conditions.

3.5. Pisco

3.5.1. Overview

Pisco, located 351 km south of Lima and 17 m AMSL, is the capital of the Pisco Province which belongs to the Ica Region. Initially funded in 1640, the city of Pisco was shifted to its current location during the period 1689-1705, in order to protect the city from pirates’ attacks and earthquakes in the late 16th century.

The city of Pisco has a population of about 54 192 according to the Census of 2005. It occupies an area of approximately 24.56 km², in a subtropical arid region of rainfalls ranging between scarce and null [7], having an average annual precipitation of 1.6 mm. In terms of economy, cotton processing factories, wineries, agriculture, fishing industries and other port-related businesses, are the most relevant.

Pisco is located directly above the central part of the estimated fault plane and a local intensity of 8.0 (MSK-64) was preliminarily estimated by Astroza [8]. According to the National Institute of Civil Defense (INDECI) the death toll in the city was 338, 70% of the whole earthquake dead toll, as of October 10, 2007 [11].

3.5.2. Geology

The geology of Pisco can be divided into two main formations [17]. One is Formation Pisco, a lithologic sequence of white color composed of diatomite with intercalation of tuff sandstones and shales, located between Pisco River and the surroundings of Camana. The other is the recent quaternary deposit, composed of clastic materials transported by water and then deposited on the river beds as coarse conglomerates intercalated with sand, silt and clay. These deposits can be observed along the river side and the terraces’ foot.

3.5.3. Early studies

The Japan-Peruvian Centre of Seismic Investigations and Disaster Mitigation (CISMID) of the National University of Engineering in Lima [13] carried out a detailed subsoil investigation, consisting of 25 trenches and 17 boreholes, for the city in 1998. The study aimed at mapping the distribution of soil types and their shear strength characteristics, identifying potentially liquefiable areas and quantifying the distribution of bearing capacity based on the usual foundation geometry used by locals. The field information collected in this study was enriched with data from even earlier studies.

Fig. 3.35 shows the proposed geotechnical zonation based on bearing capacity. The characteristics of each zone can be briefly described as:

- Zone I: Southwest of Pisco. A 0.2 m thick layer of fill material composed of clay and round gravels, overlying gravel poorly graded (GP), maximum size of 12", 22% of sand and 1.5% of non plastic and slightly wet fines. No phreatic level was identified. Bearing capacity ranges from 2.5 to 3.0 kgf/cm² (Df=0.8 m).
- Zone II: Northern and central coast of Pisco. 0.5 m of sandy clay layer overlying fine silty sand with a thickness of 1.1 m, followed by poorly graded gravel (GP). The phreatic level was found northwards at a depth of 1.4 m. The estimated bearing capacity was 2.0 Kgf/cm² (Df=1.1 m)
- Zone III: Central Pisco. 1.2 m of sandy clay layer overlying fine silty sand up to depths between 2.0 to 4.25 m, followed by gravel poorly graded (GP). The phreatic level is located between depths ranging from 1.0 to 1.8 m. The estimated bearing capacity was 1.0 Kgf/cm² (Df=0.8 m)
- Zone IV: Southeast of Pisco. 0.8 to 1.2 m of filling material composed of clay mixed with rounded gravel and debris deposits. Phreatic level was not observed and the bearing capacity was estimated to range between 2.0 and 2.5 kgf/cm² (Df=0.8-1.2 m).
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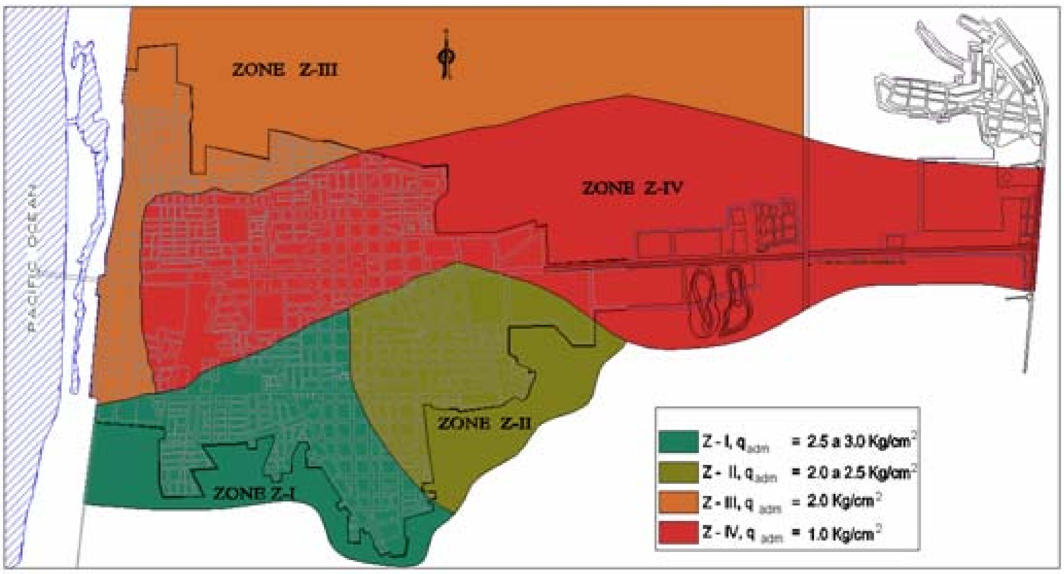


Fig. 3.35. Geotechnical zonation based on bearing capacity (Adapted from [13])

An updated version of the study mentioned before is presented by Aguilar et al, 2006 [7], whose work dealt with the estimation of the expected seismic amplifications. Fig. 3.36 shows three zones defined taking into consideration the geologic and geotechnical characteristics of soils. These three zones can be summarized as:

- Very high seismic amplification zone: Saturated lose sandy soils, with natural frequency periods greater than 1.4 sec that may amplify the bed-rock acceleration more than 3 times.
- High seismic amplification zone: Loose sandy and silty-sandy soils, slightly saturated with phreatic levels at 3.0 m depth. Natural periods between 1.2 and 1.4 sec that may amplify the bed-rock acceleration between 2.0 and 3.0 times.
- Intermediate seismic amplification zone: Sandy and gravely-sandy soils with medium levels of compaction, slightly saturated with phreatic levels at 3.0 m depth. Natural period around 1.2 sec and expected amplifications between 1.5 and 2.0.

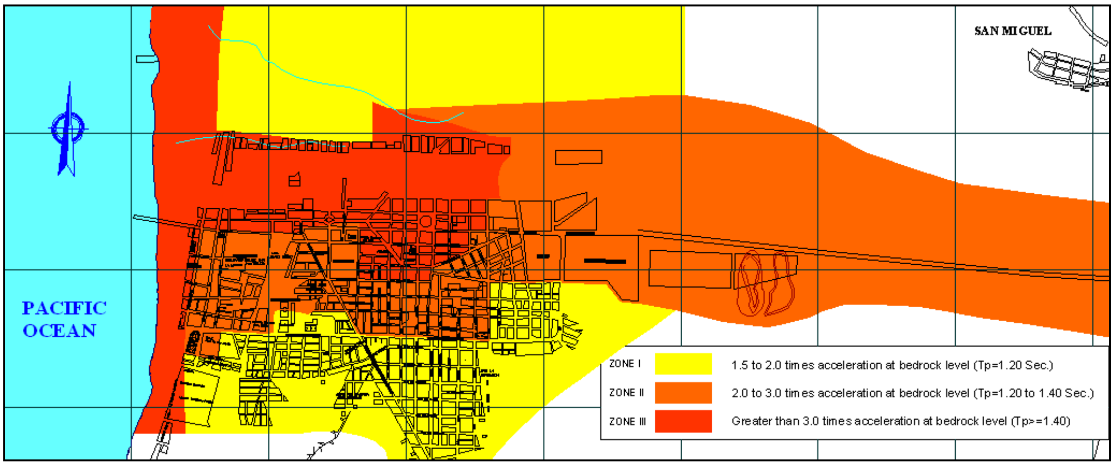


Fig. 3.36. Expected amplifications of seismic waves (Adapted from [7])

The distribution of amplifications across the city seems to follow the pattern of soil distribution, suggesting that the natural period and the expected amplifications might be based on the available information of soil characterization and phreatic level location.

Likewise, based on the information provided by the subsoil exploration, potentially liquefiable areas were identified using the method proposed by Seed et al, (1984).

Based on this, it was suggested that widespread liquefaction may take place along the coastline of Pisco. Partially liquefiable soils were identified in the northern part of the city, which corresponds to the oldest part of the city. (See Fig. 3.37)

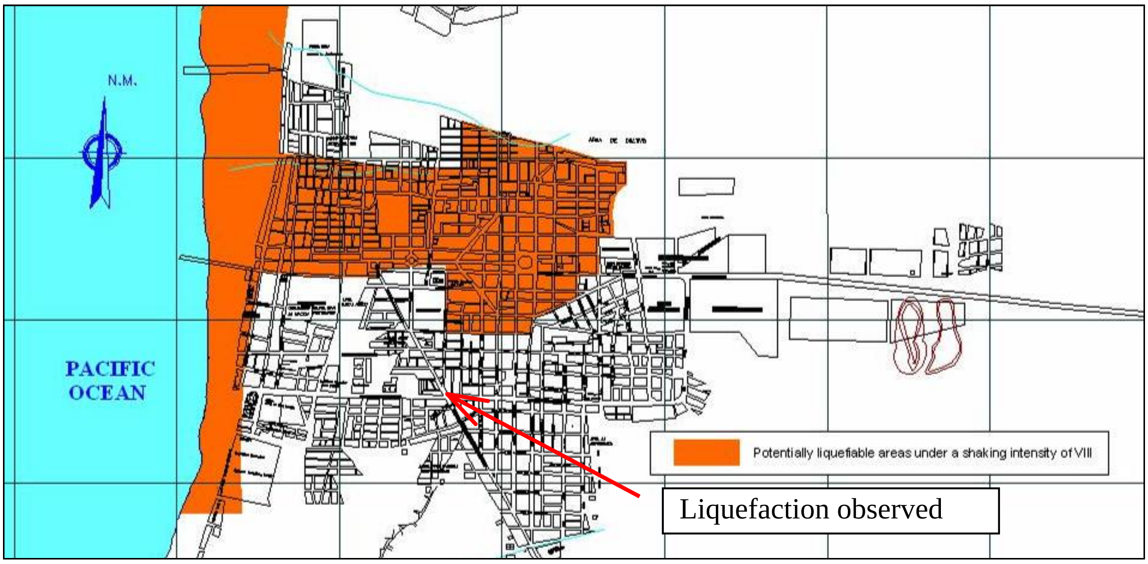


Fig. 3.37. Potentially liquefiable areas (Adapted from [7]). Liquefaction was observed outside this zone, one such location is indicated by the arrow and shown in Fig. 3.42.

Under the Sustainable City Program, which is managed by INDECI, a risk map, combining the potential effects of different hazards, such as floods, increments in phreatic level, earthquakes and tsunamis, was prepared. The Sustainable City Program aims at producing risk maps to guide the urban development of Peruvian cities. As of August 2007, maps for more than 120 cities have been produced. The risk map for Pisco City was prepared in association with the San Luis Gonzaga National University of Ica. In it, tsunami and flood hazards are considered more critical than liquefaction and ground motion amplification hazards.

Sanchez et al [17] also described the location of areas of waste disposal; some of them have been already urbanized while others might be used in future urban development. The characteristics of the deposits shown in Fig. 3.38 can be described as:

- Zone I: Located in the central and southern part of Pisco Playa. A lagoon left by the sea that later was leveled with debris aimed at future urbanization. Here soils are composed of crushed shells and construction wastes such as bricks, concrete, and sand
- Zone II: Southeast of Pisco. After being used for years as a sanitary filling, the current use of the area is the disposal of debris with similar characteristics to those of at Zone I.
- Zone III: East of Pisco. Leveled using the soil transported during the construction of the city’s reservoir and the access road; nowadays it is a landfill occupied by factories and urban slums.
- Zone IV: Located in the Southern and Northern part of the coastline of Pisco, it has been filled with waste materials, but mostly, products of the fishing grounds and a variety of elements carried by sea currents.

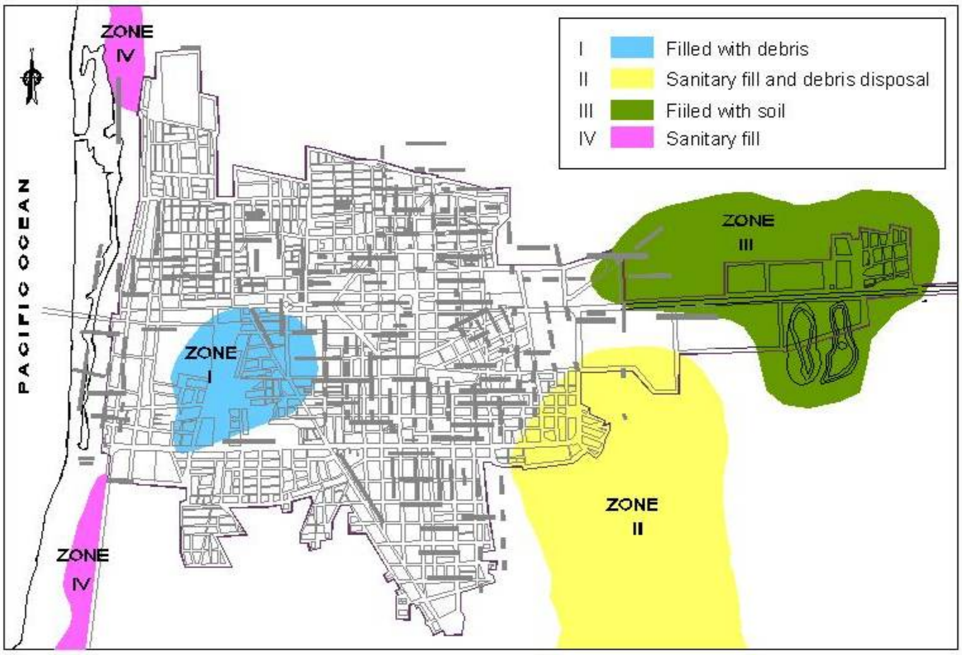


Fig. 3.38. Distribution of landfills in Pisco (Adapted from [13])

3.5.4. Overview of damage distribution

Evidences of soil deformation are clearly seen along the coast. However across the city it affected some buildings and other constructions. Areas close to the coastline particularly suffered extensive damage due to the shake but also, to the effects of the tsunami that hit the area minutes later. According to Barrientos [9], the run-up height of the wave estimated southwest of Pisco was 2.65 m.

The sewer system in Pisco, whose conditions were already poor before the earthquake, was drastically affected due to ground deformation and liquefaction. As shown in Fig. 3.39 and Fig. 3.40, central and southwest areas of Pisco had broken sewer pipes due to ground settlements and dislocated manholes were wide spread. Fig. 3.41 (Rodriguez et al [16]) also shows a lateral spreading movement along the coastline in the south of Pisco.

These points located along the coast and central part of Pisco, are within the area presented in Fig. 3.36 as prone to liquefaction. However, we observed liquefaction outside this “liquefiable zone” as indicated with an arrow in Fig. 3.36 and shown in Fig. 3.42. The extent of potentially liquefiable areas may deserve further review.

Fig. 3.39. Central Pisco (S13 42.542 W76 12.516). Settled ground as evidence of broken sewer pipes.

Fig. 3.40. Manhole pushed up and surrounded by ejected fine sand. Northwest of Pisco (S13 42.343 W76 13.029)

Fig. 3.41. Sub parallel cracks with lateral spread along the streets in the southwest of Pisco (Rodriguez et al [16])

Fig. 3.42. Liquefaction traces were observed north-west of the intersection between Valdelomar Street and Las Americas Avenue.

Agüero et al [6] has evaluated the macroseismic intensities based on the inspection of 30 buildings distributed throughout the city and using the MSK-64 scale adapted for Peru by Ocola (1979). Fig. 3.43 shows that high intensities are concentrated within the central part of the city, decreasing towards the south and southeast.

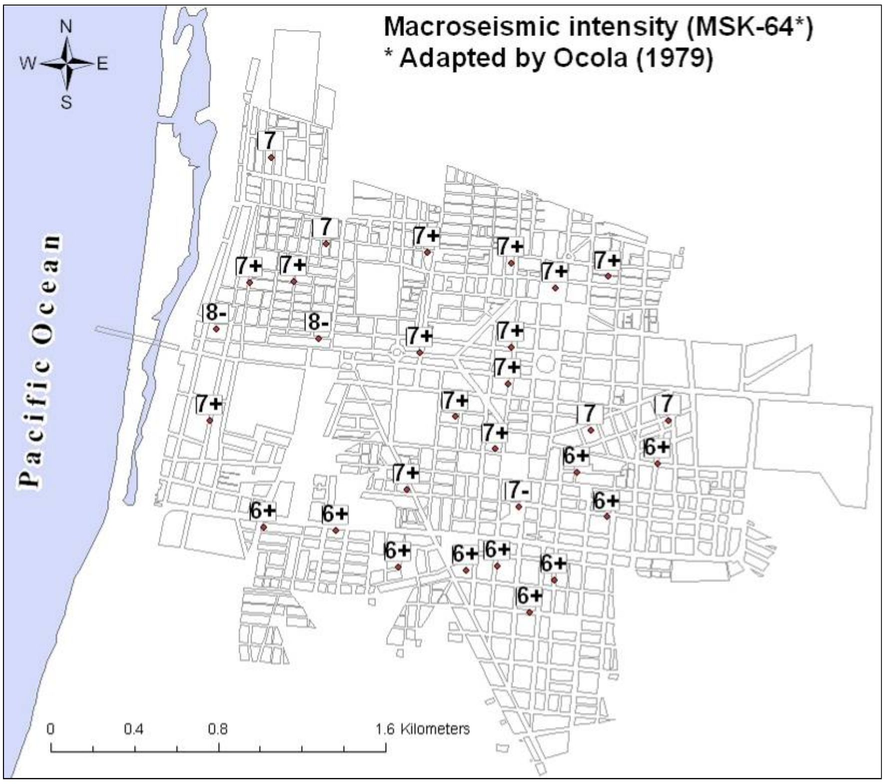


Fig. 3.43. Macroseismic intensity (MSK-64). (adapted from Agüero et al [6]

3.5.5. Microtremor measurements

We (hereafter UT) have collaborated with CISMID of the National University of Engineering (hereafter UNI) to perform a coarse microzonification of the city of Pisco (during September 15 and 16, 2007) with microtremor measurements at 34 different points in the city.

Both teams used a Geodas-10 recording equipment with CR-4.5-1 velocimeter (UNI) and CR-4.5-2S velocimeter (UT), The frequency range of 0.5-2.0 Hz for UT's velocimeters whereas 1.0-2.0 Hz for CISMID's It was defined that two sensors would be used at each point and all measurements should be 3 min long (100 Hz sampling frequency) and at least taken twice depending upon the surrounding conditions without initial filtering Before starting, sensors' response and recording parameters were a trial location.

We also performed microtremor array measurement at three locations (UNI one and UT two) across the city. We selected open areas free of topographic irregularities and evident sources of noise These data will be processed according the SPAC method [12]. Array layout and setup details are presented in Fig. 3.44 and Fig. 3.45.

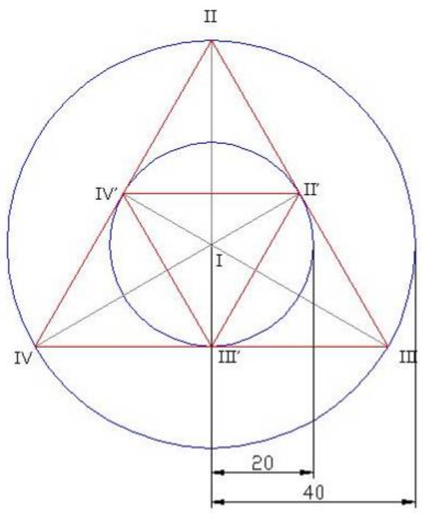


Fig. 3.44. Array for SPAC measurements. (Radii in meters)

Fig. 3.45. Open areas chosen for SPAC measurement. Below the tripod is the central sensor. (Labeled as I in Fig. 3.44)

Fig. 3.46shows the test's location, measurements taken by CISMID and UT teams are represented as red a blue dots, respectively. Also, triangles were used to identify the SPACs taken by the UT.

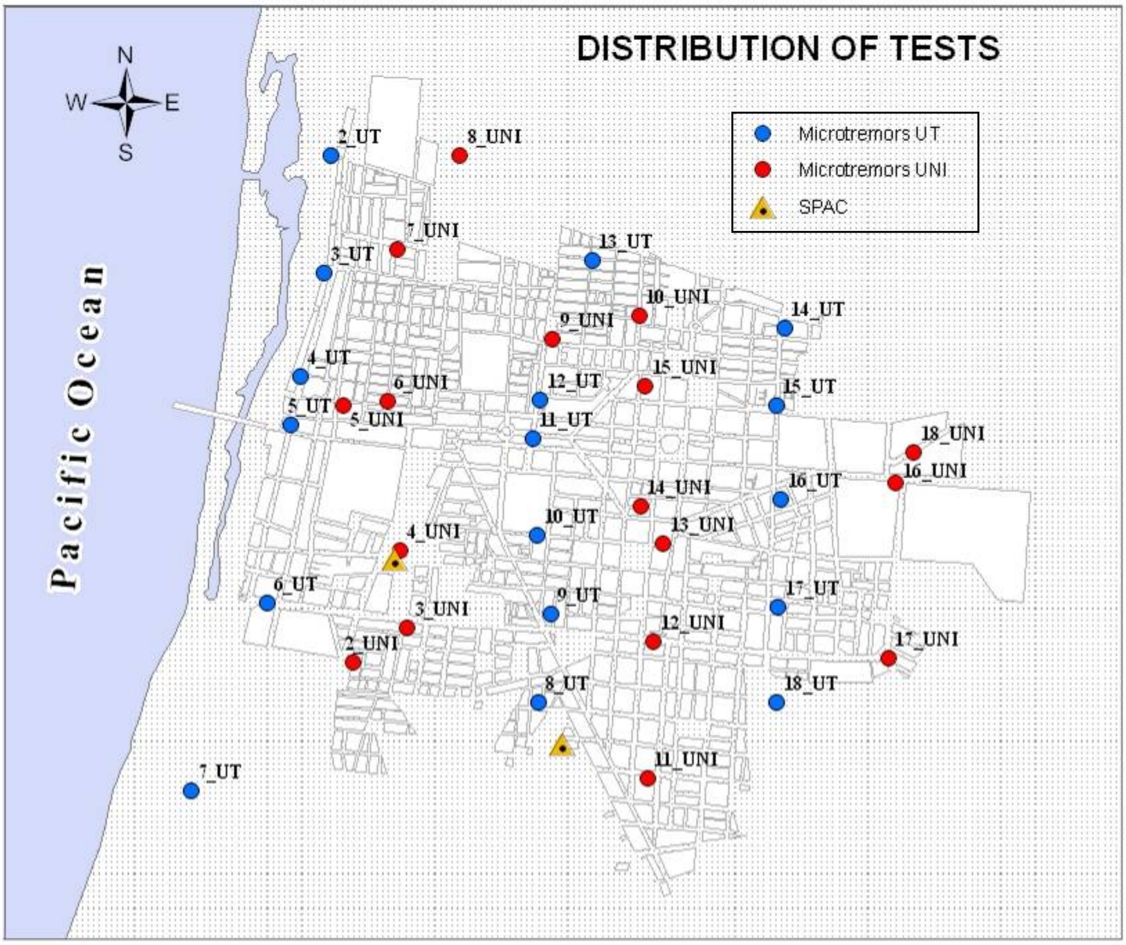


Fig. 3.46. Location of test conducted by CISMID and the University of Tokyo

Fig. 3.47 to Fig. 3.54 summarize additional comments on the surrounding conditions where microtremors were conducted. Highly contrasting characteristics between almost flat areas due to severe damage in the west side whereas scattered collapsed and less affected houses towards the east.

Fig. 3.47. (Point 2_UT) The number of standing buildings is small, high level of damage.

Fig. 3.48. (Point 5_UT) At San Martin Av. where many nearby adobe houses were about to collapse

Fig. 3.49. (Point 7_UT) In front of the beach "Camino San Andres". Non-inhabited area.

Fig. 3.50. (Point 13_UT) Less affected area with one and two story houses almost undamaged

Fig. 3.51. (Point 11_UT) At the intersection with San Martin Av, close to

Fig. 3.52. (Point 8_UT) In front of Communal gathering place. Few damages

Alexander Humbolt School. Few collapsed houses, debris deposited on the left side of the road. *in surrounding structures.*

Fig. 3.53. (Point 15_UT) Two blocks from the main square. Contrasting large amounts of debris from nearby collapsed buildings on the right side while almost undamaged houses on the left.

Fig. 3.54. (Point 17_UT). Less evident damage. However, one block northwards there was a totally collapsed adobe house, and a masonry house less severely damaged but it underwent large settlements due to soil deformation.

3.5.5.1. Results

In order to be consistent all the data was processed with same criteria using the software Geopsy [2] and Fig. 3.55 shows the H/V ratio determined frequencies for all points. 11 out 34 points did not show any clear peak, e.g. the zone of amplification was too broad to distinguish a peak, or the peak was split into two or three parts, or the amplification was less then 2. Examples of these three categories can be found in Fig. 3.56. Out of the remaining 23 points, 6 points had frequency peak beyond the sensor range, however may be accepted to a certain level since we are using the ratio of the horizontal and vertical fourier spectra. Furthermore, for neighbouring locations with such high frequencies, we obtained similar results to the UNI team.

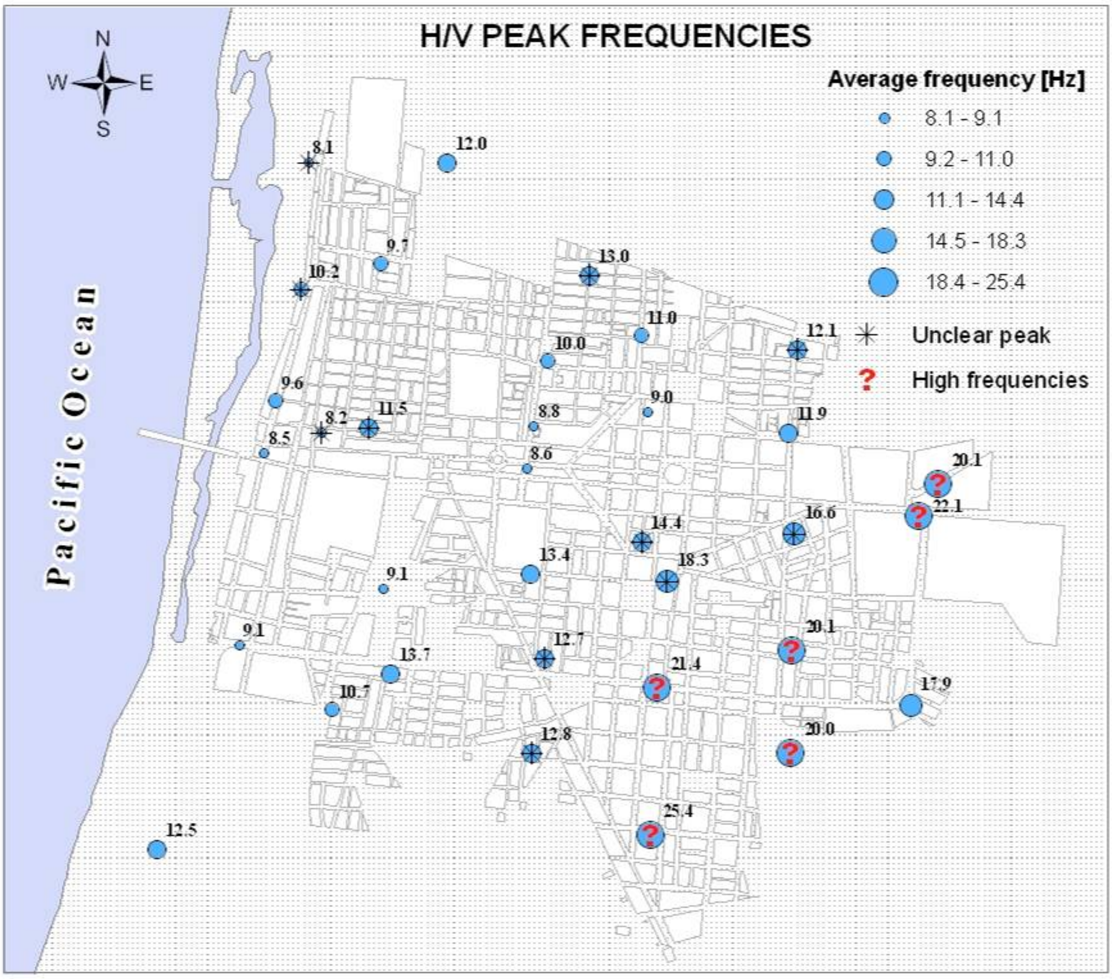
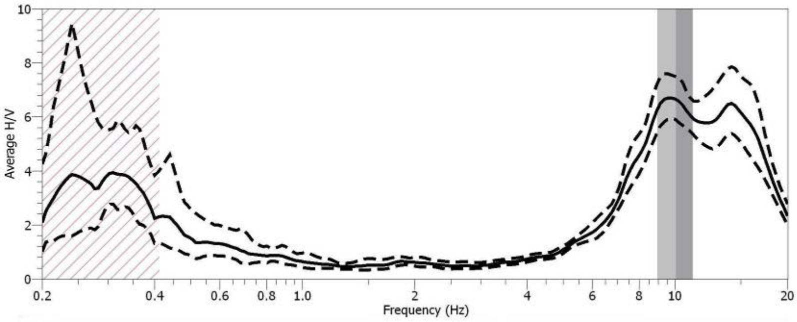
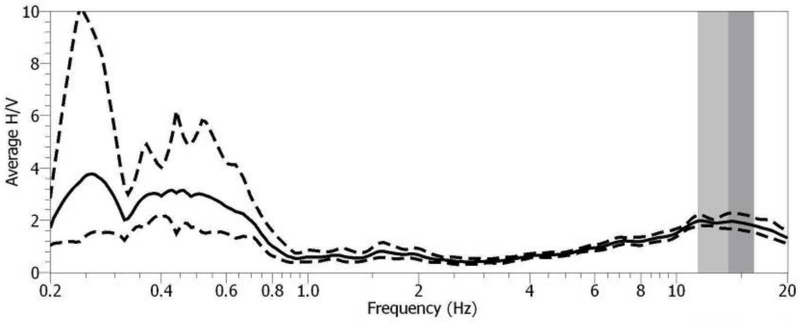


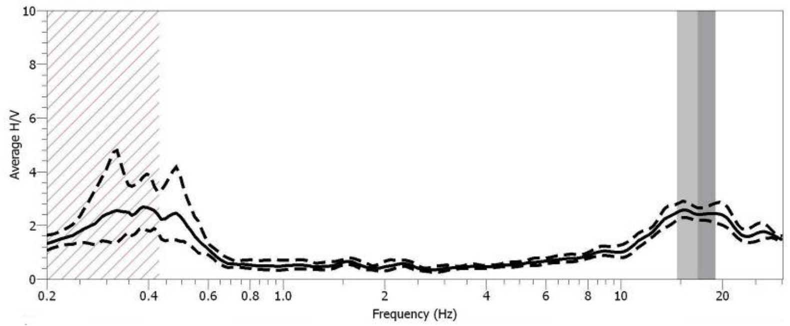
Fig. 3.55. H/V peak frequencies



(a)



(b)



(c)

Fig. 3.56. Examples of H/V spectral ratios regarded as non reliable

a. *Pont ID: 6_UNI. Clear amplification but the peak is split into two parts having similar amplitudes.*
b. *Point ID: 8_UT. Low amplification*
c. *Point ID: 13_UNI. Amplification exists but the possible range is too broad to pick up one single frequency*

Keeping that in mind, Fig. 3.57 presents the data using blue circles for easily identified peaks while the red one represents those difficult to identify. Based on the reliable points, a straightforward spline-type interpolation was made aimed at depicting the general trend of the peak frequencies. These results suggest that there is a North-West to South-East trend of increasing frequencies .

However, this interpolation should be further studied in combination with available soil classification, SPT data, and an updated lithological map (INGEMMET, work in progress).

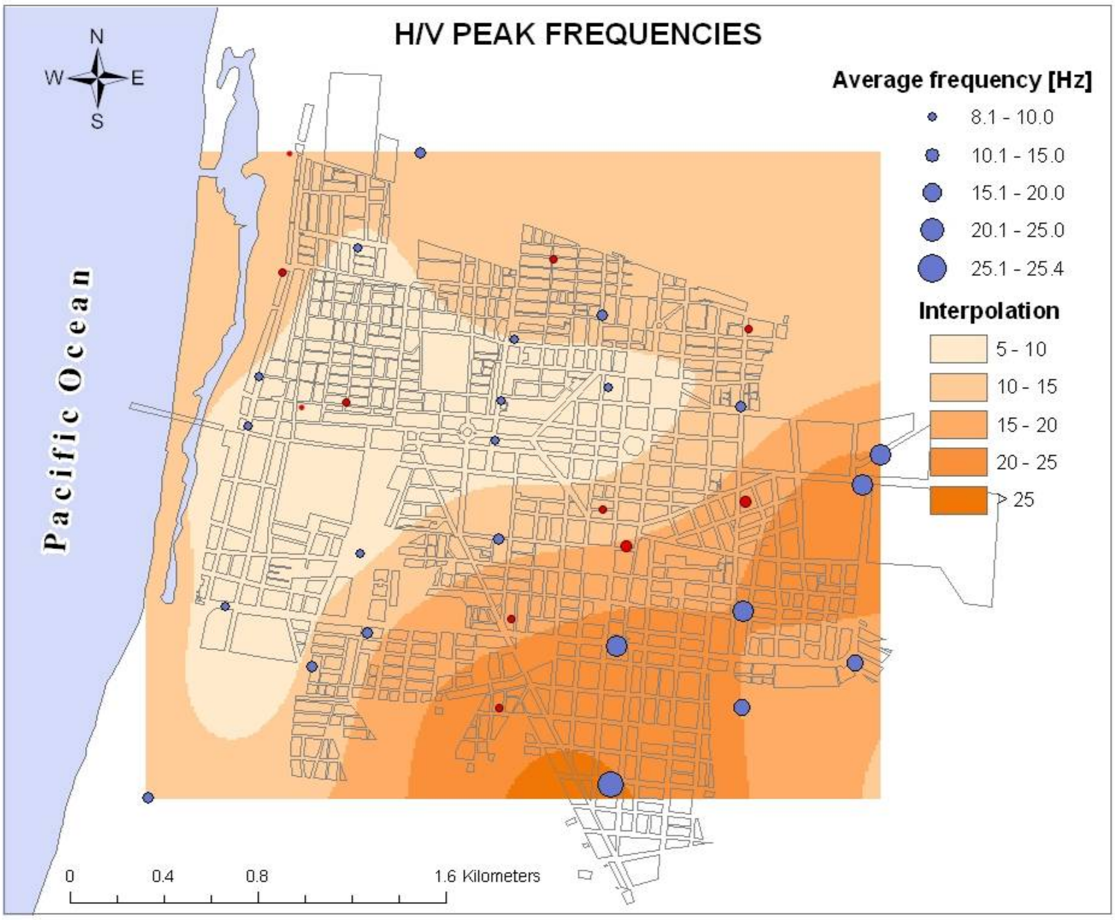


Fig. 3.57. H/V peak frequencies. Local values and contours.

Fig. 3.58 shows the local values of peak amplitudes, using asterisks (with amplification values) to mark the location of points for which it was difficult to identify the peak, while a question mark for those points where the peak frequency is out of the sensor range.

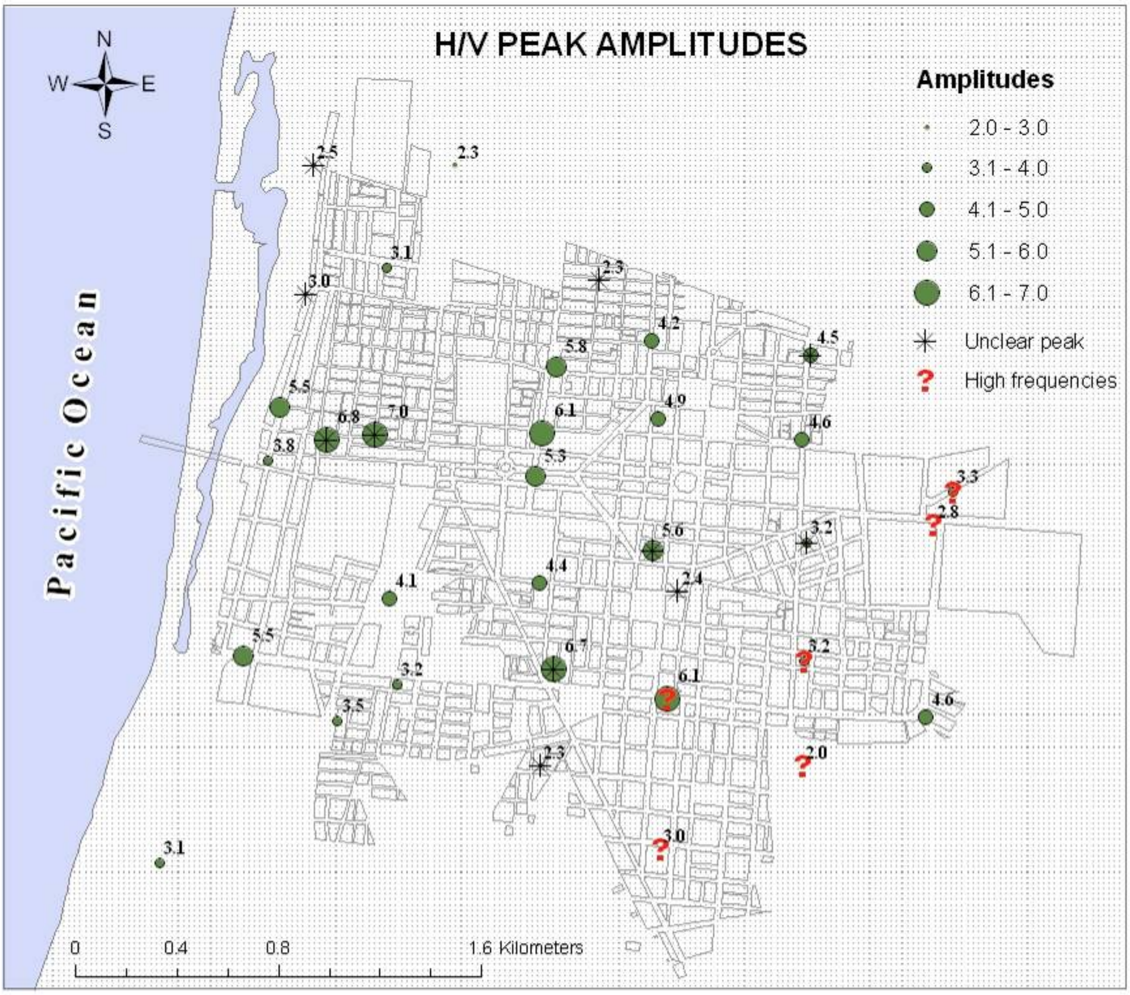


Fig. 3.58. H/V peak amplitudes

Fig. 3.59 shows the interpolated contours. It is difficult to identify a general pattern and the influence of the non-reliable points may change the geometry of these contours, thus stressing on the necessity of a denser mesh of measurements.

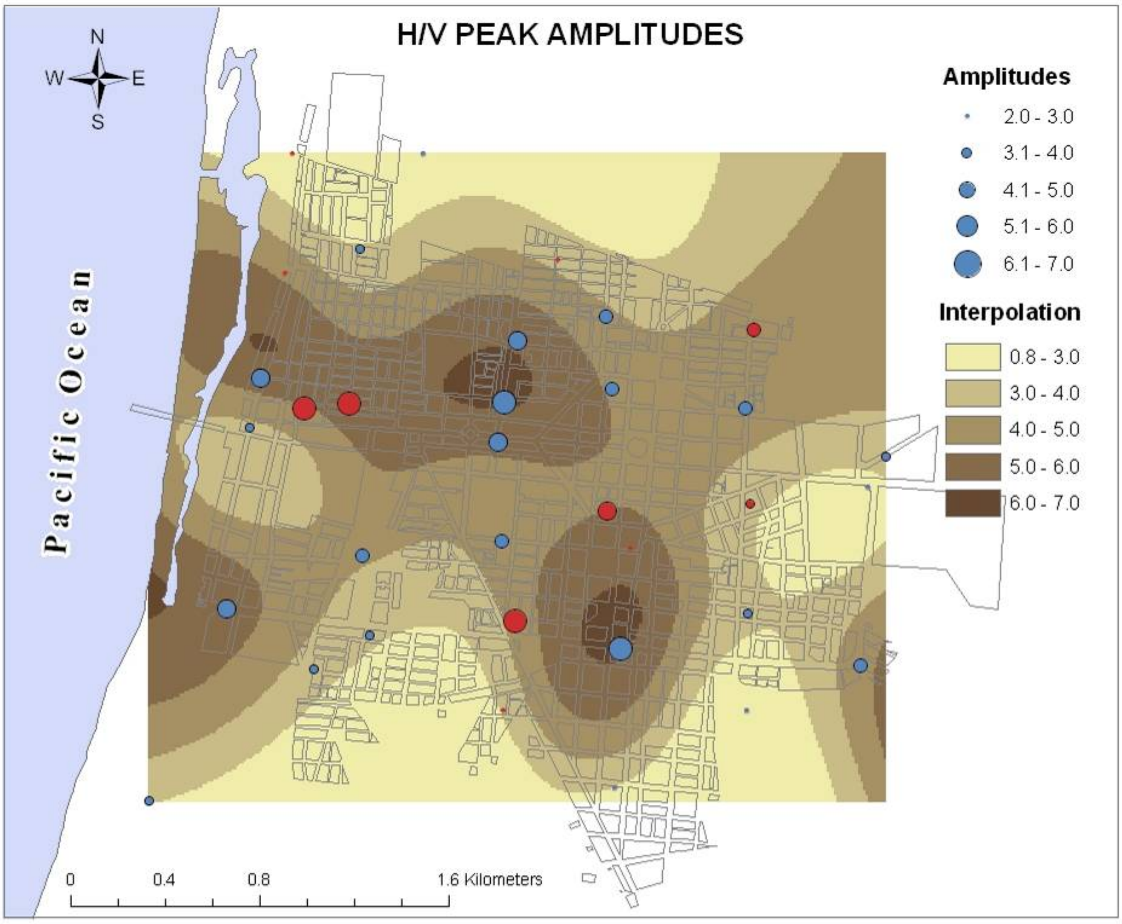


Fig. 3.59. H/V peak amplitudes. Local values and contours.

3.5.6. Discussion

By comparing the results presented in 3.5.3 with those described in 3.5.3, the following comments can be made:

- Stiffer soil and/or zones with thinner soft soil cover seem to be located in the southeast of Pisco, and it agrees to some extent with the geotechnical zonation in Fig. 3.35.
- The northern 1.2 m deep deposit of sandy clay overlying the averaged 3 m deep deposit of silty sand (identified as Zone III in Fig. 3.35) shows low frequency values whereas the south eastern deposit (identified as Zone II) having the same soil classification and depths of 0.5 and 1.1 respectively, exhibit higher frequencies; showing the effects of thickness in the H/V peak frequency.
- In the west side, the combined effect of deposit stiffness and thickness hinders the interpretation of frequencies, showing similar frequencies in the averaged 1.2 m deep deposit of clay and rounded gravel (identified as Zone IV in Fig. 3.35) and the deep deposit of gravel located in the south (referred as Zone I).

Regarding H/V maximum amplitudes, there is a sort of good agreement between the areas of maximum expected amplification in Fig. 3.36 and the H/V peak amplitudes of microtremor measurements (Fig. 3.59). Maximum values are close to the coastline and extend toward the east along the centre of Pisco, though there some areas of concentration of higher values in the southeast.

The local high value obtained at the old sanitary fill in the southeast side deserves further analysis (classified as Zone II Fig. 3.38 in), especially if this area is located in an area towards which the city is growing.

Finally, the data provided by Agüero et al [6] were plotted overlapping the peak amplitudes in Fig. 3.60. Despite of the fact that the microtermor data describe partially characteristics of the ground, while the macroseismic intensity encompasses the combined effect of building damage, ground deformations and people's perception; there is some consistency in terms of the high values observed in central and southeast Pisco in both studies. Nevertheless, it ought to be emphasised that additional site response estimations are required.

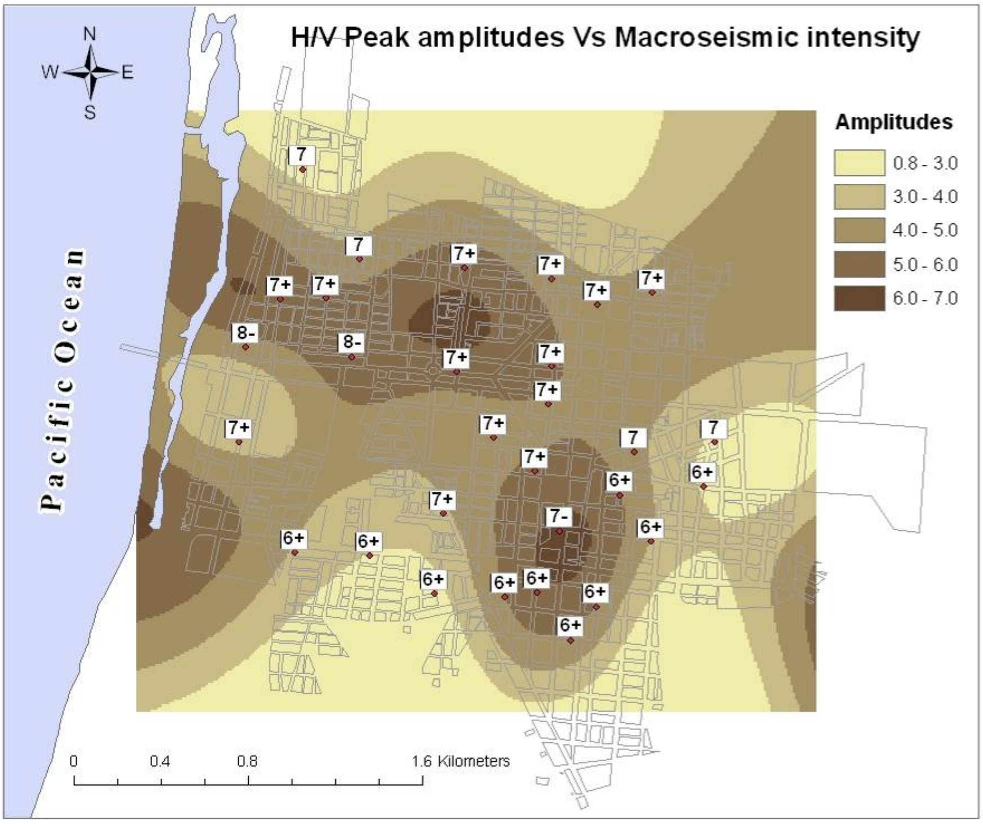


Fig. 3.60. Contours of H/V peak amplitudes and Macroseismic intensity (MSK-64, Adapted from[6].)

3.6. Conclusions and recommendations

Below follows some conclusions and recommendations based on the several examples of observed geotechnical and foundation related damages give above.

Liquefaction induced large soil cracks and displacements were observed in Tambo de Mora and Pisco. The only way to reduce the damages induced by such soil deformations is with reinforced strong, and expensive, foundations. The good performance of such foundations were clearly shown by a newer school house in Tambo de Mora and a Hotel in Pisco. The strong foundations are especially important for public buildings like schools and hospitals. Weak foundations, similar to the one of the health center in Huaytara, needs to be retrofitted or reconstructed.

In many locations we observed moist adobe walls due to the lack of foundation preventing moisture from entering the walls from the surrounding ground. In addition to reducing the earthquake resistance of an already earthquake vulnerable building type, the moisture also constitute a general health problem.

It is not easy to reduce the effects of large soil cracks, such as the ones observed in Nuevo Monte Rico. With strong reinforced foundation slab houses may have withstood some of the deformations, however rotation and or rocking of the foundation is still very likely, but people would be able to escape.

The cracks in the field are impossible to prevent. However, they can be filled up with coarser material (boulders, pebbles, gravel) and then covered with finer material (sand, clay, agriculture soil) as to allow for irrigation without “leakage” of to much water into the cracks. The wells that went dry, may become filled up again, however it the water level change is permanent then it is likely that the acquifer conditons changed and new well have to be dug/drilled. Emergency tanks could be one way provide water in case of a disaster.

While it may take time, it is very important to base the land use plans on existing hazard maps. The damages in Tambo de Mora and Pisco coincide very well with these maps, showing their importance. (Once such maps are updated, land use laws can also be updated.)

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4. BUILDING DAMAGE

4.1. Background

4.1.1. Structural types in the earthquake affected area

In the earthquake affected areas, there are different types of construction systems including: adobe, rammed earth (or *tapial*), *quincha*, reinforced concrete (RC) confined masonry, RC buildings with masonry infill. Hybrid systems, i.e. combination of any of these, are also found.

Adobe is a traditional construction system which consists of sun dried bricks laid with mud mortar. It has been used not only for houses but also for churches. In the case of houses, walls are 400mm thick whereas in churches, walls are taller and thicker, 850mm or more. If unreinforced, adobe structures are weak against earthquakes because they are heavy, inducing large inertial forces, and have almost no tensile strength. The stability of adobe walls depends strongly on their slenderness ratio. Recently, slender walls made of adobe bricks with size similar to those of baked bricks, the so called *adobitos*, have become increasingly popular. However, their largest slenderness ratio makes them even more vulnerable.

Rammed earth or *tapial* was found in the earthquake affected areas but mostly as fences marking limits of agriculture land. In other parts of the country it is also commonly used for dwellings. Similarly to adobe, it is made of mud. However, in this case the mud is compacted in situ, i.e. a wooden formwork is set and the mud is compacted in it. When the mud is dried enough, the formwork is moved sideward or upwards depending on where the wall shall continue.

Fig. 4.1 Two story adobe house mostly common in the high lands

Fig. 4.2 Rammed earth or tapial. Note the vertical and horizontal cold joints showing different construction stages

Quincha is a construction system consisting of panels with bamboo skeletons plastered with mud. It is also known as *bahareque* in other Latin American countries. The bamboo skeleton makes the system ductile and thus it has a good seismic behavior. However, bamboo deteriorates with time and this affects the structural performance.

Confined masonry is currently the most popular construction system for new houses. As long as people can afford it, it is the material of choice. It is used as an economic solution in Peru for buildings up to six stories high. If it is well designed and constructed it performs well. In this system, walls are constructed with *solid* bricks at first and then reinforced concrete confinements (columns and beams) are cast against them. According to the building code, a solid brick is defined as a brick with an area equal or more than 70% of its gross area. Column reinforcement is anchored in the foundation. Because brick wall and confinements work as a unit, the size of the columns is smaller than that of a RC building where brick walls are only supposed to work as partitions.

Reinforced concrete is also used in the affected areas but mostly for public buildings.

Fig. 4.3 Quincha

Fig. 4.4 Confined masonry

Fig. 4.5 Confined masonry in process of construction

Fig. 4.6 Reinforced concrete (RC) school

Hybrid systems are a combination of some of the previous construction systems. Some of them are the result of engineering design some others the consequence of improvisation. For example, it is common to combine confined masonry walls with

RC shear walls and columns in buildings. If these elements are well proportioned and distributed, both systems contribute to each other.

However, there are bad examples of hybrid systems. In Peru, it is a common practice to construct dwellings in stages as soon as financial resources are available and also as the resident needs increase. It is not uncommon to start a house with one story and when the family grows, a second or third story is built. If the family economic situation changes with time, the first story may be made of adobe, while the upper stories are made of confined masonry. This system was observed at several places in the earthquake affected areas.

Another type of traditional hybrid system is the one in which the first floor is made of adobe and the second is made of *quincha*. This system is very common in old 2-story houses and has had a relatively good seismic performance. However, due to poor maintenance and aging, these structures have become very vulnerable. Although this system has not been used lately, some experts are trying to revalue it.

Fig. 4.7 Old traditional structure with 1st story made of adobe and 2nd story made of quincha

Fig. 4.8 House with 1st story made of adobe and 2nd story made of confined masonry. In this case, RC columns were cast in the existing adobe walls to support the 2nd story.

There are four main types of roof systems in the affected areas. Straw mat with bamboo joists, light gage steel plate on bamboo joists, reinforced concrete joists with hollow bricks and wooden roofs. The first two are very light and are used in combination with adobe and confined masonry walls. RC joists are used with confined masonry walls and RC buildings. Wooden roofs were found mostly in old buildings and are not used in new constructions anymore.

The connection between light roofs and walls is weak but nevertheless restrains the movement of the walls on which it is supported. RC joists are cast on top of brick walls together with the confining beams and therefore is well connected to the walls.

Fig. 4.9 Roof made of straw mat and bamboo joist

Fig. 4.10 Light gage steel plate roof

Fig. 4.11 RC concrete joist with clay hollow bricks

Fig. 4.12 Wooden roof common in old constructions

4.1.2. Housing statistics

Censuses are regularly carried out in Peru by the National Institute of Statistics and Informatics (INEI), the latest one in October 2007. Table 4.1 summarizes the figures of houses distribution for the earthquake affected areas as of 2005 (data for the 2007 Census will not be available until 2008). Predominant construction material of the walls is adobe (50% of total) followed by masonry (39%) whereas in term of roofs, the predominant roof type is light mostly made of straw mats and bamboo joists (59%).

Table 4.1 Distribution of houses according to the predominant material of walls and roofs in the earthquake affected areas in thousand of units as of 2005 [1]

	Masonry	Adobe	*Quincha*	Others	Total
RC	52.950	0.718	0.000	0.030	53.698
Light gage steel	1.742	16.568	0.118	1.141	19.569
Straw mat / bamboo	19.778	79.004	5.581	9.187	113.550
Others	0.740	3.811	0.331	2.350	7.232
Total	75.210	100.101	6.030	12.708	194.049

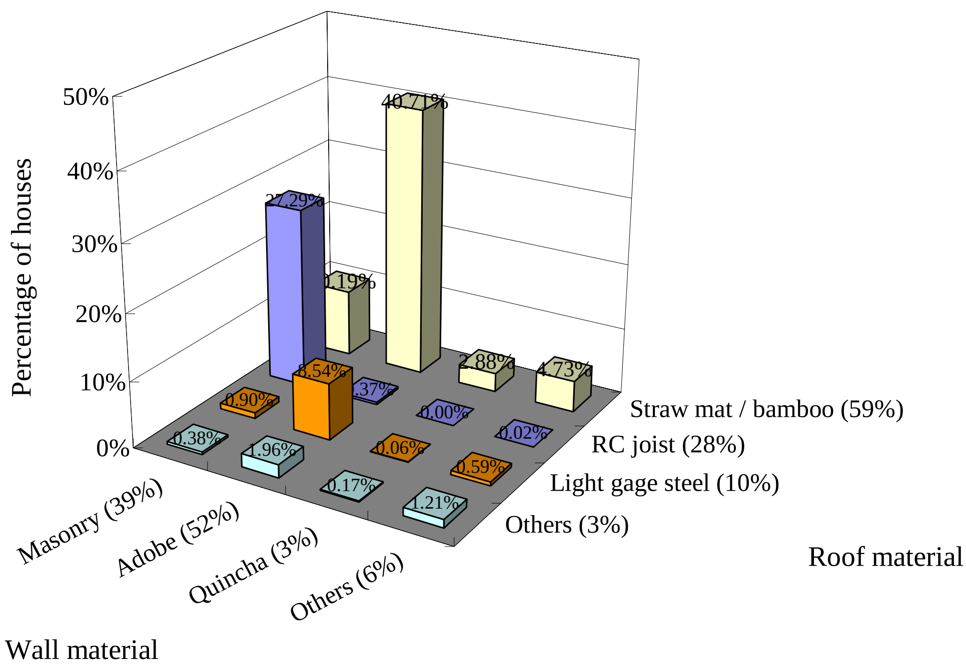
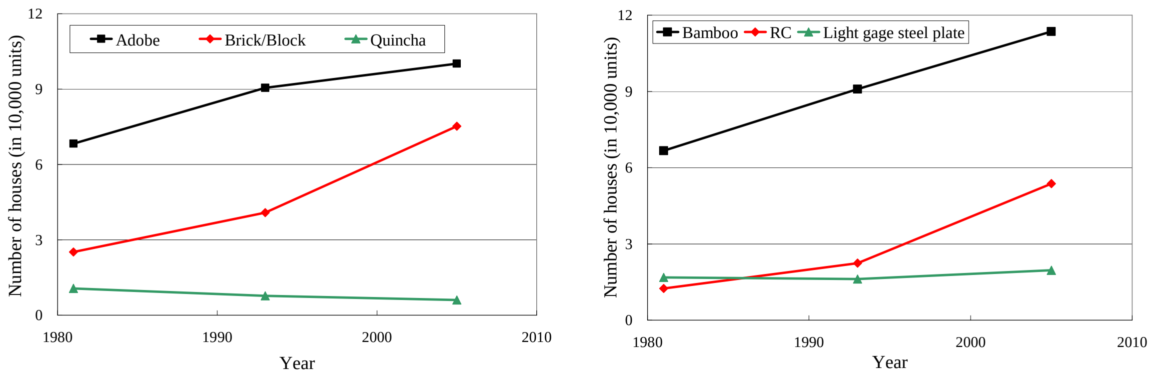


Fig. 4.13 Distribution of houses in the earthquake affected areas as of 2005 [1]

Fig. 4.14 shows the evolution of wall and roof material in the earthquake affected areas. Adobe use decline and masonry use growth are observed. If the trend continues like this, it may be expected that by 2020, masonry will become the predominant wall material as it has already happened in other regions in the country. As for the roofs, it may be expected that straw mat and bamboo will still be preferred in the coming years.

It is worth noting that more than 70% of the adobe houses are older than 25 years. It is not a common practice in Peru to invest in house maintenance. Therefore, it may be expected that the vulnerability inherent to unreinforced adobe construction is worsened by aging.



(a) Predominant material of walls (b) Predominant material of roof

Fig. 4.14 Evolution of material use in the earthquake affected regions [1, 2, 3]

4.1.3. Building code

The National Service for Training for the Construction Industry (SENCICO) has among its functions to develop regulations for building design and construction technologies that aim at improving quality and reducing costs. It is also in charge of training and certifying construction workers of different levels. Following its functions it has enacted the following building codes:

- NTE E.010 Wooden structures (latest revision 2003)
- NTE.E.020 Loads (latest revision 1985)
- NTE E.030 Seismic design code (latest revision 2003)
- NTE.E.040 Glass
- NTE E.050 Soils and foundations (latest revision 1997)
- NTE.E.060 Reinforced concrete (latest revision 1989)
- NTE.E.070 Masonry (latest revision 2006)
- NTE E.080 Adobe (latest revision 1999)
- NTE E.080 Metallic Structures

According to the seismic design code, Peru is divided in three regions as shown in Fig. 4.15. The ground accelerations for design are 0.40g, 0.30g, and 0.15g for Zone 3, 2, and 1, respectively. These are supposed to be the accelerations with a 10% probability of exceedance in 50 years [4].

Fig. 4.15 Seismic zonation of Peru

Although the above mentioned codes keep up to date the developments of design and construction technologies providing a huge amount of information, in the practice most of buildings do not comply with them, i.e. codes are enacted but not enforced. There is no statistic showing how many buildings not complying with the codes exist. However, experts suggest that between 50% and 80% of the buildings fall in this category in Lima [5, 6].

One of the main reasons why building codes are not enforced is that obtaining the license for construction, the first step of code enforcement until very recently is lengthy and costly process. It requires submitting a set of drawings (architecture, structure, utilities) with the signatures of an architect or civil engineer, a sanitation engineer, and an electric engineer, the land property certificate, and a fee payment. In addition, many people do not have a land property certificate and therefore cannot complete the required documentation. Getting the land property certificate is another lengthy procedure.

Another reason why building code is not enforced is that municipalities, which are in charge of giving the licenses and supervising that the construction is carried out following the project, are understaffed. Based on the field survey it was found that in Pisco, a city of almost 55,000 inhabitants, only four civil engineers were working at the municipality on a regularly basis.

In September 2007, a law to ease the process of obtaining construction licenses was enacted. For some constructions, the project reviewing process has been simplified and for some small projects, even eliminated. Although this may result in many more construction licenses, many fear that this will worsen the problem of code enforcement.

Self construction, an extended practice in Peru, also hinders code enforcement. Self construction is considered here as the construction by the dweller himself or otherwise a mason, without proper training. This system is much enrooted in the Peruvian society as a result of the large housing deficit and insufficient governmental policies to address the issue.

4.2. Building damage

4.2.1. Statistics

The INEI carried out a census to estimate the number of affected people and houses due to the Pisco Earthquake. According to this census, 77% of the housing units were affected in some way and 23% did not suffer any damage. The hardest hit provinces were Chincha, Ica, and Pisco, where 33.7%, 24.4%, and 22.4% of the houses, respectively, collapsed. 9.5% of the houses were slightly affected, suffering just minor damage or cracking, and therefore are suitable for living.

Table 4.2 Housing damage statistics in the earthquake affected areas

Province	Destroyed	Very affected	Affected	Slightly affected	Not affected	TOTAL
Ica	19 937	7 075	23 005	8 513	22 637	81 167
Chincha	17 763	6 911	16 619	3 414	4 231	48 938
Pisco	8 756	4 521	14 526	3 272	5 223	36 298
Cañete	4 545	3 434	18 349	4 804	18 180	49 312
Yauyos	359	675	8 028	1 289	2 427	12 778
Huancavelica	6	24	538	214	52	834
Castrovirreyna	371	520	5 931	910	465	8 197
Huaytará	434	560	6 370	1 030	726	9 120
TOTAL	52 171	23 720	93 366	23 446	53 941	246 644

Notes: **Destroyed**: houses with fallen/destroyed walls and roofs; **very affected**: house with serious damage in most of its walls (collapsed or destroyed) and is not suitable for living; **affected**: houses whose structure (walls or roof) is partially affected and require more detailed evaluation; **slightly affected**: house exhibits small cracks and minor damage and is suitable for living: **not affected**: no damage whatsoever.

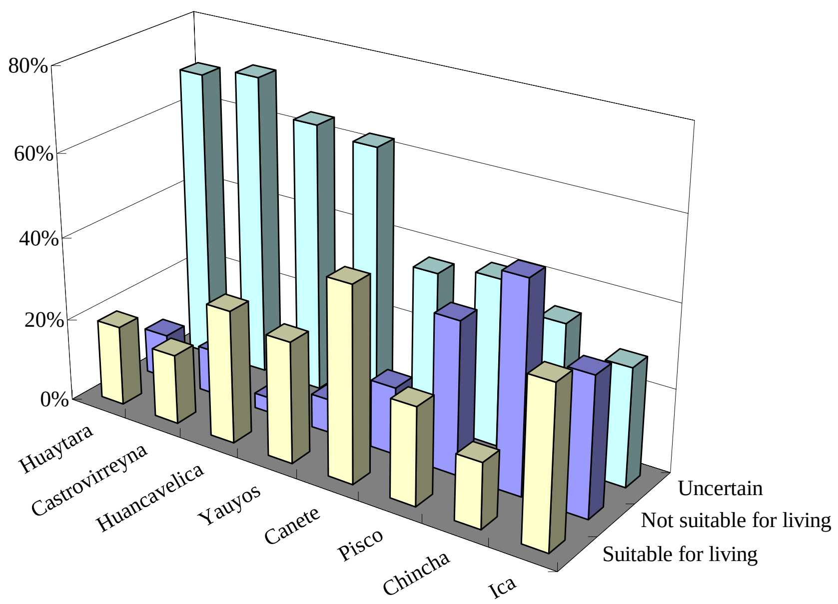


Fig. 4.16 Housing damage in the earthquake affected regions [7]

It is worth noting that the provinces located in the mountainous regions where adobe is predominant (Huaytara, Castrovirreyna, Huancavelica, and Yauyos) show the highest percentages of uncertainty regarding the conditions of their houses. Also, most of the houses in Chincha and Pisco are not suitable for living.

Regarding schools, the National Civil Defense Institute (IINDECI) carried out the initial damage evaluation shown in Table 4.3. This evaluation aims at determining whether the facilities are suitable for immediate use. A more detailed evaluation to determine the extent of the damage and the amount of investment required to recover them is responsibility of the Ministry of Education.

Table 4.3 School damage, in terms of classrooms, due to the 2007 Pisco Earthquake

Region	Schools	
	Destroyed	Affected
Ica	187	214
Lima	396	329
Huancavelica	22	71
Ayacucho	38	21
Total	643	635

The Direction of Infrastructure, Equipment and Maintenance of the Health Ministry (DIGEM) performed the evaluation of the health facilities in the earthquake affected area. Table 4.4 shows the summary of the most affected structures, i.e. with more than 15% of its infrastructure affected. Although not included in it, DIGEM concluded that all health related facilities of the provinces of Castrovirreyna, Huaytara and Huancavelica need to be replaced.

Table 4.4 Damage to health related facilities [8]

Name	District	% of infrastructure affected
Ica Departament Hospital	Ica	60%
Santa Maria del Socorro Hospital	Ica	40%
San Juan de Dios Hospital	Pisco	70%
San Jose de Chincha Hospital	Chincha Alta	90%
Tupac Amaru Health Center	Tupac Amaru	15%
San Clemente Health Center	San Clemente	30%
Casalla Health Post	Tupac Amaru	15%
Los Alamos Health Post	Pueblo Nuevo	80%
Hoja Redonda Health Post	El Carmen	60%

Note: Hospital, Health Center and Health Post are health related facilities presented in order of their size.

4.2.2. Housing damage

Damage to adobe houses may be categorized, in order of severity as: plaster spalling, wall separation, corner collapse, partial collapse of walls and total collapse of walls. Important factors increasing the vulnerability of adobe structures were: wall slenderness, construction age, and roof layout. Walls supporting light roofs, which are predominant in the region, were less likely to collapse than those not supporting it due to the restrain at the top that the roof joists provided them.

Adobe plastered walls seem stronger than those without plastering. Front walls of houses did not exhibit damage whereas the inner walls, apparently without plaster, suffered damage. A few walls which survived out-of-plane collapse developed in-plane shear cracks.

It was observed that in many locations, these houses did not have any foundation. This contributed to the moistening of the walls, where the ground water table was high, with the consequent strength reduction.

Fig. 4.17 Adobe house with plaster spalling (San Luis, Canete)

Fig. 4.18 Adobe house with cracks at wall intersections (Huaytara, Huancavelica)

Fig. 4.19 Corner collapse in adobe house (San Luis, Canete)

Fig. 4.20 Wall partial collapse. Walls supporting the roof are standing. This was observed at several locations (Ica).

Fig. 4.21 Collapsed adobe house (Nuevo Monterrico, Canete)

Fig. 4.22 Totally collapsed adobe houses (Hualcara, Canete) – The hanging electric lines show the location where houses used to be.

Fig. 4.23 RC confined adobe wall (in the back), survived the quake, and unconfined adobe wall (front) failed out-of-plane (San Luis, Canete)

Fig. 4.24 The house shown "borrowed" the wall of the neighboring adobe house, which collapsed. Only the RC columns built to support the 2nd floor survived. (Pisco, Ica)

Confined masonry houses designed and built according to the building code did not suffer major damage. All the damaged structures had some type of deficiency. The most common were the use of bricks with horizontal alveolus for load bearing walls (locally called *pandereta* and prohibited by the code in this region), lack of confinement of parapets and façade walls, insufficient wall density, badly distributed stiffness (in plan and elevation), and a poor understanding of the confined masonry construction procedure. Another deficiency found was the lack of steel reinforcement in the confining beam or the lack of confining beam altogether.

As mentioned earlier, the assumption that brick wall and RC confinement work together, which is accurate if constructed in the right way, does not hold if the RC elements are built first and then the brick wall is laid. The size and steel reinforcement of RC confinements is not enough if the RC skeleton is the main structural system.

Fig. 4.25 Load bearing wall made of pandereta bricks and poor steel reinforcement in the confinement (Pisco, Ica)

Fig. 4.26 Collapsed façade wall due to lack of confinement (Sunampe, Chincha)

Fig. 4.27 Lack of confining beam (Tambo de Mora, Chincha)

Fig. 4.28 Corroded column reinforcement (Tambo de Mora, Chincha)

Fig. 4.29 5-story confined masonry building apparently built in several stages (Pisco, Ica)

Fig. 4.30 Detail of the 5^{th} story of the building to the left. Note the small amount of reinforcement in the columns. The failure pattern suggests that the columns were built first and then the brick wall.

Fig. 4.31 Shear failure of masonry wall due to excessive interstory drift

A few apartment buildings made of RC were found in the affected areas and in some of the cases, the structure was a mixture of confined masonry and RC. Fig. 4.32 shows an apartment building with a car parking in the first floor. The RC columns used to leave space for the cars to access had smaller stiffness than the back wall, a solid confined masonry element. This generated a torsion effect imposing the columns a demand larger than their capacity.

Fig. 4.32 Apartment building with inadequate stiffness distribution (Pisco, Ica)

Fig. 4.33 Back view of the building shown in previous picture

Fig. 4.34 Beam-column joint detail of building in Fig. 4.32.

Fig. 4.35 Soft-story failure due to insufficient stiffness in one direction (Pisco, Ica)

Fig. 4.36 Shear failure of beam-column joint (Parcona, Ica)

Fig. 4.37 Weak cold joint between column and beam/slab (Parcona, Ica)

4.2.3. Damage to public facilities

Public facilities, both governmental and private, performed badly in the 2007 Pisco Earthquake. In this section, damages to hospitals, schools, churches, and hotels observed during the field survey are reported.

Hospitals

Table 4.5 summarizes the characteristics of the two health related facilities that were visited in this field survey.

Table 4.5 Health related facilities visited

Characteristics	San Juan de Dios Hospital	Huaytara Health Center
Location	Pisco, Ica	Huaytara, Huancavelica
Number of beds	100	8
Occupancy rate	50-60%	Handles approximately 100 births per year
Medical services	Surgery, Internal Medicine, Pediatrics, Gynecology, Obstetrics, Ophthalmology, Trauma	2 doctors, 1 midwife
Ambulatory services	80-100 patients /day (before the quake), 50 patients / day (as of September 13)	Prenatal checkups
Comments	Responsible of the health requirements of approximately 125,000 people	Handles births of the region
Infrastructure	Most of buildings constructed in the 30's with reinforced concrete and concrete blocks and another few 12 years ago. Two new buildings made of RC were completed this year. The New Emergency Building was unequipped before the earthquake.	Confined masonry structure approximately 18 years old

Fig. 4.38 to 4.41 show the conditions of the San Juan de Dios Hospital after the earthquake. At the time of the survey, most of the heavily affected buildings were being or had been already demolished. The only permanent operational facility was the Emergency Building which suffered no damage. It was constructed with funding of UN Health Organization and started operations the night of August 15. According to the interview survey, 200 badly injured people were evacuated to Lima for treatment. The hospital hyperbaric chamber, the only one in this region, is not functioning because the building where it operated collapsed.

Fig. 4.38 Newly constructed Emergency Building

Fig. 4.39 Heavily damaged building. Note the hyperbaric chamber on the back

Fig. 4.40 Concrete block wall collapsed out-of-plane

Fig. 4.41 A hospital building made of non-reinforced adobe was heavily damaged

The Huaytara Health Center, although smaller than the San Juan de Dios Hospital, handles most of the births in the region. As mentioned in Chapter 3, ground failure was the main reason for the structural damage.

Education related facilities

Several schools and one university were visited in the affected areas. Table 4.6 shows information of the schools where interview survey was carried out. Other schools were visited but no interview was done.

Table 4.6 Schools where interview survey was carried out

	San Juan Bautista	Beatita de Humay 22451	San Luis Gonzaga de Ica
Location	Huaytara	Humay	Ica
Education level offered	High school	Elementary and high school (2 shifts)	High school (2 shifts)
No. of students	210	460	2992
Infrastucture	Mostly RC buildings with concrete blocks (1992), one building of confined masonry (2006) and one adobe building	Elementary school classrooms made of adobe and a few new construction of RC	RC buildings constructed in the 50’s
Re-started classes on	August 22nd, 2007	Not restarted as of Sept. 11, 2007	Not restarted as of Sept. 18, 2007
Comments	Part of the school was used by the army who was assisting the disaster response activities	No debris removal had been carried out by Sept. 11, 2007.	12 wood prefabricated and 20 straw mat temporary classrooms were been set on Sept. 18, 2007

At San Juan Bautista School no major structural damage was observed. However, the masonry partition walls, which were correctly separated from the main RC structure to prevent short column effects, did not have confinements and therefore were not anchored to the beams underneath. As a result, the connection between walls and beams, most likely provided just by cement mortar, failed. Although the walls did not collapsed, they were very unstable posing risk to the people nearby. The classrooms that had this situation were not operational. In this school, the hall was made of adobe and did not present considerable damage. Classes were been held in this building.

Fig. 4.42 Masonry panels in the second floor were damaged, (San Juan Bautista school, Huaytara)

Fig. 4.43 Detail of the joint connection, (San Juan Bautista school, Huaytara)

Fig. 4.44 Non-reinforced adobe building normally used as a hall, (San Juan Bautista school, Huaytara)

Fig. 4.45 Confined masonry building did not suffer any damage, (San Juan Bautista school, Huaytara)

All of the adobe classrooms at Beatita de Humay School were left useless. Adobe walls and straw mat roofs collapsed. Fortunately, at the time of the earthquake there were no students in the facility and therefore nobody was injured there. The columns of a RC building with masonry panels exhibited mild shear failure.

The infrastructure of the San Luis Gonzaga de Ica School exhibited typical damages of RC structures such as pounding between buildings, lack of column shear reinforcement, insufficient separation between partitions and structure, and insufficient expansion joints between structural units. Also, some unreinforced brick parapets collapsed.

Fig. 4.46 Elementary school classrooms made of adobe were heavily damaged (Beatita de Humay School, Humay)

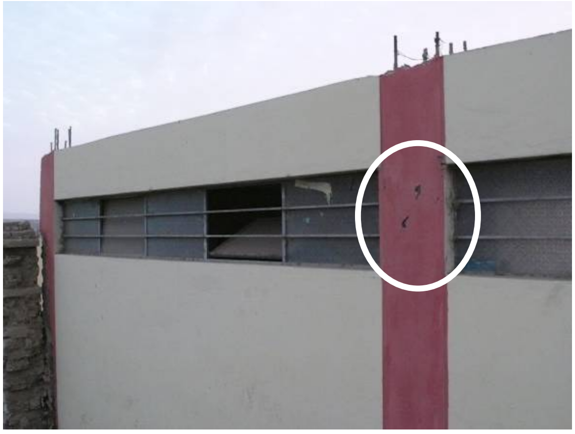


Fig. 4.47 RC-buildings with masonry panels suffered slight shear damage (Beatita de Humay School, Humay)

Fig. 4.48 Pounding between buildings (San Luis Gonzaga School, Ica)

Fig. 4.49 Parapet overturning (San Luis Gonzaga School, Ica)

Fig. 4.50 Lack of shear reinforcement in columns (San Luis Gonzaga School, Ica)

Fig. 4.51 Insufficient clearence between masonry panels and RC structure (San Luis Gonzaga School, Ica)

In general, the design/construction quality of the schools visited during the survey was very varied. For example, at Los Molinos in Ica, a very new and well constructed school (shown in Fig. 4.6) was found next to another which obviously did not followed any design or construction standard. Fig. 4.52 shows one of the building walls in which it is seen that columns in the 1st floor are not aligned with the columns in the 2nd floor. Furthermore, one of the columns is interrupted

Many classrooms made of non reinforced adobe were also found as well as schools built in places unsuitable for construction due to poor soil conditions, such as Tambo de Mora marine deposits. Although it is difficult to control informal housing construction there, public buildings, especially schools should never be built in these places.

It is worth mentioning that at many schools, non-structural measures to mitigate earthquakes, such as pasting adhesive tape to the glasses, were observed

Fig. 4.52 Bad construction example in Los Molinos, Ica

Fig. 4.53 Classroom at Tambo de Mora marine deposits, Ica.

As mentioned in Chapter 2, two strong ground motion records were obtained close to the epicenter. One of the recording instruments, belonging to CISMID, was located in the first floor of the Soil Mechanics Laboratory Building of the San Luis Gonzaga National University. In order to assess a possible effect of the structural response on the record, microtremor measurements to evaluate its dynamic properties were measured. Additionally, concrete strength was estimated with a Schmidt hammer.

The RC frame structure was built in two stages: the first floor in 1998 and the second floor in 2002. Although it did not suffer major structural damage, some of the brick partitions cracked and needed repairing. In the 1st story, where partitions suffered more damage, the joint left between structure and wall was not wide enough in some cases and in others filled with mortar. This limited the freedom of the structure to deform. The joints in the second floor were wider and thus partition damage here was less.

Fig. 4.54 Soil Mechanics Laboratory Building

Fig. 4.55 Joint between brick partition and RC structure filled with mortar

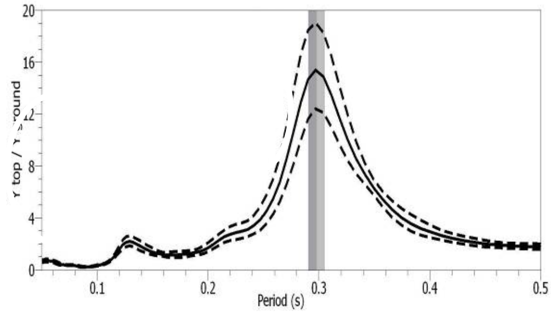


Fig. 4.56 Microtremor measurement analysis results (Transverse direction)

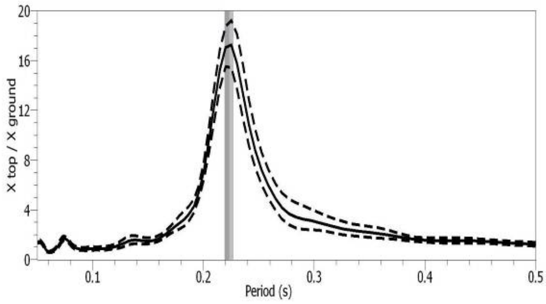


Fig. 4.57 Microtremor measurement analysis results (Longitudinal direction)

Microtremors were measured in free field, 1st story floor slab, 1st story roof, and 2nd story roof. To determine the fundamental period the ratio of the Fourier spectra of the records at the 2nd story roof and free field were calculated. The analysis suggests that the fundamental period in transverse and longitudinal direction are 0.30s and 0.22s, respectively. This frequency content do not coincide with the predominant frequencies observed in the acceleration record suggesting that the structure did not affect the measurements. However, further analysis is necessary to confirm this idea.

The Schmidt Hammer tests suggested that the quality of the concrete was good with compression strengths approximately 36MPa and 31MPa, in the 1st and 2nd floor, respectively.

One of the most damaged buildings in the campus was that of the Chemistry Faculty. These were among the first buildings in the university constructed more than forty years ago. In here, short column effect and poor shear reinforcement detailing were observed. Also, parapets with no anchorage to the structure were damaged although they did not collapse.

Fig. 4.58 Chemistry Faculty Building with short column failure and parapet damage

Fig. 4.59 Insufficient shear reinforcement

Churches

This survey did not focus in surveying churches in detail. However, it was obvious from our field work that these structures performed very badly. Reportedly, more than 30% of the fatalities due to this earthquake were caused by the collapse of the San Clemente Church in Pisco. In this church, only the portion which had been rebuilt recently did not collapse. A block away from it, only a couple of the 850mm-thick adobe walls of the Compania de Jesus Church were left standing.

Many of the churches in Peru were built before any seismic design code was enacted. There is no regulation that requires upgrading of these structures as to comply with the latest codes. These facilities belong to the Catholic Church and therefore it is under their responsibility to improve their quality. Many of these buildings are cultural patrimony and thus the National Cultural Center (INC) is also a stakeholder. There is always controversy about which is the best way to intervene this monuments without altering their original essence.

Fig. 4.60 San Clement Church (Pisco)

Fig. 4.61 Compania de Jesus Church (Pisco)

Hotels

Hotels suffered extensive damage in the affected areas putting in evidence the lack of control that the authorities have over the security of these facilities. A remarkable case was that of the Embassy Hotel one of the most exclusive in Pisco City. The first and second stories of this hotel completely collapsed. This structure had construction license for the first three stories. However, later the management decided to build two more stories without permission.

The Paracas National Reserve, which is located south of Pisco, is a tourist destination for locals as well as foreigners. Many hotels, among which the Libertador Hotel Paracas is probably the most famous, were damaged. This hotel is located in front of the coastline and was badly damaged by the shake and the subsequent tsunami.

Fig. 4.62 and 4.63 show one small hotel that was observed during the field survey. Insufficient shear reinforcement in the columns among other deficiencies was observed.

Fig. 4.62 Heavily damaged hotel (San Clemente, Ica)

Fig. 4.63 Insufficient column shear reinforcement.

4.3. Mitigation initiatives

Taking into account the vulnerability of traditional adobe houses, construction technologies to improve their seismic performance have been developed. In the affected areas, two reinforcing techniques were implemented during the last decade as part of two international assistant projects and are described below.

4.3.1. Retrofitting of existing adobe houses

The project "Retrofitting of existing adobe houses" carried out by GTZ, CERESIS, and the Pontifical Catholic University of Peru (PUCP) was developed to improve the seismic strength of existing adobe houses in 1996. The main purpose was to provide some ductility to the houses so as to allow safe evacuation. The project retrofitted 12 prototype houses located in the Ancash, Cusco, Tacna, Moquegua, Ica and La Libertad Regions, all of them seismically active.

The retrofitting system, devised at the PUCP [9], consists of placing welded wire steel meshes at the wall intersections, "columns", and also on top of the walls, "collar beams" as shown in Fig. 4.64. The meshes (1 mm wires spaced at ¾ inches) are attached to both sides of the adobe walls using nails and connected with wire connectors passing through the wall. A cement mortar cover is laid on the steel mesh.

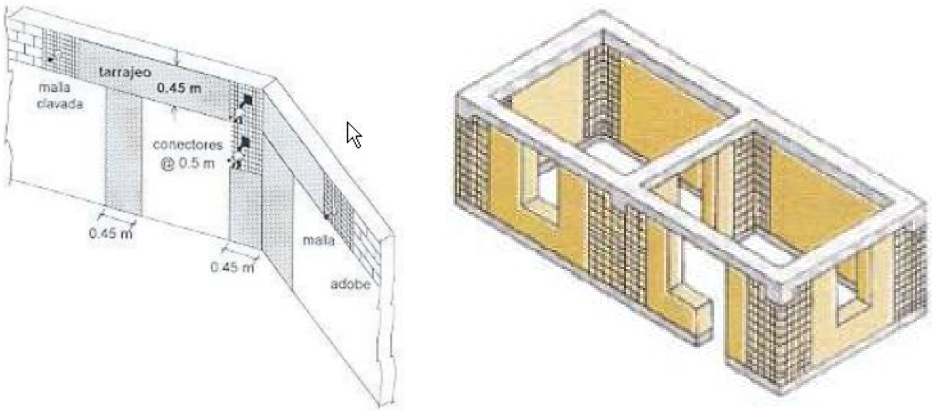


Fig. 4.64. Wire mesh reinforcement. After Blondet [9]

The construction procedure followed for the prototype adobe wire steel meshes retrofitted house is shown in Fig. 4.65.

Step 1. Remove the existing gypsum or mud plastering.

Step 2. Open 5-cm (2-inch) square holes every 50 cm (20 inches) at the intersection of vertical mesh strips. Insert small steel connectors into each hole, moisten the interior and fill them with 1:4 cement:sand mortar.

Step 3. Fasten the vertical mesh strips to the adobe wall with nails, and then the horizontal strips. The usual width of mesh strip was 45 cm (18 inches). Bend the ends of the connectors 90° and nail them to the adobe wall.

Step 4. Moisten the area and plaster it with cement sand mortar applied in two layers.

Fig. 4.65 Construction procedure for adobe wire steel meshes' retrofitted houses. Adapted from Quiun [10]

Evaluation of seismic performance of retrofitted houses

One of the houses retrofitted in the above mentioned project was located in Guadalupe, Callao Street #304, Panamerican Highway, Km. 193 (S 13º 59.179' W 75º46.458'). The house is located in a flat area in the vicinity of a small canal and surrounded by several adobe houses and two unpaved streets as shown in Fig. 4.66.

The fairly symmetric house is a one story building with a shared wall, two façade walls aligned with Callao Street and Rimac Street, respectively, and three internal walls. The roof is made of straw mat with bamboo joists. There was no evidence of foundation, however, based on an interview survey, it was found that, in this region, it is common to dig a 60cm-deep trench, place thick adobes inside, and then build walls on top of them. It may be possible that this "foundation" was used when the house was originally constructed.

Fig. 4.66. Front and side of Guadalupe retrofitted adobe house.

The house was retrofitted based on the guide shown in Fig. 4.65, and the details of the construction for the wire steel mesh are shown in Fig. 4.67. The mesh was set in all house's corners and in the intersection of internal and external walls. In the internal walls additional mesh was installed beside the doors, the backyard wall was not retrofitted at all due to budget constraint. No mesh was installed on the main entrance wall.

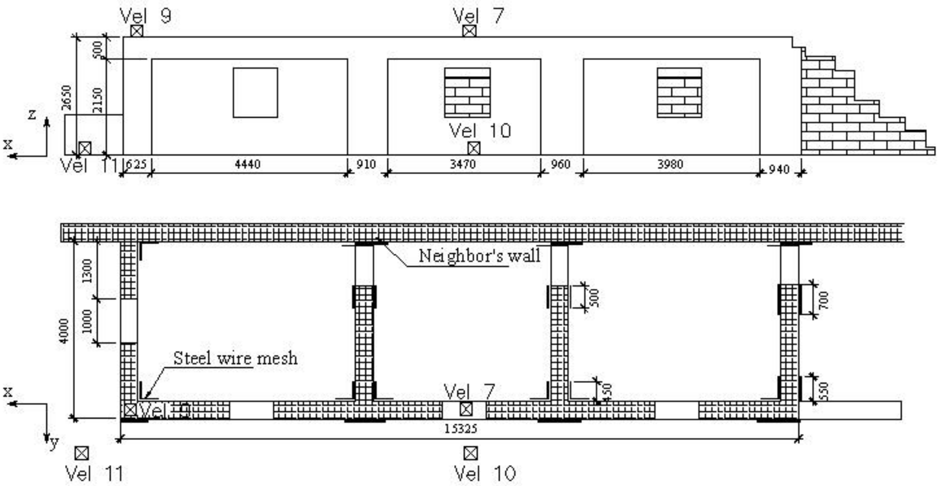
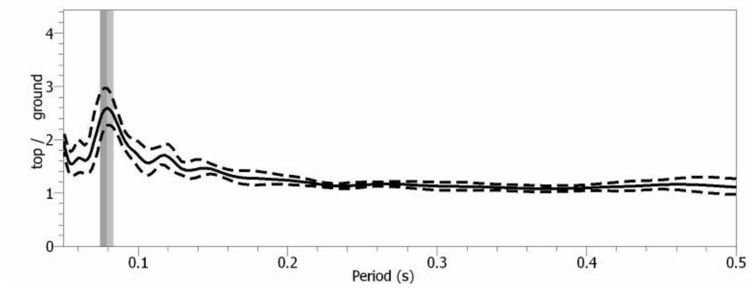


Fig. 4.67. Layout of Guadalupe adobe retrofitted house.

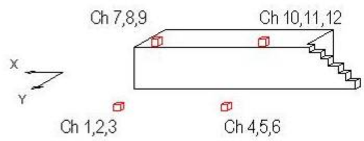
The inspection of the house showed that it suffered almost no damage due to the earthquake although the damage rate of adobe houses in Guadalupe was over 80%. A few vertical cracks were observed in the mortar cover of the “collar beams” inside the house. It is believed that they just affected the cover and did not pass through the walls. It is important to mention that the backyard wall, which was not retrofitted, collapsed due the shaking. A small portion of the steel wire mesh, without any corrosion signs, was exposed as shown in Fig. 4.68.

Fig. 4.68. Retrofitted house after the Pisco Earthquake

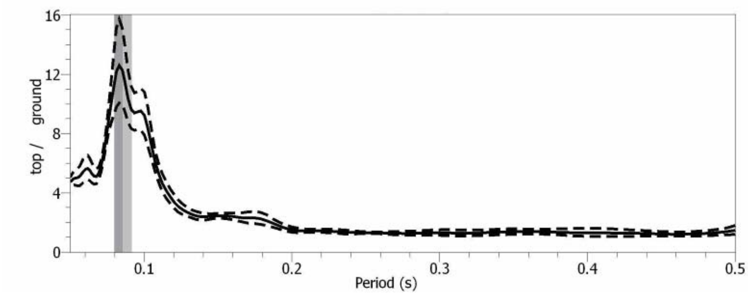
In order to identify the dynamic properties of the structure, microtremors were measured on the house roof and at the ground as shown in Fig. 4.69. Two 300sec-long measurements, sampled at 100Hz, were taken. The spectral ratios were calculated and they are shown in Fig. 4.69. A clear peak at 0.08sec is observed. This predominant period is similar to those measured in non reinforced adobe structures with similar characteristics suggesting that, as expected, the retrofitting procedure, did not affect the natural period of the structure.



(a) X-Axis



(c) Measurement arrangement



(b) Y-Axis

Fig. 4.69. Ratio of Fourier spectra of microtremor measurement in retrofitted adobe house.

4.3.2. Construction of new earthquake resistant adobe houses

The Japanese International Cooperation Agency (JICA), the Peruvian NGO Alternativa and the National Service for Training for the Construction Industry (SENCICO), worked together between 2004 and 2006 in the pilot project “Training and Diffusion of Improved Adobe Technology for the Construction of Healthy and Secure Houses”. The main purposes were to train and motivate local people to construct adobe houses using an improved technology. During the development of the project seven model houses, located in the rural areas of Lunahuana, Pacaran and Vinac in Lima Region, were constructed. All these locations are seismically active.

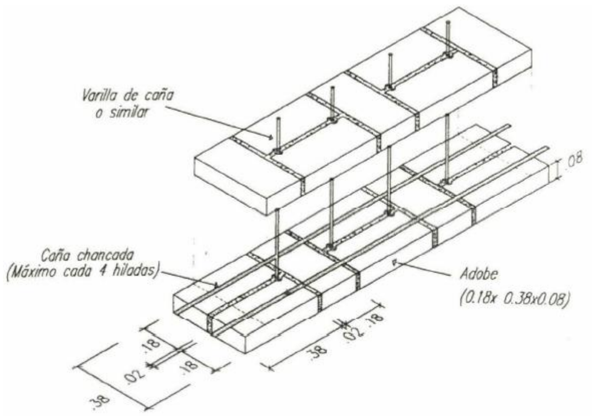


Fig. 4.70 Vertical and horizontal adobe reinforcement. After E.80 [11]

The construction technique for the model houses followed the adobe standard NTE E.80 for cane reinforcement. It incorporates techniques regarding improvements in adobe fabrication and reinforced construction processes. The cane reinforcement consisted of a grid of vertical and horizontal canes (see Fig. 4.70), tied-up in the crossing points of the walls, foundation and ring beams. This type of reinforcement improved the response of adobe walls against seismic loads. Vertical reinforcement restrains out-of-plane bending and in-plane shear, while horizontal reinforcement transmit the out-of-plane forces in transverse walls to the supporting shear walls and restrain the shear stresses between adjoining walls. An additional reinforcement used in the model houses was the timber ring beam that ties the walls in a box-like structure and supports the roof. A systematical procedure for the construction of this kind of reinforced adobe house is shown in Fig. 4.71.

Step 1. Foundation. No reinforce beam W= 55cm H=80cm. Vertical reinforcement is fixed to the beam.

Step 2 Vertical Reinforcement. Canes are placed on center of wall every 80cm, buried 10cm.

Step 3. Horizontal reinforcement. Crushed canes are placed every four layers and connected to vertical canes with nylon strings.

Step 4. Ring beam. Timber beams are fixed the top of adobe wall. (7.5x7.5cm)

Step 5. Roof. Timber beams are placed every 60 cm (5x20cm)

Step 7. Finishing.

Fig. 4.71. Construction procedure for adobe cane reinforced house. After Narafu [12]

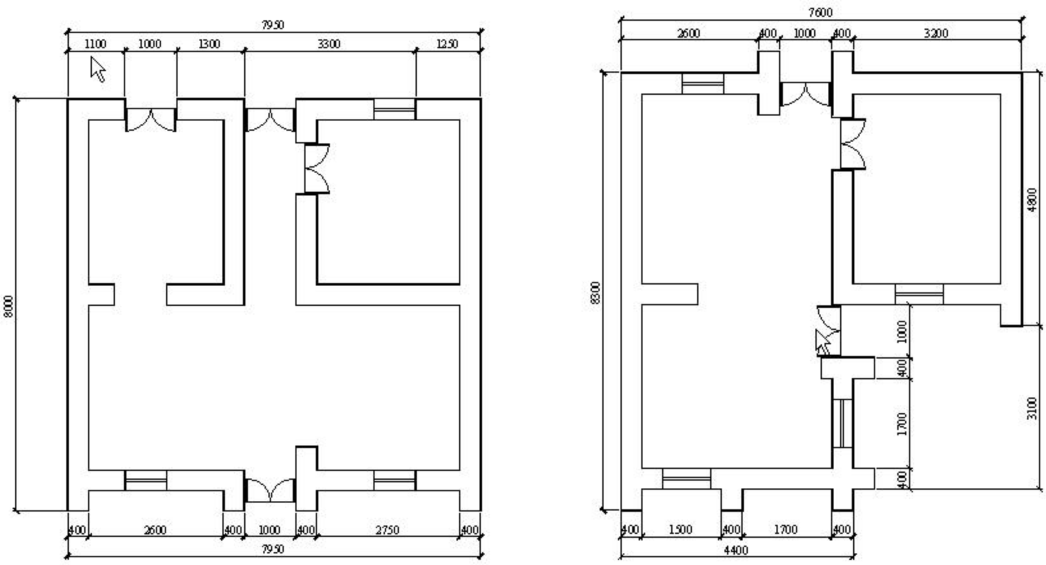
4.3.3. Evaluation of the seismic performance of reinforced houses

Three reinforced adobe houses, 1- and 2-story, inside of the affected area were visited and two of them were evaluated in detail. These are located near Pacaran city, in a flat area with a small hill at the backside (S 12º 51.719' W 76º 03.271').

(a) 1-story house (b) 2-story house

Fig. 4.72. Pacaran reinforced adobe houses.

The plan view of both houses is shown in Fig. 4.73. Both of the reinforced houses were constructed following the procedure shown in Fig. 4.71. The roofs are light and well connected and the foundations were made of unreinforced concrete. The 2nd floor of the 2-story house was made of light prefabricated quincha panels.

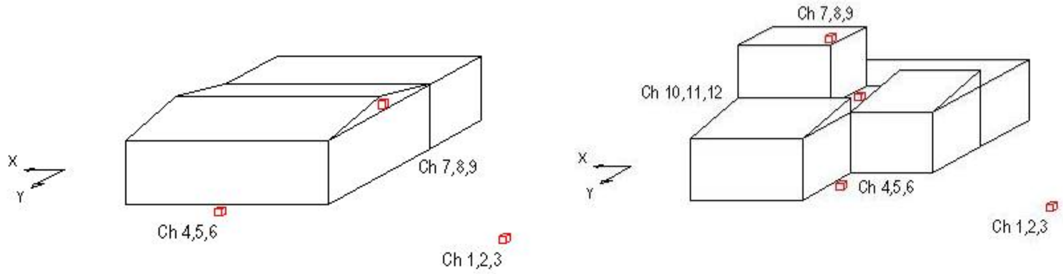


(a) 1-story house (b) Two story houses.

Fig. 4.73. Pacaran reinforced adobe houses layout.

After the Pisco Earthquake, the houses seemed to be in good condition, although some cracks in the plastering of the *quincha* panels on the second floor were observed. It is important to mention that the number of damaged houses in Pacaran was not as large as other cities inside of the affected area. However, some nearby public buildings made of adobe collapsed due to the shake.

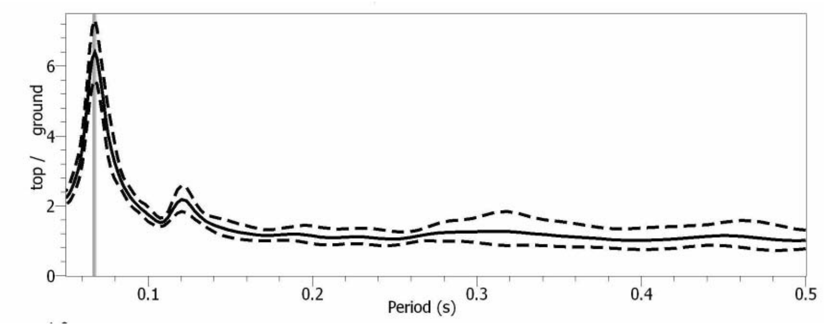
The dynamic properties of the structure were evaluated using microtremor measurements. The arrangement used for reinforced houses is shown in Fig. 4.74. In this case one sensor was located in open field, another close to house's foundation, and the other ones on the roof of each floor.



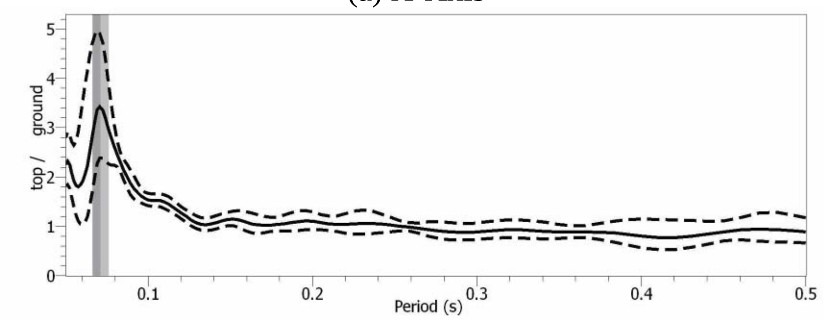
(a) 1-story house (b) 2-story house

Fig. 4.74. Pacaran reinforced adobe houses microtremor arrangement.

Three measurements were taken at 100Hz during 300 sec. The spectral ratio was calculated and it is shown in Fig. 4.75 for the 1-story house. A clear peak at approximately 0.07 sec is observed in both X- and Y-directions. Compared to the house measured at Guadalupe, Ica, this structure is stiffer. This may be due to the buttresses which are used in this structure and the stiffer roof.



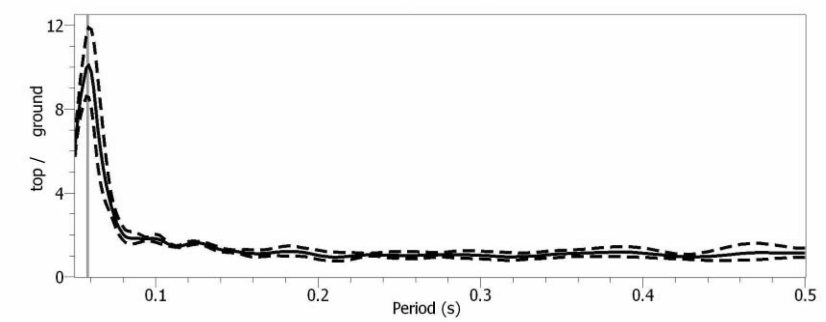
(a) X-Axis



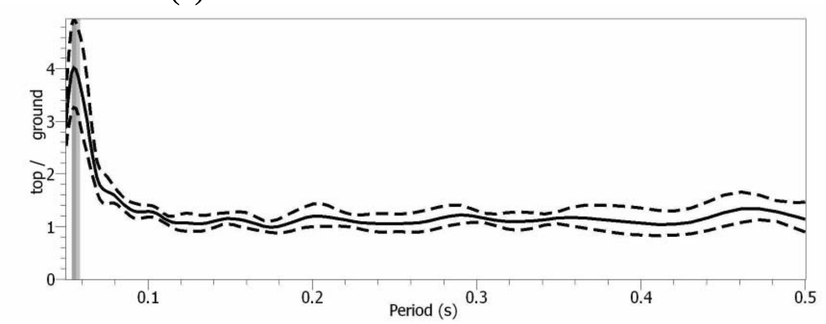
(b) Y-Axis.

Fig. 4.75. Ratio of Fourier spectra of microtremor measurement in reinforced 1-story adobe house.

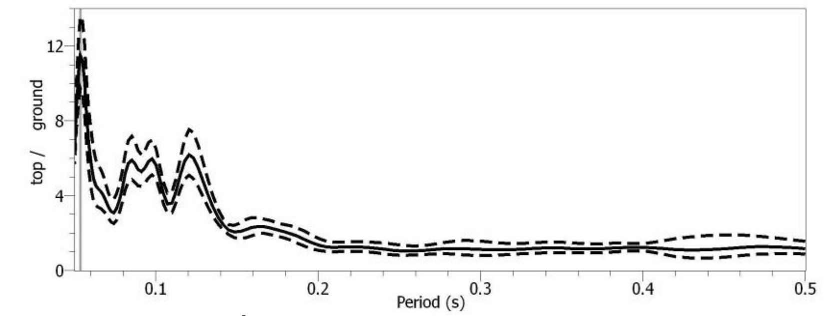
For the 2-story house, spectral ratios 1st Floor Roof / Free field and 2nd Floor Roof / Free field were calculated and are shown in Fig. 4.76. Although the response at the 1st floor roof shows one clear peak at 0.06s in X- and Y- directions, the response at the 2nd Floor roof is more complex and shows multi peaks. The lowest period corresponding to one of these peaks is 0.06s, in both X- and Y-directions, which coincides with the natural period of the 1st floor roof response. This may suggest that it is the effect of the 1st floor on the 2nd. The remaining peaks may indicate additional vibration modes active for the 2nd floor, which are not transmitted to the 1st floor because the mass of the second floor is very small compared to that of the 1st floor. Further analysis is necessary to confirm these interpretations.



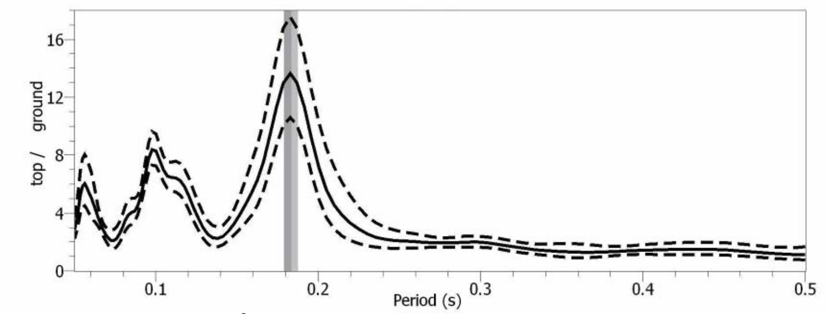
(a) 1st Floor Roof / Free field - X-Axis



(b) 1st Floor Roof / Free field - Y-Axis



(c) 2nd Floor Roof / Free field - X-Axis



(c) 2nd Floor Roof / Free field - Y-Axis

Fig. 4.76. Ratio of Fourier spectra of microtremor measurement in reinforced 2-story adobe house

4.4. Final Remarks

Predominant construction systems in the areas affected by the 2007 Pisco Earthquake are adobe and confined masonry combined with light roofs made of either straw mat or light gage steel plates. Although the relatively small death toll during this earthquake was mostly due to the time occurrence, 18:41, the predominant light roofs may have also contributed to keep this number low.

The structures that were designed and built according to the construction codes performed well. Design and construction deficiencies caused most of the observed structural damage.

Many public facilities, including schools, hospitals, churches, and hotels, performed badly. More than 30% of the casualties in this earthquake were caused by the collapse of San Clemente Church in Pisco. The main hospital of Pisco City was also heavily damaged as well as large part of the school infrastructure.

A few reinforced adobe houses were located in the affected area and performed well during the event. They demonstrate that adobe can have a good seismic performance if adequately treated. The reinforcement with bamboo is adequate for new constructions as long as there is enough bamboo. The reconstruction experience after the 2001 El Salvador Earthquake showed that in some cases, when the number of houses to be reconstructed is too large, there may not be enough material available and using industrial materials is needed.

For retrofitting existing structures, the steel wire mesh has showed good performance. However, there is controversy among experts who argue that instead of increasing strength, as with this method, it is more important to increase ductility. In addition, this system is still expensive for the majority of the Peruvian population. Other cheaper solutions which address the ductility issue are presently available such as external coatings with polymer meshes and PP-band meshes [18, 19, 20].

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5. ROADS AND BRIDGES

5.1. Background

5.1.1. Peruvian road network

The Peruvian road network is an extensive system of roads crossing most of the mountain and coastal regions. It consists of 78 318 Km classified in three categories: national highways, regional roads, and rural roads (see Table 5.1). Most of the national highways have two lanes and one safety lane for each travel direction whereas regional roads have one lane and one safety lane.

Table 5.1. Road classification in Peruvian road network. Adapted from [1]

Category	Length [Km]
National Highway	17158
Regional Road	14251
Rural Road	46909

Only 12% of the Peruvian roads, mainly the national highways, are paved. Forty-five percent of the roads do not have surface treatment, mostly in the rural areas, and 23% have base but not pavement. (See Fig. 5.1).

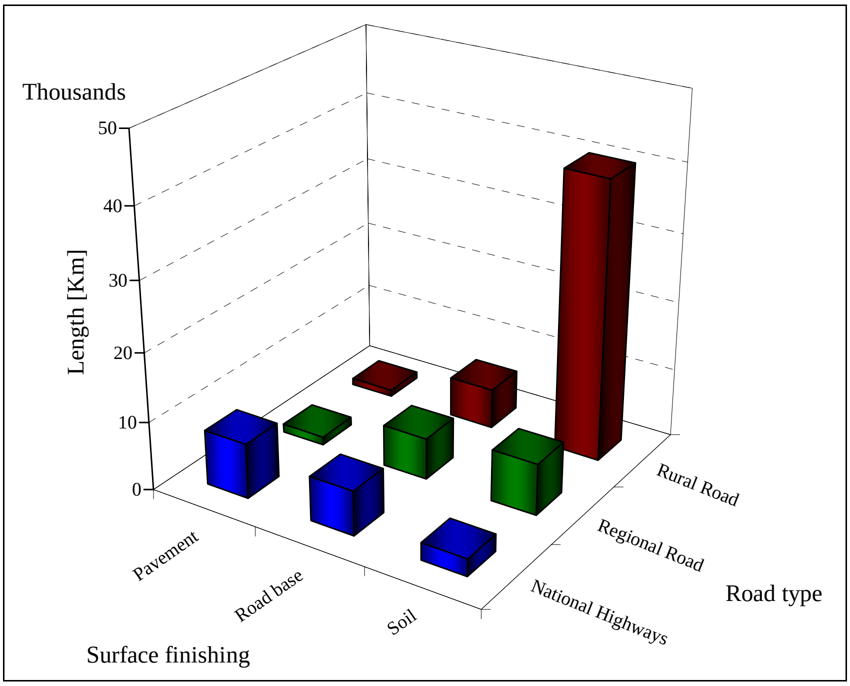

Fig. 5.1 Peruvian road network distribution based on road surface conditions. Adapted from [1]

The main roads are the Pan-American Highway, which runs parallel to the coastline, the Central Highway, which connects the capital, Lima, with the Central Andean highlands, and the Marginal Highway, which penetrates deep into the northeastern Amazon region.

The Ministry of Transportation and Communications (MTC) has developed guidelines for road design and construction as shown below:

- Highway geometric design manual (DG 2001)
- Technical specifications for construction of roads (EG 2000)
- Materials testing manual (EM 2000)
- Bridge design manual (DG 2003)
- Unpaved road design manual (084-2005-MTC)
- Routine and periodic maintenance manual for regional roads (026-2006-MTC)

5.1.2. Concession system of transport infrastructure

The Concession Program was established by the MTC under the Infrastructure Development Plan in order to guarantee infrastructure development and maintenance. The Concession Program promotes the construction, improvement, rehabilitation, operation, and management of infrastructure by private operators in order to resolve investment difficulties that have been affecting the Peruvian road system. The first concession in the Peruvian road system was the Arequipa Matarani Highway given in 1994 to CONCAR S.A. During the team interview surveys, it was found that approximately 10% of the Peruvian road network is currently under concession.

The main access road of the affected region, the South Pan-American Highway, was given in concession under a contract signed on September 20, 2005 on the road stretch between Km 58 and Km 290. The investor COVIPERU (Concesionaria Vial del Perú S.A.), which was given the concession for 30 consecutive years, committed to invest US$157 million in the highway. Furthermore, COVIPERU has the obligation to insure, the entire highway given in concession, against any event, including an earthquake. Table 5.2 shows the length of the concession.

Table 5.2. Sub-stretches of the South Pan-American Highway, Pucusana Bridge–Cerro Azul–Ica Stretch. Adapted from [2].

Sub - stretch	Department	From	To	Length [Km]
1	Lima	Pucusana Bridge	Cerro Azul	72.700
2	Lima	Cerro Azul	Cerro Calavera	1.600
3	Lima	Cerro Calavera	Pampa Clarita	18.701
4	Lima/Ica	Pampa Clarita	Chincha Alta	33.085
5	Ica	Chincha Alta	San Andres	41.114
6	Ica	San Andres	Guadalupe	54.495

A part of the concession contract includes shifting a portion of the Pan-American Highway towards the west to avoid passing through Canete and Chincha cities, as it presently does. This investment was supposed to be gradually done from 2008 until 2022. The Pisco Earthquake encouraged the MTC to bring forward this schedule, so that the new road is finished by 2011.

5.2. Road Damage

The South Pan-American Highway widespread damage was mainly due to landslides, rock falls, lateral spreading, and liquefaction. The MTC released a preliminary report of the damaged areas shown in Table 5.3.

Table 5.3. Damage in the Pan-American Highway due to Pisco Earthquake
Adapted from [4]

Location Name	Type of failure	Km
San Jeronimo Surco	Slope failure	56 to 57
Mala	Slope failure and pavement cracks	79 to 80
Jahuay - Chincha	Pavement cracks	177 to 178
Jahuay - Chincha	Slope failure	179
Jahuay - Chincha	Embankment failure. L=200m	190 to 191
Jahuay - Chincha	Embankment failure. L=20m	213
	Pavement cracks. L=200m	217 to 218
Huamani	Embankment failure.	222

COVIPERU has among its responsibilities to repair and replace the damaged infrastructure after a disaster to fully restore the service within 15 days. Although traffic was briefly disrupted, 5 hours after the event restricted transit was possible and within 48 hours fully traffic was reestablished. Most of the repair works, except for the reparation of the Huamani Bridge, were finished two weeks after the earthquake. This was a critical fact, considering that South Pan-American Highway is the main access to the affected area, especially for the aid coming from Lima city.

The regional and rural road networks were mainly affected by slope failures and rock falls, which in many cases disrupted the traffic.

Typical road damage induced by the earthquake may be categorized as: slope failure, embankment failure, longitudinal cracking, settlement, shoulder settlement/displacement, road distortion and pot holes. Most of damages are caused by failure of the unstable foundation due to liquefaction. Fig. 5.2 to Fig. 5.7 show typical damage examples.

Fig. 5.2. Slope failure caused by liquefaction induced lateral spreading

Fig. 5.3. Liquefaction induced embankment failure

Fig. 5.4. Cracking along the pavement due to landslide induced movement

Fig. 5.5. Shoulder settlement and displacement

Fig. 5.6. Road distortion due to liquefaction induced lateral spreading

Fig. 5.7 Pot holes caused by rock falls

The South Pan-American Highway was heavily damaged where it turns west to enter Chincha City. This location coincides with the limit where the Canete Formation meets a marine deposit. The Pleistocene Canete formation consists of alternating layers of sand and silt stones, with marine or eolic deposits above it. Widespread liquefaction observed in this area may have caused much of the road damage. At this location, uplifting of the slope side shoulder occurred. This is likely due to loss of the base support of the slope, which then moved towards the road (see Fig. 5.8) lifting it up. Liquefaction /lateral spreading induced loss of base support caused the slope failure damage shown in Fig. 5.9.

Fig. 5.8 Lifted shoulder at Playa Jahuay. South Pan-American Highway

Fig. 5.9 Road failure due to lateral spreading at the foot of the slope. South Pan-American Highway

A massive rock fall occurred along the Canete-Yauyos road, as shown in Fig. 5.10, (S 12º54.778’ W 76º05.852’). Debris completely covered the road surface disrupting traffic. The rock formation at this location is constituted by blocks of partially weathered igneous intrusive rock.

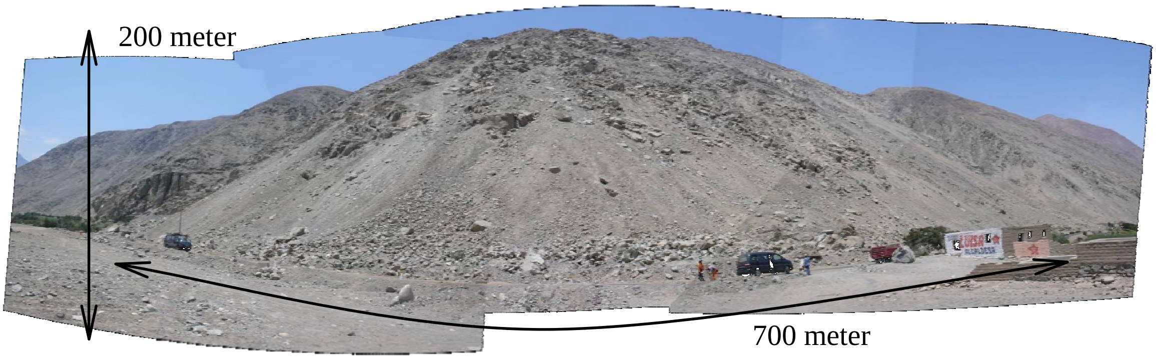

Fig. 5.10. Rock Fall. Canete-Yauyos Road, 60km from epicenter.

A slope failure was observed at the Km.23 of the Canete-Yauyos road. This is the exact point where the road and an irrigation channel meet. Although there was no evidence suggesting channel damage or water leakage, the possibility that its presence may have somehow affected the slope stability needs further assessment.

Fig. 5.11. Google earth view with black arrow indicating the slope failure at Canete-Yauyos road (Km. 23) (13° 3'3.08"S, 76°13'32.85"W).

Fig. 5.12. Slope failure at Canete-Yauyos road (Km. 23)

Fig. 5.13. Slope failure at Canete-Yauyos road (Km. 23)

5.3. Bridge Damage

A few bridges were surveyed in the affected areas along the Pan-American Highway, Los Libertadores Highway, and the Canete-Yauyos Road. Most of the visited sites had little damage, mostly in the form of settlement of the fill behind the abutments. At one of the bridges, a rock impacted on the sub-structure, causing a spalling damage.

Fig. 5.14 Mild settlement of the fill behind abutment (La Quinga Bridge, Los Libertadores Highway)

Fig. 5.15 Rock impacted on bridge sub-structure (Tsej Tji Bridge, Los Libertadores Highway, close to Huaytara)

The most affected bridge was by far the Huamani Bridge, which crosses the Pisco River. This reinforced concrete bridge, designed for a HS-15 truck load, was built in the 50's. At that time, bridge seismic design was quite primitive in Peru. These structures were designed to withstand 0.04, 0.06, and 0.08g base shear force for hard, medium, and soft soils [5].

The 136-m long Huamani bridge follows the configuration of a typical Gerber bridge. Two rather slender abutments (typical Base/Height = 0.3) and four intermediate pillars are supported on 5.4m-deep and 7.3m-deep caissons, respectively. According to the bridge drawings, there is no connection between the abutments/pillars and the caissons, i.e. the pillars could slide/rock upon the caisson top. Fig. 5.16 shows the layout of the bridge. The superstructure consists of five sections.

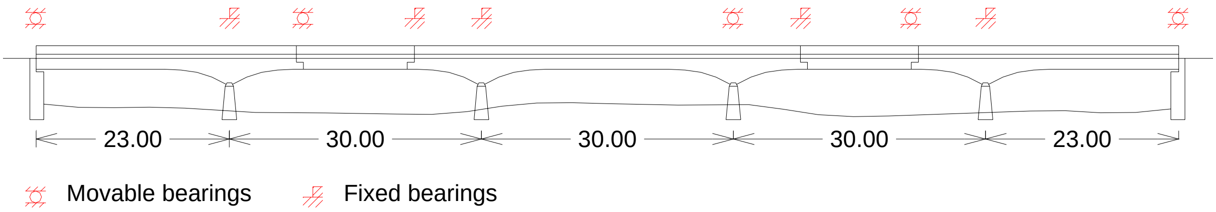

Fig. 5.16 Layout of the Huamani bridge (downstream direction)

Fig. 5.17 Overview of the bridge (downstream direction)

Liquefaction induced lateral spreading was observed in the northern upstream bank of the Pisco River and also south of the south embankment. Evidence of liquefaction was also found around the bridge pillars.

Fig. 5.18 Liquefaction induced lateral spreading (Pisco River north upstream bank)

Fig. 5.19 Liquefaction at the bridge pillar

The southern abutment tilted towards the north some 7% due to the Pisco earthquake [5] and settlement and cracking of the embankment also occurred. The intermediate pillars also rotated. Although the north abutment was not as damaged as the southern, settlement of the backfill was observed there. The geological formation at the bridge north access belongs to the Miocene/early Pliocene age whereas alluvial deposits are found in the south.

Fig. 5.20 South abutment, upstream

Fig. 5.21 South abutment, downstream

The bridge superstructure is supported on fixed and movable bearings as shown in Fig. 5.16. The movable bearings are made of steel rollers as shown in Fig. 5.22 and Fig. 5.23. Note the steel stoppers installed to prevent the movement in the bridge transverse direction. The steel bearings were quite corroded.

Fig. 5.22 Movable bearings on the pillars

Fig. 5.23 Movable bearing at the southern abutment

The bridge superstructure permanently moved upstream as shown in Fig. 5.24. The blue dots represent the superstructure sections and the measurements indicate relative displacements between adjacent sections or between superstructure and abutments. At the movable bearings on the abutment, the steel fittings separated from the concrete structure (Fig. 5.23). The stoppers on the pillar movable support, bottom, were not found. The lateral movement of the bridge caused damage to the concrete wings of the pillars, especially that with the movable bearing. These wings had very little steel reinforcement.

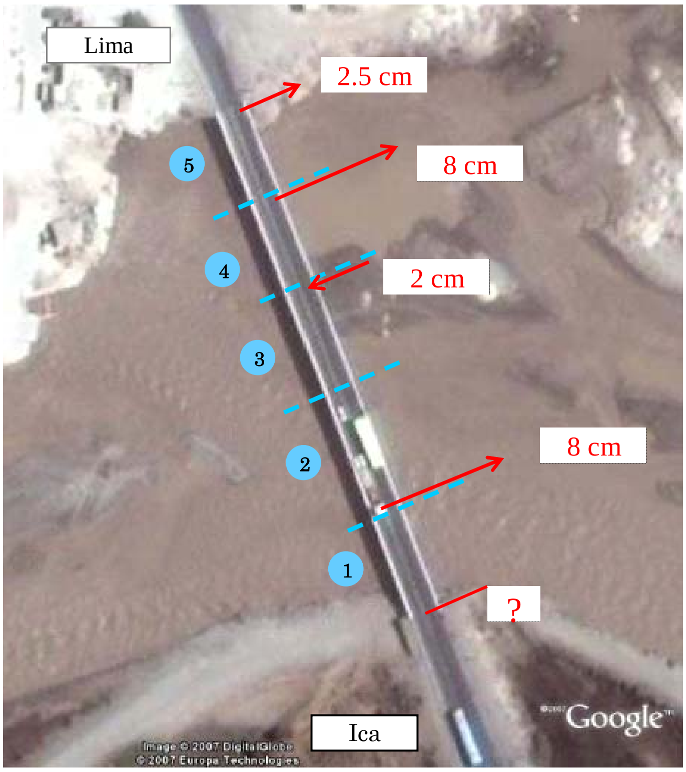

Fig. 5.24 Google earth view of the displacement of the bridge superstructure.

Fig. 5.25 Bridge slab displacement (picture taken towards the north). Arrow indicates the gap corresponding to the southern 8 cm gap shown in Fig. 5.24

Fig. 5.26 No bottom steel stoppers were found at the pillar movable bearing.

Fig. 5.27 Failed wing with poor reinforcement (pillar with movable bearing)

Fig. 5.28 Failed wing with poor reinforcement (pillar with movable bearing)

The displacements and rotations of the bridge segments concentrated stresses on the superstructure transverse beams which suffered cracking.

Fig. 5.29 Damaged transverse beams

Fig. 5.30 Cracks in the wing of the pillar with fixed bearing

In spite of the damage observed in the bridge, it performed very well. Immediately after the earthquake, traffic continued, but was restrained to one truck at a time. To improve the traffic conditions, a temporary passage along the riverbed was later prepared and was still in use while the bridge was been repaired when we passed this location on several occasions from September 8 to 18.

Because it is expected that in the near future the stretch of the Pan-American Highway to which the Huamani bridge belongs will be shifted towards the west, the reparation works done were aimed at restoring its original capacity, not improving it.

5.4. Summary

Road damage due to the 2007 Pisco Earthquake extended over a wide area. The South Pan-American Highway which was the most affected and also pivotal for the response actions was recovered in a relatively short time. Because this portion of the highway has been given in concession, revisions of the investment schedules and contract terms are currently under discussion.

Regional and rural roads were affected mainly by rock falls and landslides, problems which afflict them on a regular basis.

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6. DISASTER RESPONSE AND RECOVERY/RECONSTRUCTION

6.1. Response

Disaster response is a function that belongs to the National Institute of Civil Defense and the local governments. Therefore, coordination among these entities is fundamental for a successful response. Incidentally, in January 2007, the authorities at local governments changed and therefore, most of them, except for those who were re-elected, had less than eight months in office. In addition, there are few disaster management career officials at the local governments. These two factors hindered the response capacity of local governments. In this section, some of the disaster response aspects will be discussed.

Debris removal

Debris removal proceeded swiftly with heavy machinery in Pisco immediately after the earthquake. After this, there was a period in which removal was carried out by crews, approximately 1 800 people, hired by the Ministry of the Presidency in the framework of the Building Peru Program. No heavy machinery was observed in Pisco by our team in this period. Eventually, almost a month after the earthquake, heavy machinery re-started cleaning Pisco. Table 6.1 shows a summary of debris removal as of October 24, more than 2 months after the earthquake.

Table 6.1 Progress in debris removal [2]

Province	Volume to remove [m^3]	Progress as of Oct. 24 [m^3]	Progress as of Oct. 24 [%]
Chincha	2 858 000	382 895	13.3
Ica	2 023 645	284 058	14.0
Pisco	2 120 000	441 927	20.8
Canete	791 820	113 514	14.3
Yauyos	440 000	6 624	1.5
Total	8 233 465	1 229 019	14.9

Residents who had their houses collapsed could request assistance from the municipality to remove the debris from their lots by submitting a form. In addition, many people were cleaning their properties by themselves. This was observed by the reconnaissance team especially at Tambo de Mora and Guadalupe, Ica. It is worth noticing that the cleaning progressed faster due to self support in towns where tourism is the main economic activity, such as Lunahuana, in the region of Lima.

Fig. 6.1 Cleaning crew hired in the framework of the Building Peru Program

Fig. 6.2 People removing debris from their homes by themselves

Temporary facilities

A few temporary houses were observed in downtown Pisco as shown in Fig. 6.3 and 6.4. To be eligible for this, the beneficiary should first clean his/her lot from debris. Many people, who could not benefit from these facilities, build their own temporary houses with the material they could recover from their roofs, mainly straw mats.

Fig. 6.3 A temporary house provided by BANMAT or Materials Bank a governmental agency under the Ministry of Housing.

Fig. 6.4 Wooden temporary house

Fig. 6.5 A temporary house built by a resident (Guadalupe, Ica)

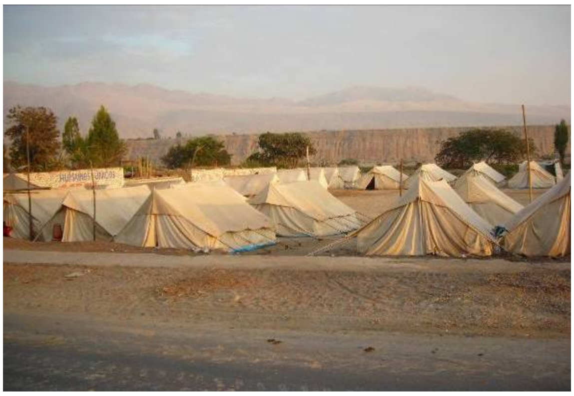

Fig. 6.6 Tents were used to cover the housing shortage in most of the places visited (Humay, Ica)

Temporary houses were not observed outside Pisco. At the other visited locations housing requirements were mostly covered by tents as shown in the table below or self constructed shelters.

Table 6.2 Number of tents distributed [2]

Province	No. of tents
Pisco	3 443
Chincha	2 500
Ica	2 000
Canete	390
Total	8 333

At schools, such as the San Luis Gonzaga high school in Ica, temporary classrooms were being installed while the team was surveying. Also, temporary health centers were installed in Pisco.

Fig. 6.7 Temporary classrooms under construction in San Luis Gonzaga School (Ica)

Fig. 6.8 A day-care center wawa wasi functioning in a tent (San Luis, Canete)

Fig. 6.9 Temporary health center in Pisco (Ica) (courteousy of Shizuko Matsuzaki)

Refugee camps

Table 6.3 summarizes the refugee camp situation as of October 24, 2007. According to a Health Ministry Situational Report [3], in most of the camps, there were insufficient tents for the sheltered population. Other problems include insufficient temporary toilets and cylinders for solid waste collection, which just cover approximately 20% of the demand. Water was distributed by EMAPISCO in cistern trucks and food was distributed by PRONAA and SODEXHO (a private company) and when necessary cooked in the camp.

Table 6.3 Refugee camps [2]

Province	Installed camps	No. of families	No. of people
Pisco	22	2 628	9 282
Chincha	49	1 872	8 621
Ica	1	29	98
Canete	19	5 170	5 170
Total	91	5 563	23 171

Response issues

Through the interviews and data collection carried out during our survey, the team could identify some disaster response issues as summarized below:

- Information disclosure to the general public: People were not well informed about the situation and this generated unrest.
- Looting: Immediately after the earthquake there was social turmoil which was resolved with the arrival of the Army.
- People did not know how to behave during the earthquake. Reportedly, two people died because they stood under the door entrance of their adobe house and the concrete lintel fell on their heads. Standing under the door entrance is a commonly recommended action to take when an earthquake hits. People believed that running into the churches would safe them when actually these structures were heavily damaged.
- Difficulties faced by the province municipalities to gather information from their districts. At Huaytara Province the lack of a system that effectively connected the

capital with all the districts, either physically, roads, or virtually, telephones/INTERNET, delayed the response actions.
- Corruption: A few cases were reported and investigated by the relevant authorities.

6.2. Recovery/Reconstruction

FORSUR

There seems to be no governmental agency in Peru which is responsible for the integral disaster management of the country including mitigation, preparedness, response, and recovery/reconstruction. Although, INDECI is the leading agency in the first three, i.e. mitigation, preparedness, and response, it is not specifically given the responsibility for reconstruction, although, in a sense, reconstruction is mitigation for the next event.

To coordinate all the reconstruction efforts in this occasion, the executive proposed to the congress the creation of the Fund for the Reconstruction of the South (FORSUR), which the latter accepted almost two weeks after the earthquake [4]. It was conceived following the model of the Fund for the Reconstruction of the Eje Cafetalero, in Colombia, which took over the reconstruction of the region hit by the 1999 Armenia Earthquake. FORSUR is under the Presidency of the Ministry Council (PCM) and its board is constituted by: a president, who represents the Peruvian President, the Presidents of Ica, Lima, and Huancavelica Regions, the Majors of Ica, Chincha, Pisco, Canete and Yauyos, the Ministers of Transportation and Communications, Health, Housing, Construction and Sanitation, Education, Energy and Mining, and Economy and Finance, or its representatives, and four representatives from the private sector. All of them work *ad honorem*.

FORSUR has been in office for almost two months and has reportedly made progress in the reconstruction planning [5]. However, this is not perceived at the affected provinces. As a result, the population is taking reconstruction steps on their own.

Financial support for house reconstruction

Shortly after the 2007 Pisco Earthquake, the government announced that it will provide S/. 6 000 to the people who lost their houses. This money will come from the Contingency Fund that the Ministry of Economy and Trade prepares every year, S/.30 million for 2007. However, one of the requirements to be eligible for this assistance was to submit among others a land property certificate. As mentioned in Chapter 4, informality, in this case, lack of property certificate, is one of the main issues in Peru.

Because irregularities in the land property in Peru are the rule, not the exception, the Commission for the Formalization of the Informal Property (COFOPRI) was created to deal with this problem before the earthquake. COFOPRI’s main mission is to give land property titles to those that do not have it and who are eligible according to COFOPRI standards. After the earthquake, COFOPRI started working in the affected areas to try to solve the problems of land property. It estimated that approximately 30% of all the lots in Pisco were not registered [6]. Furthermore, of the more than 75,000 houses that are estimated will be reconstructed, 50% do not have property title [5].

Because the S/.6 000 will be insufficient to reconstruct a house, the government is planning to use the program TECHO PROPIO to provide additional money. This program, sponsored by the Ministry of Housing, was already in place before the earthquake to help low income people procure themselves with adequate housing. It consists of a grant of US$3 800. According to FORSUR, these two grants will cover almost 70% of the reconstruction cost and the 30% left will be obtained in the form of soft 20-year long loans. For receiving both grants, property title is a requirement and because of the irregular situation of most of the affected, the reconstruction process is not proceeding swiftly.

Fig. 6.10 The only way left to establish property rights is writing the resident name and address on the walls left standing (Tambo de Mora, Ica)

Recurrent deficient construction practices

During the survey it was observed that at many places, adobe blocks from the collapsed houses were neatly piled next to the lots suggesting that they may soon be used for reconstruction. In other places, people were trying to reuse the few walls that were left standing as the first walls of their new constructions.

The National Service for Training for the Construction Industry (SENCICO) has signed agreements with some municipalities, such as San Antonio, Cerro Azul and Lunahuana, to assist them with mason training. Unfortunately, these courses do not include guidance on adobe construction, which in our view is indispensable.

INDECI has also signed a MOU with SENCICO for the same purpose and reportedly FORSUR has approached it for advice.

Fig. 6.11 Front adobe wall, which did not collapse during the earthquake, is reused in the new structure with some "reinforcement"

Fig. 6.12 Adobes from collapsed walls are kept to be used as construction material

Fig. 6.13 Units from collapsed walls piled up ready to start the reconstruction

Other issues

Other reconstruction issues that were identified during our survey and interviews are summarized below:

- Material construction prices have increased affecting reconstruction process.
- People did not accept to be relocated unless they were given a land property title at another location. Many of these people do not have property titles for the places were they used to live and therefore there is no evidence of ownership other than their presence next to the debris.
- It seemed that there was no government coordination/ supervision of the activities of some NGO's.

6.3. Summary

In spite of the great efforts of the organizations in charge of disaster response, the magnitude of the disaster has overwhelmed them. This has translated in delays in the debris removal, insufficient temporary houses and tents, and poor conditions at the refugee camps. The affected people are trying to fill these need gaps by themselves.

An independent agency has been created to coordinate the reconstruction efforts. Although reconstruction plans seem to have progressed, works have not started yet and the public is growing increasingly impatient. It is of great concern that people have started reconstructing their houses with the same poor construction practices and bad quality materials. Some courses to train masons on good construction practices have been organized. However, the benefits of these efforts are yet to be seen.

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7. RECOMMENDATIONS

Based on the field survey findings and the numerous interviews held, the team's recommendations are summarized below. These are aimed at providing ideas on how to improve the disaster resilience capacity of the areas affected by the earthquake in particular, and the country as a whole. We have tentatively ordered the recommendations based on their impact to reduce human and property losses in future earthquakes, the most impacting being presented first. However, it is our understanding that this ordering is just tentative and the final one should be a result of discussion among relevant parties.

■ Structural and construction issues

- Strengthen the system of code enforcement not only at the design but also at the construction stage. Three components are necessary for this purpose: a) municipalities, which should have an adequate, in number and expertise, team of specialists to assess the projects' design and supervise that the construction follows the design; b) Association of Civil Engineers, which licenses the engineers responsible for the projects, to ensure that engineers manage projects according to their expertise level; c) an independent entity, which investigates and establish responsibilities when there are construction irregularities.
- Although the above mentioned system should, ideally, be also applicable for house construction, in practice, it will take time for this to become a reality in Peru. In the case of house construction, training masons in good construction practices (also for Adobe structures) may be a more feasible way to improve the construction quality. An agency like the National Service for Training for the Construction Industry (SENCICO) could be a very important component for this purpose.
- Require that all public buildings, governmental and private, are upgraded to the latest revision of the codes. It is practically impossible to retrofit all public buildings, it may even be impossible to assess the vulnerability of all of them. Therefore, a methodology to establish the order in which structures should be assessed and retrofitted is desirable.
- Promote retrofitting of seismically weak houses.
- Establish the mechanisms to effectively close the facilities which are deemed unsafe by the National Institute of Civil Defense (INDECI).
- Continue with pilot projects to introduce to the population earthquake resistant construction techniques, including a follow-up component to estimate the impact of these projects and the archiving of these experiences to serve as reference material for future initiatives.
- Explore cheaper construction technologies to retrofit adobe houses, for instance with plastic meshes. Solutions that may be suitable for one situation may not be for another. Reinforced and retrofitted adobe houses performed well, demonstrating that adobe can be made earthquake safe.

- Emphasize the retrofitting of public structures which have a special significance to the population, for instance churches, and use these opportunities to create disaster awareness among the population.

■ Disaster awareness issues
- Carry out activities to increase the public disaster awareness. Mass media can be a very useful tool for this. Outreach to the young generation at elementary and high schools through imagination exercises in which they explore the possible consequences of a disaster and drills. Promoting disaster awareness among young people has a multiplying effect and also creates a conscious next generation.

■ Issues related to future earthquake affecting Lima
- Study the possible impact, direct (human and property losses) and indirect losses, for an expected earthquake in Lima. The Peruvian Capital concentrates more than 30% of the country population, the central government, and also an important share of the country economy. Although every people we met agreed that an earthquake in Lima would be a tragedy, nobody could give specific numbers regarding the potential losses. Such an assessment can have a huge leverage for promoting mitigation.
- Extend the Sustainable City Program, which is being carried out by INDECI, to cover all the major cities in the country especially Metropolitan Lima.

■ Land use issues
- While it may take time, it is very important to base the land use plans on existing hazard maps. The damages in Tambo de Mora and Pisco coincide very well with these maps, showing their importance and necessity. When such maps are updated, land use laws should also be updated if deemed necessary.
- Accelerate the process of formalization of property rights.

■ Foundations and geotechnical issues
- Liquefaction induced large soil cracks and displacements were observed in Tambo de Mora and Pisco. The only way to reduce the damages induced by such soil deformations is with reinforced, strong, and expensive foundations. The good performance of such foundations was clearly shown by a newer school house in Tambo de Mora and a Hotel in Pisco.
- The strong foundations are especially important for public buildings like schools and hospitals. Weak foundations, similar to the one of the health center in Huaytara, needs to be retrofitted or reconstructed.
- Foundations preventing moisture from entering the adobe walls from the surrounding ground are necessary. In addition to reducing the earthquake resistance of an already earthquake vulnerable building type, moisture also constitutes a general health problem.
- It is not easy to reduce the effects of large soil cracks, such as the ones observed in Nuevo Monterrico. With strong reinforced foundation slabs, the houses may have withstood some of the deformations.

- Disaster response and reconstruction issues
  - Create a digital and interactive disaster management manual, effectively a database, in which the roles and duties of each stakeholder are included. With this type of system strengths and weaknesses can be pinpointed helping to improve it. It can be enhanced with the experiences collected in drills and during disaster events.
  - It should be desirable that the experiences of the Fund for the Reconstruction of the South (FORSUR), which has been created just to address the reconstruction of the areas affected by the 2007 Pisco Earthquake, are archived for future reference as well as all disaster management experiences.
  - Encourage disaster management related officials at all government levels, central, regional, and local to stay at their positions for longer periods. In this way, disaster management policies can have continuity even under different administrations and also, people experienced in disaster response are available when a disaster hits.
  - Establish procedures to release accurate and timely information to the population in order to avoid rumors and tensions.

- Seismic network
  - Strengthen the system for sharing strong ground motion recorded information, through, for instance a common INTERNET platform from where the information of all relevant institutions can be downloaded as soon as it is available. E.g. instrumental intensity maps based on all records could be provided.
  - Adding more seismographs to the networks, especially to the bigger cities, and converting analog instruments to digital, would e.g. allow for quicker estimation of affected areas.