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Magnitude 7.9 Earthquake
near the Coast of Central Peru

Earthquake Field Investigation Team (EEFIT) Field Mission, 5-12 SEPTEMBER 2007 / Final Report

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Foreword

This is the final report of the findings from the field mission carried out during the week of 5-12 September 2007 in the areas affected by the 15 August 2007 Magnitude 7.9 Earthquake near the Coast of Central Peru.

The mission was carried out by a team of three engineers: Fabio Taucer (Team Leader – Joint Research Centre, European Commission, Ispra - Italy), John Alarcón (Arup, UK) and Emily So (University of Cambridge, UK), all members of the Earthquake Engineering Field Investigation Team (EEFIT – The Institution of Structural Engineers, London).

The main objectives of the mission were to collect data and make observations leading to improvements in assessment and design methods and techniques for strengthening and retrofit, to gather data on socio-economic aspects and management of the disaster, as well as to assist the phase of reconstruction. The mission focused on the behaviour of non-engineered structures, in particular those of adobe construction, which caused 519 deaths and 1,366 injuries following the collapse of more than 58,000 houses.

The mission was carried out in close collaboration with the Delegation of the European Commission in Peru, with assistance from the *Pontificia Universidad Católica del Perú* and PREDECAM (*Apoyo a la Prevención de Desasters de la Comunidad Andina*); contacts were made with representatives of the Peruvian Civil Protection (*Instituto Nacional de Defensa Civil* -INDECI), as well as with NGO's present and active in Peru.

The field mission consisted in surveying the damaged areas of the Province of Ica, in particular the cities of Pisco, Ica and Chincha Alta, as well as the smaller city centres of Tambo de Mora, Paracas, Guadalupe and El Carmen, and the Port of San Martín. Special attention was given to surveying the rural mountain areas up the valley of the Cañete river: Lunahuaná, Zúñiga, San Jerónimo and Huangáscar. The survey focused in documenting the damage and interviewing the affected population, with the purpose of gathering not only technical information, but also to understand the socio-economic aspects of the disaster in order to draw recommendations concerning the management of the disaster and the reconstruction phase.

EEFIT Team: Fabio Taucer, Emily So, John Alarcón

Acknowledgements

The authors wish to acknowledge their gratitude towards the European Commission, Arup (UK), and the Engineering and Physical Sciences Research Council (UK), for providing the necessary funding for the field mission.

The support given in the field by the Delegation of the European Commission in Peru, in particular of Karl-Heinz Vogel, *Agregado de Cooperación*, as well as the discussions and valuable information provided by Ana Campos García, Director of PREDECAM, and Harald Mossbrucker, *Jefe de Asistencia Técnica Internacional* of PREDECAM, are greatly appreciated.

The assistance, technical and logistic support given by Prof. Marcial Blondet, from the *Pontificia Universidad Católica del Perú* (PUCP), was extremely valuable for planning the field mission; the discussions with Prof. Daniel Quiun Wong and Ing. Wilson E. Silva Berrios, both from PUCP, are also appreciated.

The meeting held with Econ. Percy Alvarado Vadillo, Director of the *Secretaría Permanente de los Consejos Consultivos y de Coordinación* of INDECI, and with his team at the Area 51 Air Base in Pisco, was very valuable for obtaining information concerning the management of the disaster and the extent of damage sustained in the Ica region; likewise, the discussions with Prof. Jorge E. Alva Hurtado, Dean of the Civil Engineering Faculty of the *Universidad Nacional de Ingeniería* provided information concerning the seismological, geological and local site effects related to the earthquake.

The EEFIT team acknowledges the support provided by Nicola Tarque, in providing the contacts with Astrid Tolmos, from the University of Ica, who was responsible for carrying out the questionnaire survey of survivors of the earthquake.

The authors thank the reviewers of the report: Zygmunt Lubkowski and Dr Matthew Free, Arup (Sections 1, 2, 3 and 4); Robin Spence, University of Cambridge (Sections 6, 8, 9, 11, 12 and 13); and Paolo Negro, Joint Research Centre (Sections 5, 7, 10, 14 and 15); as well as Domenico del Re (RMS London, UK) for carrying out a final review of the report.

Finally, the support given from the EEFIT members, Domenico del Re (EEFIT Chairman), Joe Barr, Navin Peiris and Berenice Chan (EEFIT Technical Officer) during the preparation and carrying out of the mission is much appreciated.

EEFIT acknowledges the support of its corporate members: Arup Group Ltd, BGS, Buro Happold Ltd, CREA Consultants, Gifford Consulting Engineers Ltd, Halcrow Group Ltd, Risk Management Solutions, Sir Robert McAlpine, Sellafield Ltd.

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1 Description of the Earthquake Event

Written by Dr John Alarcon, Arup

Reviewed by Zygmunt Lubkowski, Arup

On 15 August 2007, at 23h 40min 59sec (UMT) – 18h 40min 59sec (local time), a 7.9 Mw magnitude earthquake occurred off the coast of Central Peru. A summary of the location and magnitudes assigned to this earthquake by the local and by three international agencies is shown in Table 1.1. A point to highlight is that the epicentre given by the United States Geological Survey (USGS) is located approximately 45 km northeast of the epicentre given by the Geophysical Institute of Peru (IGP). The difference in the reported moment M_w and local M_L magnitudes estimates of IGP may be due to saturation of the local scale. Figure 1.1 presents the IGP epicentral location of the earthquake (red star) and the epicentral distribution of events recorded from 1996 to 2006, discriminated according to focal depth.

Table 1.1 Earthquake parameters

Agency	**Epicentre location**		**Focal Depth (km)**	**Magnitude**		
	Latitude S°	**Longitude W°**		**M_w**	**M_s**	**M_L**
IGP (Peru)	-13.670	-76.760	40	7.9		7.0
USGS (USA)	-13.354	-76.509	39	8.0		
HU-CMT (USA)	-13.73	-77.04	34	8.0	8.0	
ISC (Internet)	-13.358	-76.522	30		7.8	

IGP: *Instituto Geofísico del Perú* (Geophysical Institute of Peru) HU-CMT: Harvard University CMT catalogue

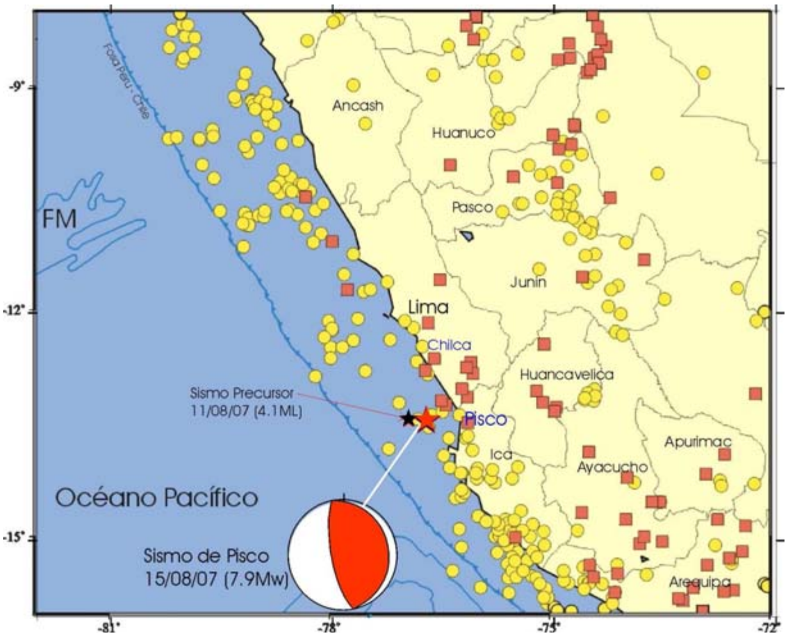

Figure 1.1 Earthquake epicentral location (red star) and seismic activity in the region from 1996 to 2006. Black star shows the location of a $4.1M_L$ foreshock. Circles represent events with focal depths of less than 60 km while squares show earthquakes with deeper focal depths (Source: www.igp.gob.pe)

The 15 August 2007 event occurred in the subduction boundary between the Nazca and South American plates, in which the Nazca plate slides underneath the American plate. The velocity of relative displacements between these plates has been estimated as 70-80 mm/yr (e.g., Norabuena et al., 1999). The tensor solution assigned to this event corresponds to a reverse fault with strike 324°, dip 27° and slip 64° (USGS). This focal solution is preferred over the alternative one based on regional tectonics, which generally dips towards the NE. The earthquake occurred in an identified seismic gap along the coast of central Peru, as presented in Figure 1.2. The gap was identified based on recorded earthquakes from 1940 to 1996.

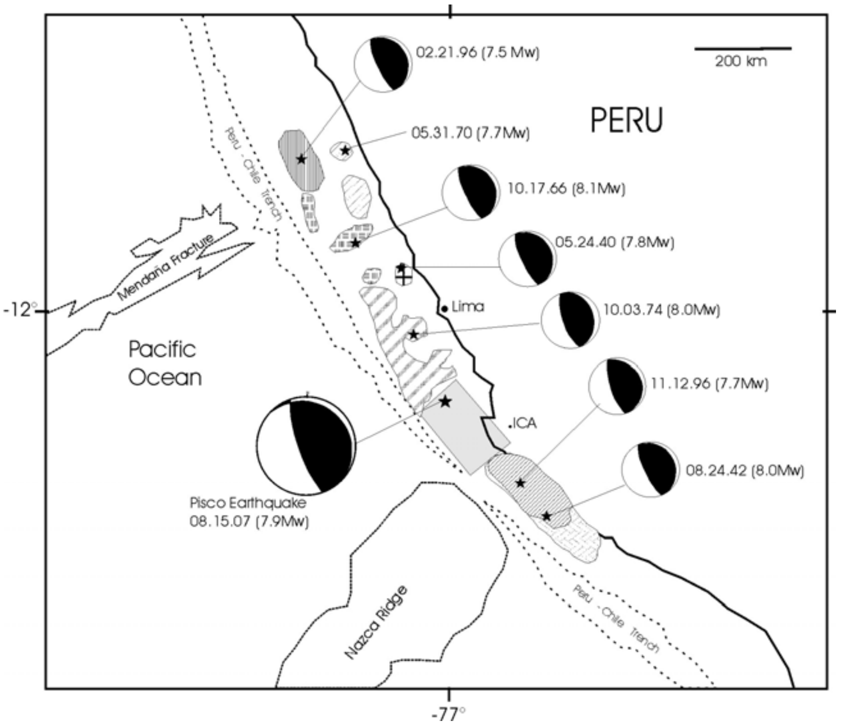

Figure 1.2 Location of large subduction earthquakes along the central coast of Peru from 1940 to 2007 (after Tavera et al., 2008)

The areas mostly affected by the earthquake are within the Ica, Huancavelica and Lima regions (see Figure 1.1), with an official death toll of 519 people and 1,366 injured, a total of 58,581 houses destroyed or demolished as a result of the severe damage induced, and 13,585 houses affected to some degree (OCHA SR21, 2007; www.onu.org.pe). The Peruvian Government estimated losses from the earthquake in US$450 millions, and expected a reduction in the economic growth of 0.3% for 2007 as a direct cause of the event[1]; detailed information concerning damage distribution and people affected is discussed in the following chapters of this report. Figure 1.3 presents the intensity map generated by the USGS after the earthquake, using ShakeMap (Wald et al., 1999); the maximum intensities (MMI VII) were reported to have occurred between the cities of Imperial in the North and Ica city in the South. Even though Lima city is classified with intensity VI, little damage was reported there. Figure 1.4 presents the intensity map prepared by IGP, whose maximum intensity (VII) distribution is similar to that from the USGS, but whose areas of intensity VI and V occur closer to the epicentre than in the USGS map (i.e., the area of intensity VII is smaller than that calculated by the USGS).

IGP published the distribution of 355 aftershocks with local magnitudes M_L equal to or larger than 3.0, which occurred between the 15th and the 20th of August 2007 (see Figure 1.5). These aftershocks have focal depths of less than 50 km, and are grouped into three clusters (G1, G2 and G3). According to the location and distribution of aftershocks, IGP suggests a rupture process occurring south-eastward in an area of approximately 150x100 km.

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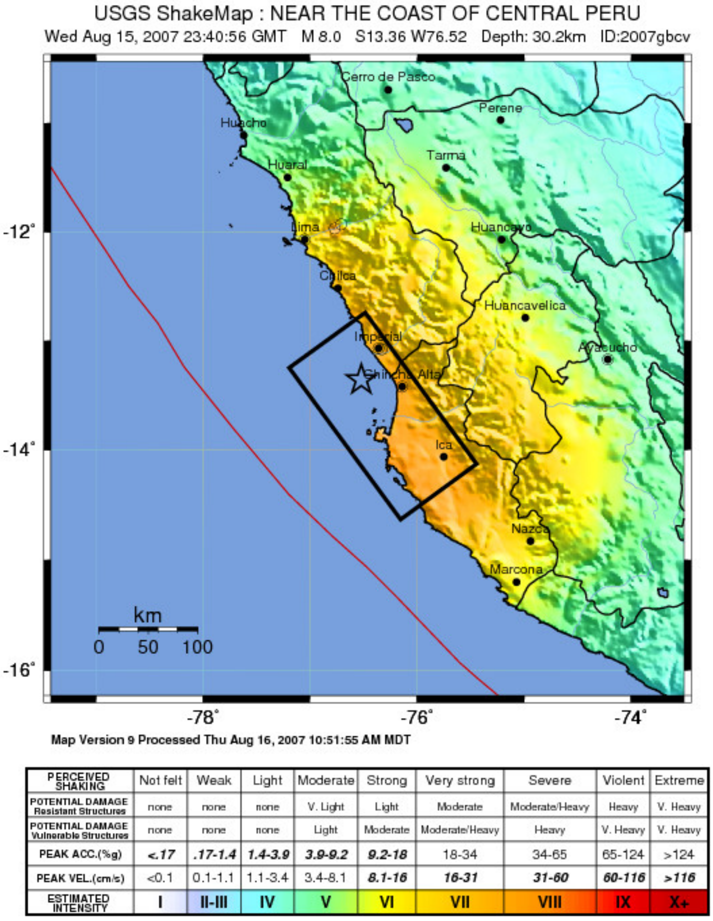
[1] The information was retrieved from the Peruvian press during the first weeks following the disaster

On the other hand, Ji & Cheng (2007) estimated the source process of the 15 August 2007 mainshock from teleseismic inversion (see Figure 1.6). From these results, two predominant slip areas are observed at the epicentre and at a region southeast of it. Tavera et al. (2008) show that these two areas coincide with the larger aftershocks recorded by IGP (Figure 1.5), constituting the basis to explain the special characteristics of the recorded strong ground motions, as described below.

A total of 18 accelerometer stations recorded the 15 August 2007 mainshock, with most of the instruments being located in the city of Lima and two of them installed in the city of Ica. Since a thorough examination of these ground motions is presented in Tavera et al. (2008), in the following a more general study of some of the recordings is presented.

From the 18 accelerometer stations mentioned above, only four recordings from the city of Lima and one from the city of Ica (located at approximately 150 km and 110 km from the epicentre, respectively) were available to the public by mid November 2007 at the website of the Peruvian-Japanese Centre of Seismic Investigation and Hazard Reduction (CISMID). These time histories were filtered and processed at Imperial College London as described in Tavera et al. (2008). Table 1.2 presents a summary of the maximum recorded accelerations for each orthogonal component at these stations, including some relevant characteristics as site conditions and the source-to-site distance computed adopting three different methods. Complementary, Figure 1.7 presents the E-W components of the five time histories presented in Table 1.2.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
POTENTIAL DAMAGE Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
ESTIMATED INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1.3 Intensity map generated using ShakeMap (Source: www.usgs.gov). The plot includes the fault rupture area (rectangle) and the epicentral location (star) estimated by the USGS

Figure 1.4 MMI intensity map generated by IGP (Source: www.igp.gob.pe)

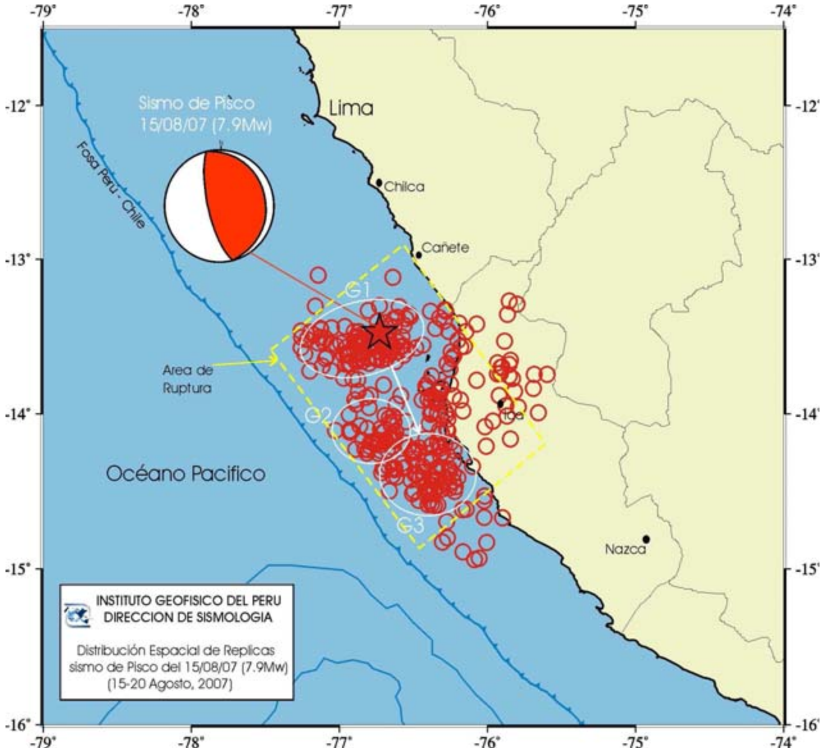


Figure 1.5 Aftershock distribution of events with local magnitude M_L equal to or larger than 3.0, recorded between the 15th and the 20th of August 2007. (Source: www.igp.gob.pe)

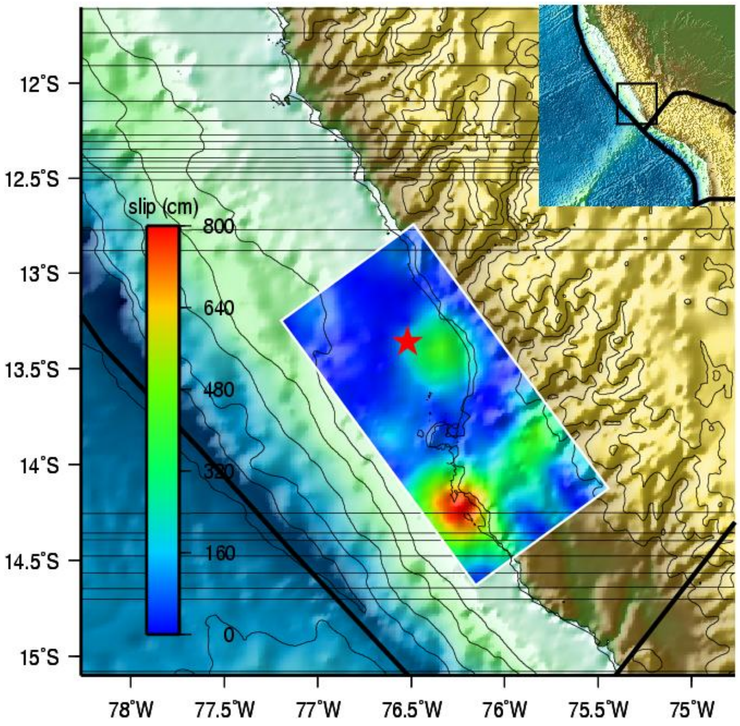


Figure 1.6 Earthquake slip distribution (Source: www.usgs.gov)

Table 1.2 Horizontal and vertical peak ground accelerations (PGA) values for the East-West, North-South and vertical recorded ground motions

Station	**CISMID (Lima)**	**San Isidro (Lima)**	**Callao (Lima)**	**La Molina (Lima)**	**Ica Univer. (Ica)**
E-W PGA (cm/s^2)	73.7	54.49	100.9	78.1	272.2
N-S PGA (cm/s^2)	59.98	57.88	58.41	18.46	334.1
Vertical PGA (cm/s^2)	32.58	32.21	31.7	56.21	192.2
Site conditions (NEHRP)	C	C	D	C	D
Site conditions V_{s-30} (m/s)	250	-	350	470	250
R_{epi} distance (km)	159	152	159	145	117
R_{jb} distance (km)	103	96	105	86	0.0
R_{rup} distance (km)	112.6	105	112	98	36.9

Notes: V_{s-30} values from Tavera et al. (2008). R_{epi} is the epicentral distance; R_{jb} is the Joyner-Boore distance definition; R_{rup} is the closest distance to the fault rupture (see Abrahamson & Shedlock, 1997).

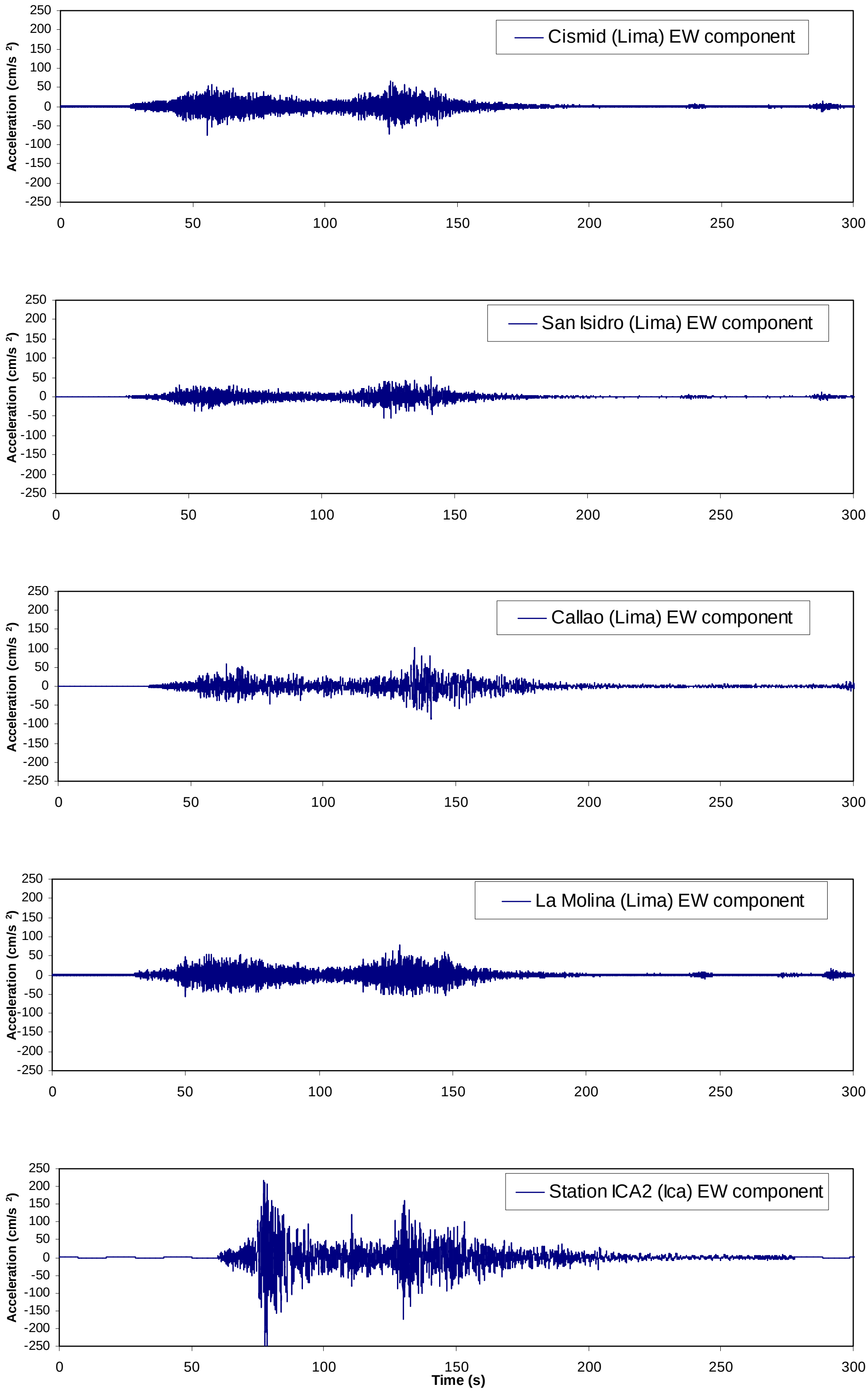


Figure 1.7 Strong ground motion recordings at CISMID, San Isidro, Callao, La Molina and ICA2 stations.

Two relevant features of the recorded time-histories are the length and the amplitude distribution in time of the ground motions. All recordings show total durations of approximately 160 seconds (about 2.6 minutes) with three sequences of motions: the first one lasting around 30-50 seconds (this duration varies from Lima to Ica recordings, with the latter ground motion having shorter duration), followed by relative uniform and smaller amplitudes that last 20 to 30 seconds, and a final sequence of larger motions. This particularity of the ground motions being distributed in two strong packs helped most of the population to evacuate their houses during the intermediate part of the shaking (see Section 12.1). The principal explanations for the duration and distribution of these ground motions are the rupture model having two zones of large displacements (which generated the two packs of motions) and the low fault rupture velocity, calculated at about 1.4 km/s, which is almost one third of the mean expected velocity in similar earthquakes (Tavera et al., 2008).

Figure 1.8 presents the peak ground acceleration (PGA) values according to a seismic zonation study published by the Geophysical Institute of Peru, for horizontal accelerations with 10% probability of exceedance in 50 years. From this map, the zonified PGA at Ica city is between 550 to 600 cm/s^2; the maximum recorded PGA at Ica during the 15 August 2007 event, equal to 334 cm/s^2, is slightly larger than half of the zonation value.

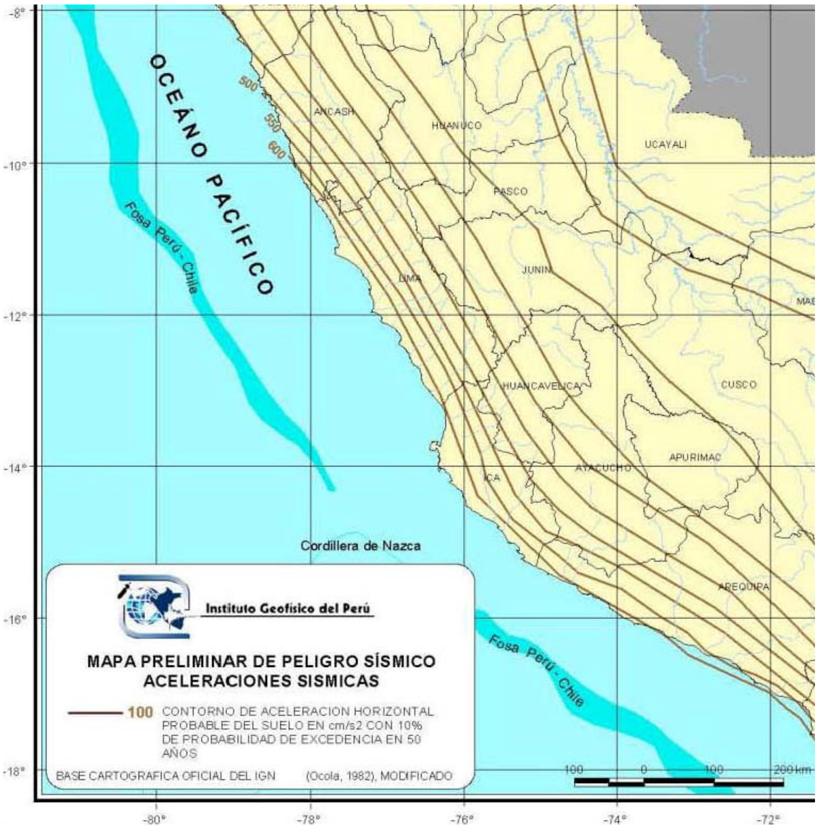


Figure 1.8 Peak ground acceleration (cm/s^2) zonation map (Source: www.indeci.gob.pe); no information was found about soil conditions for this map, but it is thought to be for rock sites

Figure 1.9 shows the response spectra of three of the ground motions recorded (two at Lima and one at Ica); the spectra for the N-S and E-W components are plotted for each station. These spectra are compared to those calculated using the Atkinson & Boore (2003) and the Kano et al. (2006) predictive equations, derived from databases for subduction events. Source-to-site distances and specific site conditions for prediction at each station were selected accordingly with the data consigned in Table 1.2 (e.g., following $V_{s\text{-}30}$ values for application into Kano et al. (2006); NEHRP site class for application into Atkinson & Boore (2003)). The comparison shows that independent of site conditions, the predictions at Lima tend to overestimate the results from the actual recordings, with the exception of the Atkinson & Boore (2003) predictions at large periods. With respect to the recording at Ica, Kano et al. (2006) predictions are larger by factors of 2 to 3, while the predictions using Atkinson & Boore (2003) equations are closer to the recorded motions at short periods, but are smaller at periods greater than 1 second. In view of the good prediction obtained at the ICA2 station, the Atkison & Boore (2003) response spectrum is employed in a structural back analysis presented in Section 5.2.3 for the collapse of a reinforced concrete board in the town of Pozo Santo, where short period responses are expected to be of relevance in the analysis.

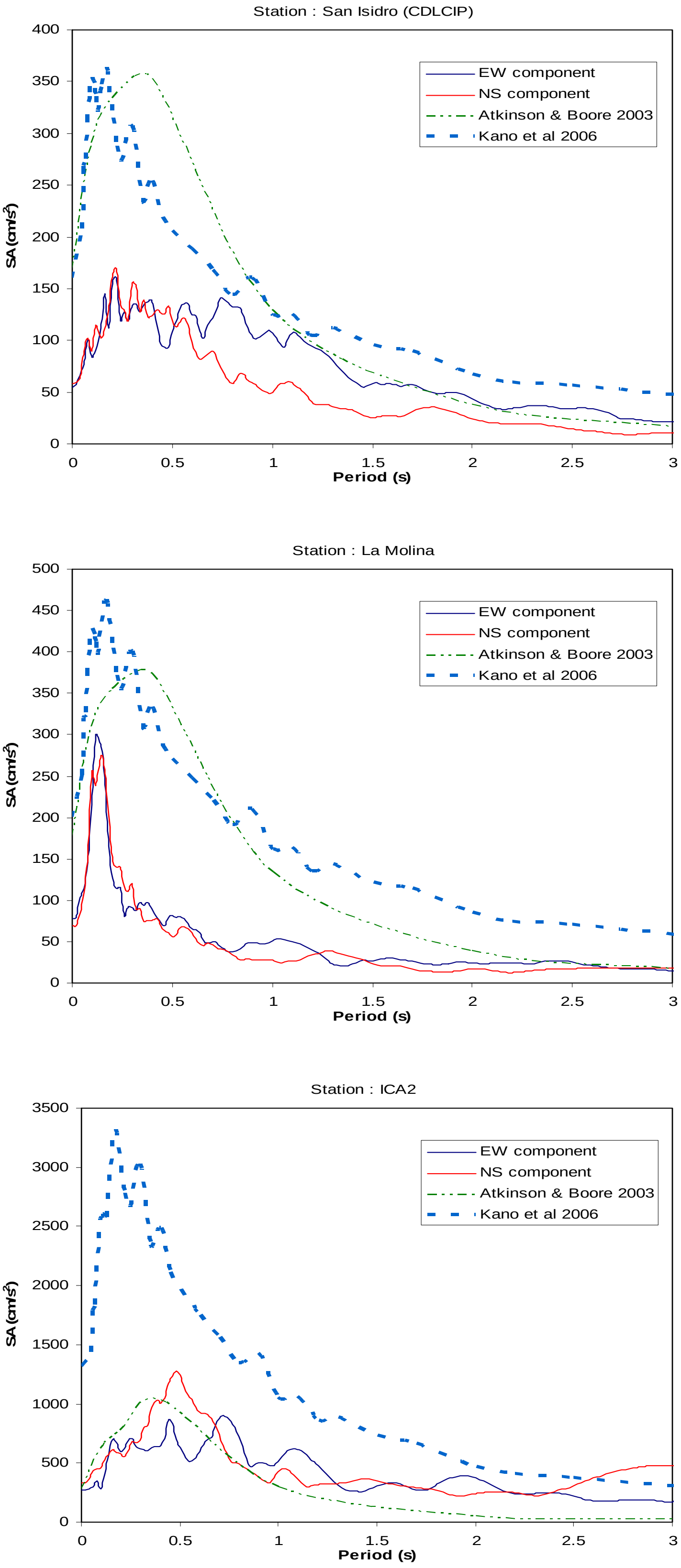


Figure 1.9 Comparison of recorded spectra at three stations with predicted spectra using the Atkinson & Boore (2003) and Kano et al. (2006) predictive equations. Note that scales are different in each plot

1.1 References

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CISMID, *Centro Peruano Japonés de Investigaciones Sísmicas y Mitigación de Desastres*, www.cismid-uni.org.

IGP, *Instituto Geofisico del Perú*, www.igp.gob.pe.

INDECI, *Instituto Nacional de Defensa Civil*, www.indeci.gob.pe.

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2 Earthquake Affected Region

Written by Dr John Alarcon, Arup

Reviewed by Zygmunt Lubkowski, Arup

The most severely affected area, which spreads between the Pacific Coast and the Andes, corresponds to a desert region with few small settlements located between larger agglomerations and cities. The areas visited during this EEFIT mission are shown in Figure 2.1 and listed in detail below (the number assigned to these areas does not correspond to the chronological order of the visit):

1. San Vicente de Cañete / Imperial
2. Chincha Alta / Chincha Baja / Tambo de Mora
3. Pisco / San Andrés
4. Paracas
5. San Martín (Puerto)
6. Pozo Santo
7. Ica / Guadalupe / El Carmen / San Juan Bautista
8. Lunahuaná
9. Zúñiga
10. Huangáscar

A summary of the number of inhabitants in some of the visited districts/cities is presented in Table 2.1. The information presented in this table is based on the national census carried out in 2005 (*Instituto Nacional de Estadística e Informática*, INEI), and the population shown corresponds to the number of inhabitants in the city/village and its suburban/rural areas. The districts that concentrate most of the population in the earthquake affected zone are, in decreasing order, Ica, Chincha Alta and Pisco.

The economy of the area visited is based on agriculture (mainly grapes and asparagus), wine production, fishing and its derived industry producing fish-flour for exportation, and tourism around the Nazca lines and the Paracas National Reserve (see Section 12.3).

Table 2.1 Population of some of the areas visited. Number of people includes city/village and suburban/rural areas belonging to the district (INEI, www.inei.gob.pe)

City/Village	Population	City/Village	Population
Chincha Alta	56,085	Pisco	54,193
Chincha Baja	12,052	San Andrés	14,134
Huangascar	724	San Vic. Cañete	43,943
Ica	117,939	Tambo de Mora	4,682
Lunahuaná	4,383	Zúñiga	1,194
Paracas	1,252		

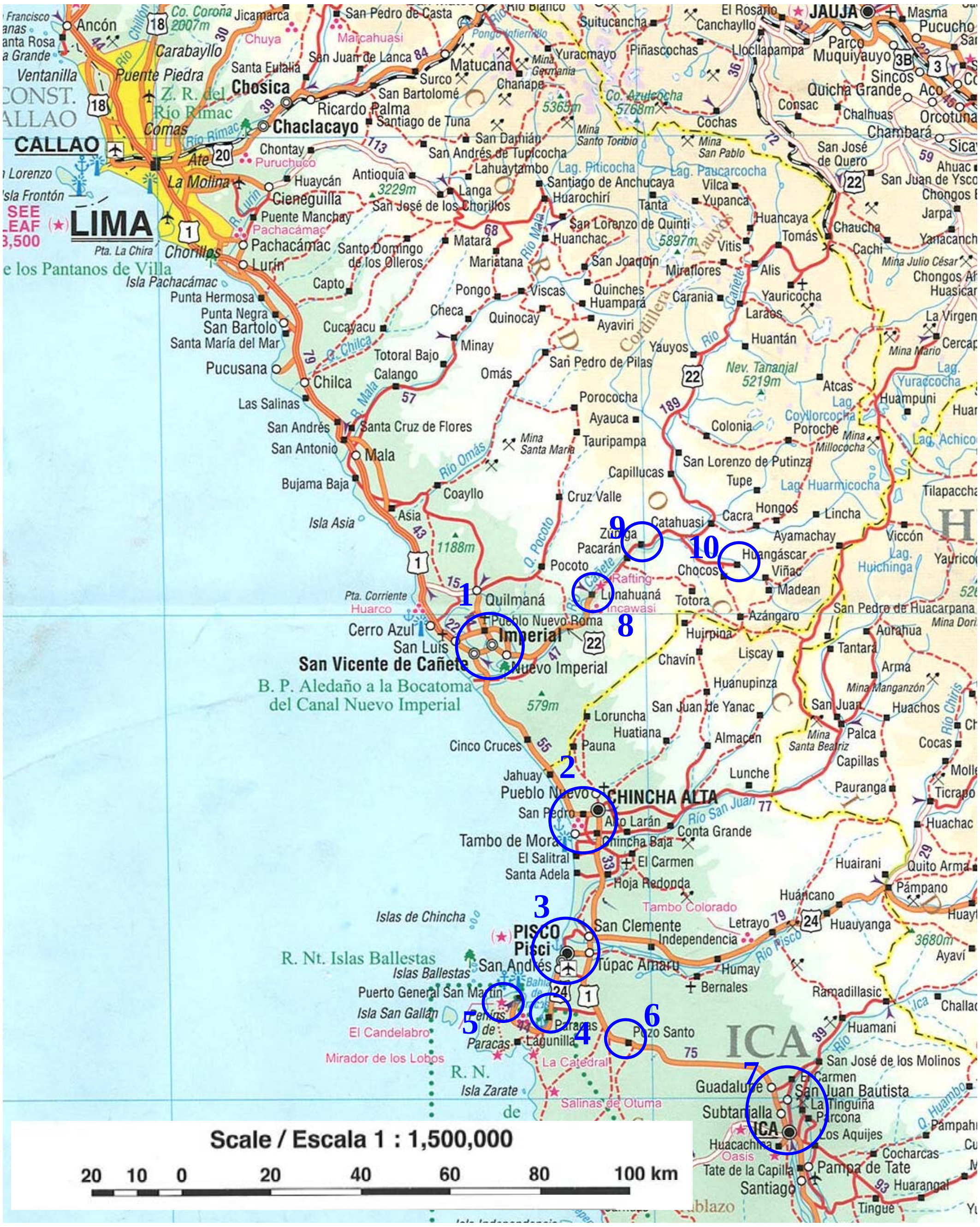

Figure 2.1 Areas visited during the Earthquake Engineering Field Investigation Team (EEFIT) mission to Peru (base map from ITMB Publishing Ltd). The entire area visited is within seismic zone 3 as prescribed in the Peruvian design code (see Figure 2.2)

The seismic resistant design code of Peru (Norma Técnica de Edificaciones E.030, 1997), divides the entire country into three regions, assigning peak ground accelerations of 0.15g, 0.30g and 0.40g for regions 1, 2 and 3 respectively (see Figure 2.2). These acceleration values correspond to ground motions with a probability of exceedance of 10% in 50 years (i.e., ground motions with a return period of 475 years). The area severely affected by the 15 August 2007 earthquake is classified as Zone 3 (see red strip in Figure 2.2); the maximum acceleration recorded at Ica (0.30g) corresponds to 75% of the design acceleration given by the Norma Técnica de Edificaciones E.030, 1997.

Figure 2.3 presents the geological map of the Ica region, on the top of which is marked the area visited during the EEFIT mission (bounded with a blue line). The figure shows that most of the area visited corresponds to Quaternary deposits (Qh-c).

Figure 2.2 Peruvian seismic zoning map for design (Norma Técnica de Edificaciones E.030, 1997)

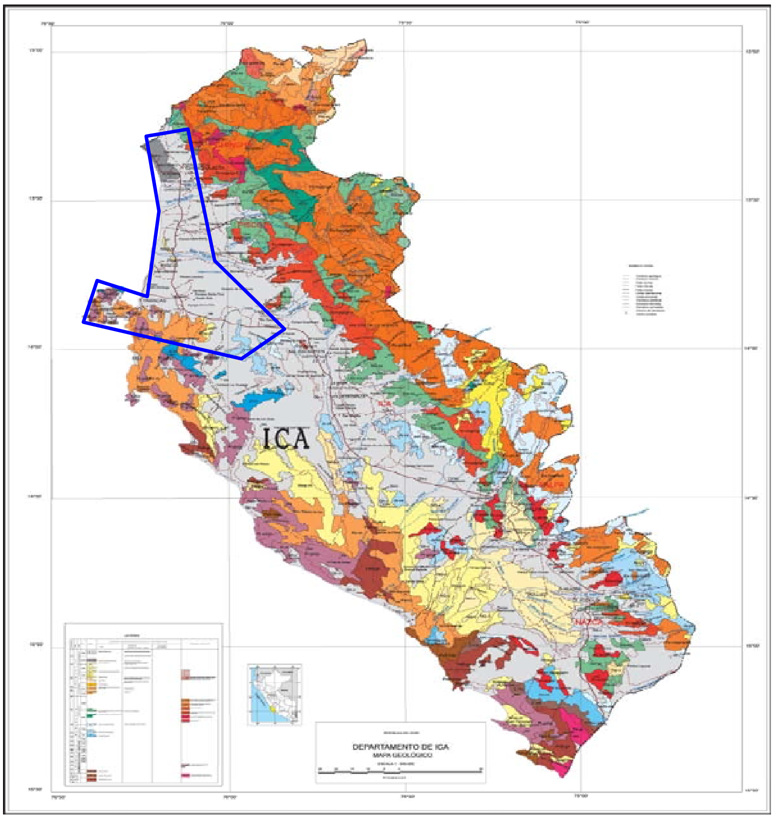

Figure 2.3 Geological map of Ica Department. A large portion of the visited area in this department (shaped in blue) corresponds to Quaternary deposits. (www.ingemmet.gob.pe)

2.1 References

INGEMMET. *Instituto Geológico Minero y Metalúrgico del Perú*, www.ingemmet.gob.pe

Norma Técnica de Edificaciones E.030 (1997) “Diseño sismorresistente - Reglamento nacional de construcciones”, *Ministerio de Transporte y Comunicaciones*, Lima.

3 Geotechnical Features

Written by Dr John Alarcon, Arup

Reviewed by Zygmunt Lubkowski , Arup

This section presents relevant geotechnical features observed during the EEFIT mission. These features include liquefaction, landslides and site responses.

3.1 Liquefaction

The western area of the town of Tambo de Mora (site number 2 in Figure 2.1) was severely affected by liquefaction. Even though the total area in which liquefaction occurred covers an area of approximately 2 km^2, the zone of housing affected covered an area of only 200x350 m, where the liquefied sand was observed inside houses and on the sides of the streets (Figure 3.1). Most of the structures affected correspond to 1 to 2 storeys high reinforced concrete (RC) confined masonry (Figure 3.2), which suffered settlements from 0.2 to 1.0 m relative to street level (Figure 3.3 and Figure 3.5). The paved road serving these houses was in good condition, with no evidence of severe damage (Figure 3.1), which lead to the conclusion that the liquefied stratum corresponds to a shallow layer removed/replaced during the construction of the streets, but left for the foundation of the houses. The street lamps toppled at the base to angles of up to 50° with respect to the horizontal plane (Figure 3.4). There were 5 deaths in the area and many people were able to escape from their homes as they exited after the first half of the ground motion (see Section 12.1). People commented that if they had not done so, they would have been trapped, since the second part of the ground motion was stronger, making the houses to settle dramatically. Liquefaction was also observed at the town jail, 2 km north of the housing zone severely affected (photos were not allowed to be taken for security reasons).

According to the inhabitants of the neighbourhood affected in Tambo de Mora, the area had experienced liquefaction in the past, in 1970 and 1974, with “water and sand coming from the earth”. Damage during those past events was light though, and no family was relocated as a measure of prevention.

The foundation details of these houses could not be inspected during the visit, but are expected to be similar to those observed in the neighbouring town of Chincha Alta (see Section 3.3). Since each house affected by liquefaction settled relatively uniformly, it may be concluded that these foundations correspond to shallow continuous footings. The large settlements observed suggest the occurrence of large cyclic stress ratios in the sand layer.

Figure 3.1 Liquefied uniform medium/fine size sand (note undamaged street to the left of the boat)

Figure 3.2 Houses in the area affected by liquefaction were mostly confined masonry

Figure 3.3 Large settlements reached values of approximately 1.0 metre

Figure 3.4 Street lamps toppled at the base up to approximately 50° with the horizontal plan

Figure 3.5 Large settlements reached values of approximately 1.0 metre

Figure 3.6 Liquefaction affected houses being demolished by the government

3.2 Landslides

Landslides were reported to occur along the Pan-American Highway, which extends from Alaska to Chile crossing Peru along its coast from North to South; this is the main highway of Peru. At the time of the EEFIT team visit, 22 days after the main event, the Pan-American Highway had been cleared from debris and entirely repaired. According to information received at the *Pontificia Universidad Católica del Perú* (PUCP), the area mostly affected was the stretch between Chincha Alta and San Clemente (see area limited in blue colour in Figure 3.7).

A section with slope instability was observed along the Pan-American Highway at approximately 10 km north of Cincha Alta (see point No.1 in Figure 3.7 and Figure 3.8). The landslide covered an area of approximately 50 x 10 m, affecting a soil mass (quaternary deposits of predominantly granular material) of up to 10,000 m^3. The largest vertical displacement of the scarp was measured at 0.4 m (Figure 3.9). Evidence of few shallow landslides was observed in the stretch between Chincha Alta and Pisco, but the material had been removed at the time of the visit.

A 4 metre high stone retaining wall that supported a 20 m stretch of the road between Lunahuaná and Imperial failed at approximately 2 km from Lunahuaná (Figure 3.7); tension cracks were evident on the road, which led to closure of one traffic lane.

On the last day of the mission, the EEFIT team travelled eastwards to the mountains in order to identify the boundary between areas of significant and minor damage. During this journey into the mountains the most common process of instability observed were debris flows and rock falls, such at those shown in Figure 3.11 and Figure 3.12. The rock fall given in Figure 3.11 hit the abutment of a pedestrian bridge, leading to the collapse of the structure (see Section 6.2). No evidence of deep landslides was observed during the field visit.

Figure 3.7 Stretch of the Pan-American Highway affected by landslides and soil failure of road structure (delimitated in dark blue colour). Points 1 and 2 (violet circles) show the location of landslides observed during the visit.

Figure 3.8 Scarp of landslide on the Pan-American Highway; two tension cracks are observed at the bottom of the picture

Figure 3.9 Detail of landslide scarp; the largest vertical displacement was measured at 0.4 m

Figure 3.10 Stone retaining wall failure close to Lunahuaná

Figure 3.11 Rock fall that hit the abutment of a pedestrian bridge crossing the Cañete river (see point No.2 in Figure 3.8 for location)

Figure 3.12 Debris and rock flow on the slope of mountains; most of the landslides shown in the photo were already there before the earthquake

Figure 3.13 Debris fall in the mountain area along the Cañete river valley

3.3 Foundation behaviour

Evaluation of foundations is rather complex since access to them is rarely possible; foundation failure is only observable in extreme cases when its failure is evident, which was not the case in any of the areas visited in Peru. Considering the structural typology of most of the structures observed during the visit, foundations can be assumed to be shallow with isolated poorly connected footings. Exceptions may be schools, hospitals and in general engineered structures. In the city of Chincha Alta (site No.2 in Figure 2.1) a foundation reconstruction process was observed in which the footings were joined with poorly detailed reinforced concrete (Figure 3.14). In general terms, such foundations did not suffer serious problems during the earthquake, with the exception of the liquefaction induced failures reported in Section 3.1.

Figure 3.14 Reconstruction of a house in Chincha Alta; individual footings are joined using poorly detailed reinforced concrete

3.4 Site effects

Site effects may be evident in the level of damage observed in the city of Pisco and the town of San Andrés. Besides political limits, the boundaries between these two agglomerations are indistinguishable and thus, from the spatial point of view, can be considered as one city. Damage in Pisco, especially in the central part of the city, showed a greater degree of damage than in San Andrés. This may be due to various reasons, such as age of constructions (being older in central Pisco), structural typology and quality of construction (being better in San Andrés), and more unfavourable site conditions in central Pisco, as shown by the hazard zonation map elaborated by the Peruvian National Civil Defence (INDECI) (Figure 3.15). Characteristics of the delimited zones are:

- Very high hazard (Zone a – red colour): soils with undrained strength capacities between 0.5 to 0.75 kg/cm^2 (about 50-75 kPa)

- High hazard (Zone b – orange colour): soils with undrained strength capacities between 0.5 and 1.5 kg/cm^2 (about 50-150 kPa)

- Intermediate hazard (Zone c – yellow colour): soils with undrained strength capacities between 1.5 and 2.0 kg/cm^2 (about 150-200 kPa).

The thickness of the soil deposits is not given in the information available at INDECI website, however, during a meeting with INDECI personnel it was mentioned that the deposits at the centre of Pisco were deeper than in the rest of the affected area.

It is important to note that the INDECI zonation map of Pisco summarises a broad group of hazards, including seismic hazard, tsunamis and floods caused by both heavy rains and river overflow. A more helpful way to identify and address each problem appropriately would be to plot and make available to the community and governmental institutions maps for each one of these natural events. Similar maps exist for Chincha (Figure 3.16) and Cañetes (not included in this report).

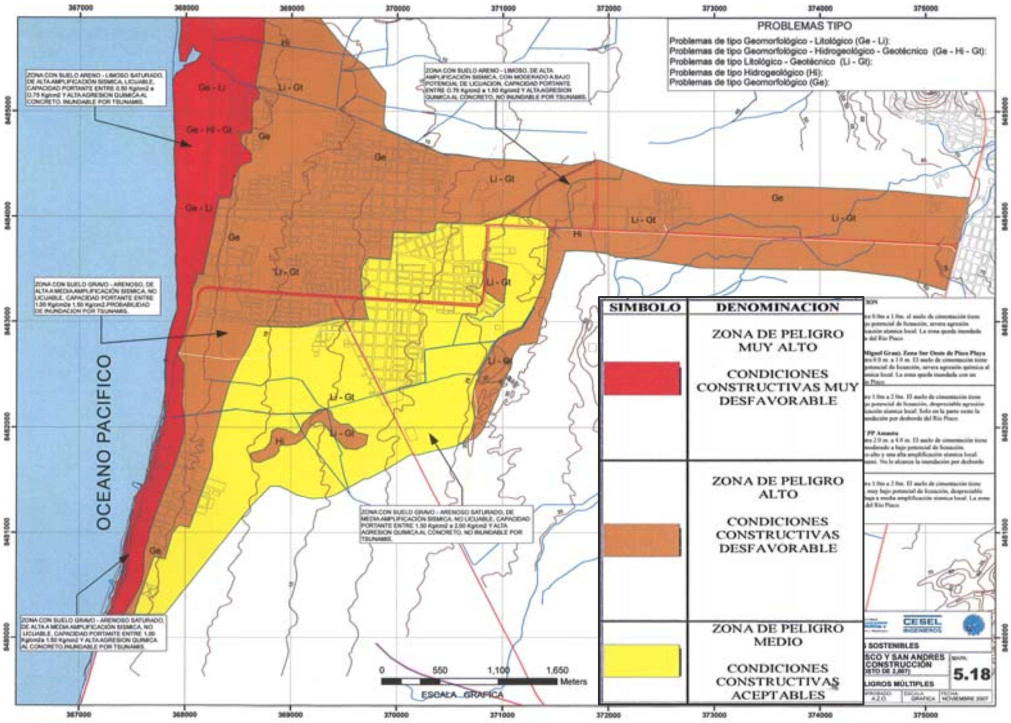

Figure 3.15 Hazard zoning map of the city of Pisco (source: INDECI); the map summarises hazard evaluation from earthquakes, tsunami and floods

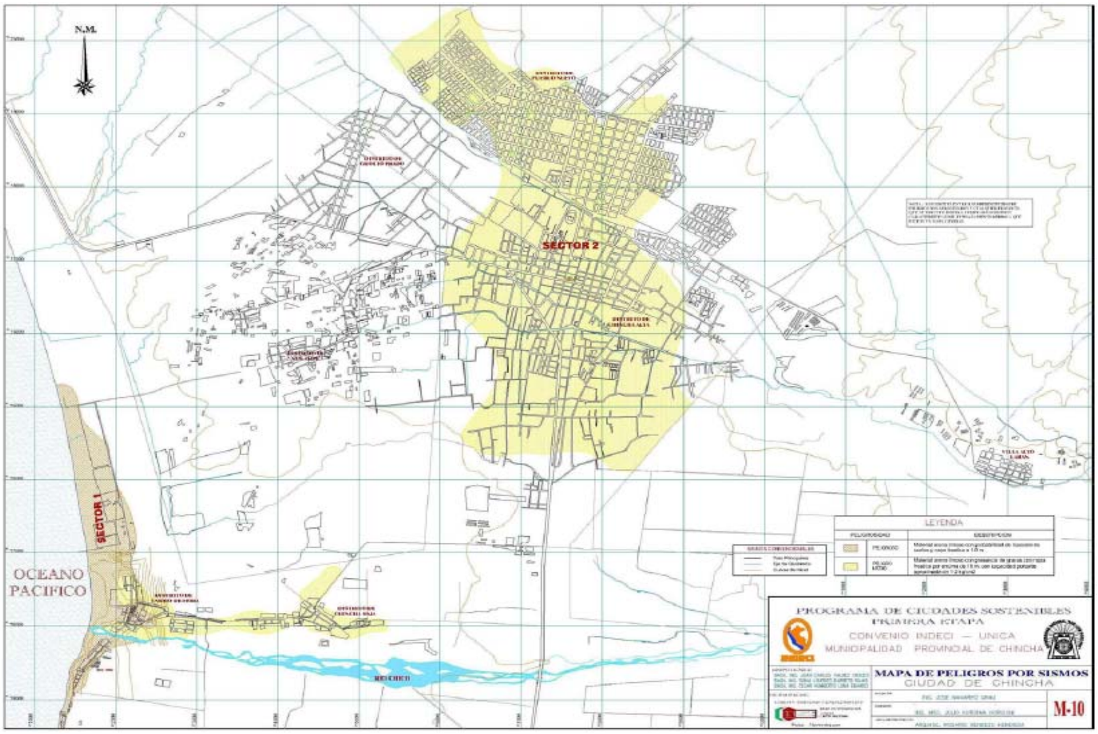

Figure 3.16 Hazard zoning map of the city of Chincha (source: INDECI)

3.5 References

INDECI, *Instituto Nacional de Defensa Civil*, www.indeci.gob.pe

4 Tsunami

Written by Fabio Taucer, Joint Research Centre / Dr John Alarcon, Arup

Reviewed by Zygmunt Lubkowski, Arup

Following the main event, a tsunami warning was issued for Chile, Colombia, Ecuador and Peru by the Hawaii Institute of Geophysics. The tsunami waves travelled as far as Japan, where heights of 0.5 m were recorded. Leaders of traditional fishermen unions from San Andrés creek in Pisco estimated that about 107 boats were damaged, 50 destroyed and 2,000 fishermen (about 17,000 families) affected as a consequence of the tsunami triggered by the earthquake (OCHA SR10, 2007).

Along the Peruvian Coast, the EEFIT team evidenced tsunami damage in Paracas (see point No. 4 in Figure 2.1), 20 km south of the city of Pisco, and at Tambo de Mora, where widespread liquefaction was observed as discussed in the preceding section.

Paracas is a tourist town with beach front restaurants and well constructed hotels and restaurants, mainly constructed if reinforced concrete confined masonry. Further south are holiday villas and a yacht club, where damage to a private jetty was observed, which shifted in the longitudinal direction and failed after developing hinges at the connections with the underlying piles (Figure 7.12); it was not clear whether damage to the jetty was due to the tsunami, the induced ground motions or both.

Figure 4.1 Tsunami water height in holiday villas at Paracas

Figure 4.2 Tsunami water height in holiday villas at Paracas

Figure 4.3 Tsunami damage at shore in front of holiday villas in Paracas

Figure 4.4 Tsunami damage at Paracas waterfront

Along the road next to the holiday villas of Paracas, there was very little visible structural damage, with only one wooden access-gate smashed due to water ingress and some damaged light structures for keeping boats; water marks were measured at 1.4 m with respect to the ground (approximately 2.5 m with respect to sea level), as shown in Figure 4.1 and Figure 4.2.

Locals in the town of Paracas recall a wave height reaching up to 1.6 m at the coast, which damaged a row of lightweight vendor stalls along the beach (the wave height was measured with respect to ground level at the vendor stalls). When the team visited the area, these stalls had already been reconstructed, as shown in Figure 4.6. Along the water front promenade of Paracas, opposite to where the vendors were located, water marks of up to 1 m were observed (with respect to the RC pavement of the waterfront); an underground fresh water cistern of a restaurant in front of the promenade was flooded with sea water. The local population informed the EEFIT team that the runup of the tsunami went as far as 200 m inland, though no clear evidence was observed.

Structural damage in Paracas included a jetty (larger than the one found at the yacht club) and cracking of the concrete pavement of the waterfront promenade (Figure 4.4 and Figure 4.5), including localised cracks in adjacent columns, while the building stock, composed mainly of 1-2 storey RC confined brick masonry houses showed only minor damage, with a few adobe houses suffering moderate damage. No deaths, collapses or heavy damage was reported to have occurred as a consequence of the tsunami.

Figure 4.5 Cracking of RC pavement/slab at Paracas waterfront

Figure 4.6 Reconstructed vendor stalls along the Paracas beach front

In Tambo de Mora, locals mentioned observing a tsunami wave height of approximately 2.5 m. The EERI tsunami reconnaissance team determined a maximum run-up of 10 m south of the Paracas peninsula occurring along unhabited areas (EERI, 2007).

4.1 References

EERI (2007) “Learning from Earthquakes – The Pisco, Peru, earthquake of August 15, 2007”, *Earthquake Engineering Research Institute*, Special Earthquake Report, www.eeri.org.

Hawaii Institute of Geophysics and Planetology, http://www.higp.hawaii.edu

OCHA Situation Report 10 (2007) “Peru Earthquake Report No. 10”, *United Nations Office for the Coordination of Humanitarian Affairs*, 24 August.

5 Performance of Structures

Written by Fabio Taucer, Joint Research Centre

Reviewed by Paolo Negro, Joint Research Centre

The damage sustained by building structures, especially residential, was the main cause of economic losses in the area affected by the earthquake. The description of the performance of building structures is introduced in this chapter by distinguishing two types of design situations: non-engineered and engineered structures. Whereas non-engineered structures were responsible for most of the damage observed, engineered structures performed satisfactorily, with the exception of buildings of low construction quality and non-conforming earthquake designs.

5.1 Non-Engineered

According to Arya (1994), “non-engineered buildings” are defined as those that are spontaneously and informally constructed in a traditional manner without any or little intervention by qualified architects and engineers in their design. These vernacular dwellings are proportioned based on experience and are mostly made out of wood, clay, concrete blocks, sun-dried clay bricks (adobe), field (or rubble) stone and brick, as well as combinations of locally available materials; cement, lime, or clay-mud are generally used for mortar compositions. A thorough description of this type of structures and their distribution in Latin America is given in Papanikolaou and Taucer (2004).

Most of the non-engineered houses in the area affected by the earthquake are made of adobe construction, usually located in rural areas outside large urban centres with characteristics that further contribute to their vulnerability (Lizarralde, 2000), namely:

- Lack of proper access roads to the rural areas;
- Lack of a wide coverage of public services;
- Lack of education of the residents (including high levels of illiteracy);
- Poverty of most of the population;
- Lack of political influence and social isolation in some cases;
- Difficulties in receiving information, and little access to knowledge;
- High risk locations, usually on slopes and in proximity to water resources (therefore prone to floods);
- Lack of building codes and construction supervision.

These issues are further discussed in Section 12.

For the purposes of the present report, non-engineered structures are classified as: traditional earth structures, masonry structures and infilled RC frames.

5.1.1 Traditional earth structures

There are three main types of traditional earth structures in the affected area:

- adobe, usually one storey high along the coast, and up to two stories in the mountain areas (Figure 5.9);

- a combination of adobe and *quincha*[1] at the second storey;
- *tapial* or *tierra pisada*[2]

Figure 5.1 Pisco historic waterfront: damaged adobe building with *quincha* at second storey

Figure 5.2 Pisco historic waterfront: adobe building with *quincha* exposed at second storey

Adobe structures are the most common type of earth construction in Peru; structures using *quincha* at the second storey are less frequent, being usually present in cultural heritage areas (Figure 5.1 and Figure 5.2) along the coast. Tapia structures, which are mostly used for the construction of boundary walls in rural areas, suffered damage from overturning, without causing injuries or substantial economic losses.

Figure 5.3 Collapsed adobe house in Ica

Figure 5.4 Debris of collapsed adobe houses in Ica

According to information received from INDECI, in the most affected areas (Pisco, Chincha Alta and Ica) approximately 80% of adobe houses collapsed (Figure 5.3 and Figure 5.4)[3], an outcome that was more than predictable in view of the lessons learned from previous disasters in Peru and worldwide (Eje Cafetero, Colombia, 1999; Bam, Iran, 2003; El Salvador, 2001), as well as from the research

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[1] In Peru, *quincha* consists of wooden frames in-filled with interwoven cane and coated with a mixture of mud (*barro*) and plaster, gypsum or sand combined with concrete on both sides.

[2] *Tapial* is constructed by erecting wooden or metal forms for the walls and filling them with a moist cement stabilized earth mix which is compacted by pounding with hand tools or with a mechanical compactor.

[3] INDECI informed that 85% of housing was damaged, while in the province of Ica, 60% of houses in poor areas had been destroyed (OCHA SR3, 2007).

carried out on the earthquake performance of adobe houses in universities across Latin America, especially in Peru, Colombia and Mexico

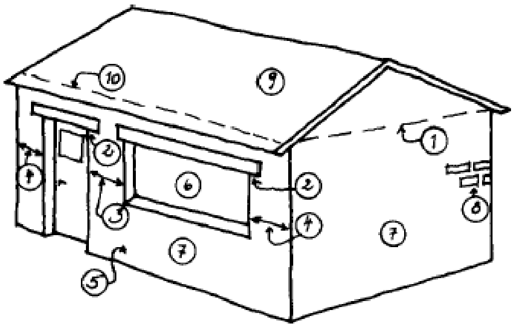
Adobe structures are constructed following traditional techniques using material and labour locally available, based on experience and in general without accounting for earthquake resistant design principles. The collapse of adobe structures is due mainly to the following factors:

- Heavy mass, thus inducing large inertial forces from the earthquake.
- Very low strength with respect to the density of the material (among the lowest of all construction materials).
- Failure of the material in a brittle manner, thus not allowing for energy dissipation and giving no warning to occupants before collapse.

Other factors or a combination of them, that contribute to the collapse of an adobe structure are:

- Low quality of construction, especially of mortar.
- Slender walls and long unsupported lengths.
- Large percentage of openings (windows and doors).
- Unstaggered brick arrangement at corners, thus leaving a clean joint between perpendicular walls.
- Flexible roofs and/or floors that offer no restraint to out-of-plane bending of walls, and absence of a ring-beam (Figure 5.6 and Figure 5.7)
- Heavy roofs (only in mountain areas; along the coast, due to the absence of rain, roofs are flexible and light) that increase inertial mass, thus leading to a higher the base shear.

A sketch summarizing the typical construction mistakes, which are held responsible for the partial or total collapse of earthen structures, as observed in the areas affected by the earthquake, is provided by Minke (2001) in Figure 5.5.



1. Ring beam is lacking.
2. Lintels do not reach deeply enough into masonry.
3. The distance between door and window is too small.
4. The distance between openings and wall corner is too small.
5. Plinth is lacking.
6. The window is too wide in proportion to its height.
7. The wall is too thin in relation to its height.
8. The quality of the mortar is too poor, the vertical joints are not totally filled, the horizontal joints are too thick (more than 15 mm).
9. The roof is too heavy.
10. The roof is not sufficiently fixed to the wall.

Figure 5.5 Graphical indication of the most common deficiencies found in self-built adobe houses (Minke, 2001)

Adobe houses typically fail by out-of-plane bending and overturning of walls, further accelerated by the demands imposed in the in-plane direction. No matter how well an adobe house is constructed (avoid the problems given in the second list of factors contributing to failure), an adobe house is bound to collapse in a sudden, brittle manner. Improving construction techniques, geometry, detailing and arrangement of walls (Figure 5.8, Figure 5.10 and Figure 5.11) only retards their collapse, as shown by some adobe houses, especially farther away form the epicentre, with lower storey heights (up in the mountains due to the cold weather) (Figure 5.12) and/or better quality construction (cultural heritage or haciendas, Figure 5.11 and Figure 5.13), that did not collapse or sustained only limited damage.

Figure 5.6 Flexible roof offers restrain in only one direction

Figure 5.7 Walls not restrained by the roof collapsed out-of-plane

Figure 5.8 Sturdier walls up the Cañete river valley in Zúñiga close to collapse

Figure 5.9 Two storey adobe house damaged in Huangáscar

Figure 5.10 Freestanding adobe wall near Guadalupe with lateral supports (or *machones*)

Figure 5.11 Manor in Lunahuaná showing walls laterally supported by *machones*

11 SEP 2007

Figure 5.12 Low height adobe houses up the valley of river Cañete showing no damage

11 SEP 2007

Figure 5.13 Historic hacienda in El Carmen showing limited damage

The only factor that prevents the collapse in a brittle manner of an adobe house is the inclusion of reinforcement, either in the form of bamboo rods inserted inside of walls or as steel or polyester nets tied and plastered onto the surface of walls, as described in Section 5.2.1, that hold together the adobe bricks and provide for ductility and energy dissipation.

5.1.2 Masonry structures

Masonry structures have been included in the list of non-engineered structures as their large majority was built prior to the existence of modern construction codes. These structures correspond mainly to cultural heritage and official buildings, and are mostly found near the central squares of cities and towns.

The masonry structures of the areas visited are built from clay bricks, usually with elaborate facades and arches at the front. Apart from a few collapses, such as the one described in the last paragraph of this section, these structures showed medium to light damage.

The performance of masonry structures was somehow satisfactorily due to the following reasons:

- The quality of construction of these structures, owing to their institutional or cultural importance, is in general higher than that of standard buildings.
- The walls of these buildings have in general a large thickness and thus provide a larger out-of-plane resistance.
- These buildings have rigid roofs and/or slabs that act as a rigid diaphragm restraining the out-of-plane displacements of walls.

In spite of the good performance observed, it is possible to say that had the earthquake ground motion been higher at the visited locations, these structures would have inevitably collapsed in a brittle, sudden manner.

At the Plaza Mayor in Ica, a large institutional building of masonry construction with a series of arches at the front was reported with no damage along one of the sides of the square (Figure 5.14), whereas at the opposite side of the square, the same type of building (probably of newer construction, as evidenced by the larger, square windows) had failed at the corner (Figure 5.15), probably due to pounding from an adjacent, taller RC building, confirming the brittle mode of failure of these structures.

Figure 5.14 Masonry structure in Plaza de Armas, Ica, showing no damage

Figure 5.15 Severely damaged masonry structure in Plaza de Armas, Ica, at corner next to a RC building (Photo: Dr. Ing. Jorge E. Alva Hurtado, *Universidad Nacional de Ingeniería,* Peru)

5.1.3 Infilled reinforced concrete frames

Infilled RC frames included in the category of non-engineered structures correspond to those buildings non-conforming to earthquake resistant design standards; this type of structure is common in Northern South American countries (e.g., Venezuela and Colombia), where adobe construction is no longer part of traditional construction practice and has been replaced by the local population for RC frames with hollow clay infill bricks used without qualified assistance.

Figure 5.16 RC infilled confined brick masonry house in Guadalupe

The factors that can make infilled non-engineered RC frames highly vulnerable to earthquakes are:

- Irregular designs both in height and in plan, resulting from using the first storey as parking or commerce, or from the sequential addition in time of new portions of the house, with non-coincident or discontinuous beams and columns, and abrupt changes in stiffness and mass.
- Poor detailing, in particular insufficient stirrups and splicing lengths of reinforcement, resulting in inadequate shear and flexural capacity, as well as in limited confinement, thus rendering the structure brittle with low energy dissipation capacity.
- In contrast to adobe houses that are in general one storey high, infilled RC structures easily reach two or three storeys and have heavy slabs, which induce large shear loads at the base, making this type of structures extremely vulnerable and leaving little time for occupants to escape in the event of an earthquake.

In the region visited, very few of this class of structures were found and no collapses were observed. The low number of RC infilled frames in the Peruvian building stock is due to the fact that building owners with limited economic means can only afford adobe construction, whereas families higher in the economic scale often choose to build with RC confined brick masonry with the assistance of qualified engineers, although the low quality of some constructions (Figure 5.16) may lead to conclude that in many cases no qualified assistance had been provided. However, since most of the RC confined masonry structures performed well, even those that may had not been designed by an engineer, they are included in Section 5.2 as engineered structures.

5.2 Engineered

Engineered constructions make up only a fraction of the total number of houses of the Ica region, and are concentrated in the major cities of Ica and Pisco. This type of structures performed in general satisfactorily, apart from a few cases described in Section 5.2.3.

Earth structures constructed for earthquake resistance are included in this section, as they are designed by qualified engineers, even though in many cases some of the principles adopted may not be contained in the provisions of current construction standards in Peru.

5.2.1 Earthquake resistant earth structures

During the field reconnaissance, a few examples of adobe houses designed or upgraded for earthquake resistance prior to the disaster event were found in the towns of Guadalupe, Zúñiga and Huangáscar, all performing satisfactorily during the earthquake.

Figure 5.17 Adobe house in Guadalupe upgraded with steel net reinforcement plastered to the exterior and interior surface and showing good performance

Figure 5.18 Collapsed right corner of the adobe house shown in Figure 5.17 (not upgraded due to insufficient funds)

Nearby Ica, in the town of Guadalupe, an adobe house was upgraded by the *Universidad Pontificia Católica del Perú* (PUCP) by means of strips of steel net tied and plastered to the exterior and interior surfaces of the adobe walls (Figure 5.17) (San Bartolome et. al, 2004); the house exhibited good performance after the earthquake, with the only portion of the wall not upgraded (due to insufficient funds) collapsing out-of-plane (Figure 5.18). The technique used in retrofitting this house was developed at PUCP; Figure 5.19 and Figure 5.20 show ongoing research where a polymer mesh (similar to the type used for stabilising soil) is used in place of a steel net, with the purpose of achieving a more ductile design (Blondet et al., 2006). It is interesting to note that most dwellers of adjacent streets to the upgraded house knew about “the house that resisted the earthquake”.

Figure 5.19 Detail of polymer (left) and steel (right) nets used for reinforcement of adobe walls

Figure 5.20 Reinforcement of adobe walls with nylon net at the laboratory of PUCP

In the town of Zúñiga a new two-storey house built by the Japan International Cooperation Agency (JICA) resisted the earthquake with minor damage (Figure 5.21), apart from some cracks that developed at the corners of window openings at the second storey *quincha* walls. The design features that contributed to the good performance of the house were: well constructed thick adobe walls, *machones* (thicker portions of the wall) spaced at short intervals and at corners, a rigid wooden roof connected to all walls through a wooden ring-beam, a rigid slab foundation at the base, and, although not verified in the field, bamboo reinforcing rods running inside the adobe walls. It is worth noting that nearby houses of traditional adobe construction did not suffer significant damage, probably because of weaker ground motions due to attenuation effects or from better ground conditions, as well as due to the lower height of the adobe walls of these constructions.

Figure 5.21 Two-storey adobe (and *quincha* at second storey) built by JICA in Zúñiga for earthquake resistance

Figure 5.22 Adobe house in Huangáscar built by JICA and designed for earthquake resistance

Other adobe houses designed with earthquake resistant features were found in the village of Huangáscar: a first group of two storey houses similar to that visited in Zúñiga was found at the entrance of the village, whereas a second house, at the centre of the village, was constructed with closely spaced *machones* providing lateral support to the walls (Figure 5.22). While these houses were built by JICA and performed satisfactorily during the earthquake, other nearby houses of adobe traditional construction in Huangáscar were severely damaged (Figure 5.9).

5.2.2 Reinforced concrete confined masonry

Most of the engineered houses found in the affected area were of reinforced concrete confined brick masonry. This type of construction consists in constructing first the clay brick walls while leaving an empty space for placing the reinforcement; concrete is then poured with wooden formwork nailed to the exterior and interior surfaces, thus obtaining a solid joint between the RC frame and the clay bricks. In this way the wall structure provided by the clay bricks, which is stiffer than the frame structure of the RC elements, shares most of the lateral load of the structure. The construction procedure of this type of structures is show in Figure 5.23.

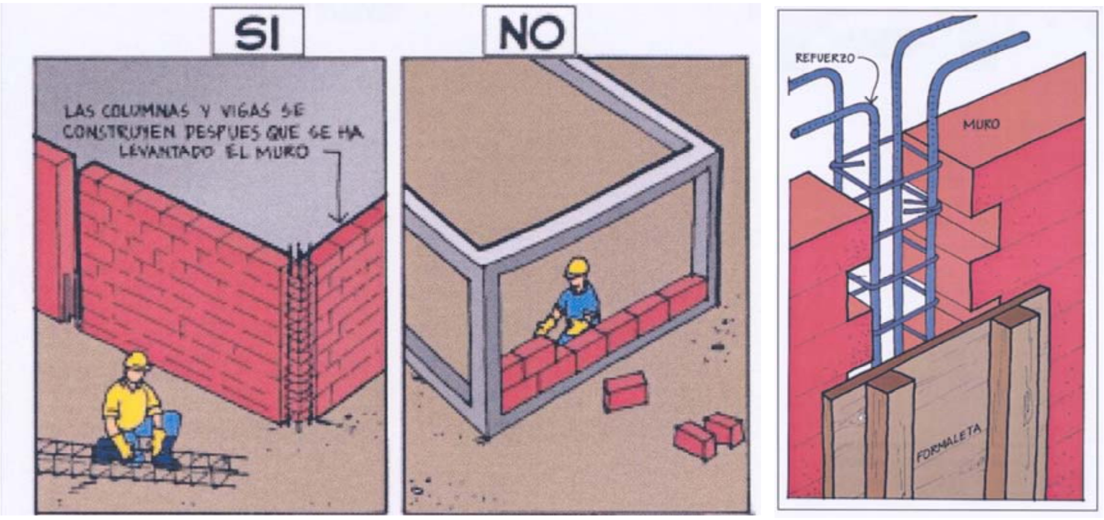


Figure 5.23 Construction procedure of confinement elements (AIS, 2001)

RC confined masonry structures performed very well during the earthquake, with minor or no damage, as shown in Figure 5.24, where a two storey building standing next to a collapsed adobe house shows no signs of damage in its tile covered façade.

Figure 5.24 Undamaged two storey RC confined masonry building next to a collapsed adobe house in Ica

Figure 5.25 Six-storey RC confined masonry building in Ica, showing no signs of damage

The good performance of RC confined brick masonry houses, which may reach a height of up to six storeys (Figure 5.25), may be explained by the inherent large capacity of the structure to resist lateral loads. However, these structures, when reaching their ultimate capacity after failure of the clay brick masonry walls, may form soft storey mechanisms if not properly detailed and designed. It is possible that this type of failure may have developed in many buildings had the ground motions been higher in the affected areas, especially for structures with low construction quality. Therefore, it is recommended that the complete load displacement path of these structures up to failure is carefully examined, assessing the level of energy dissipation that they can provide and the associated type of failure mechanism.

5.2.3 Reinforced concrete infilled frames

Reinforced concrete infilled frames are most commonly found in the largest city centres of Pisco and Ica, as multi-storey residential, commercial or office buildings. Only a small number of these structures were observed in the visited areas, and many were under construction. In RC infilled frames, infill panels are placed in the structure after casting the RC frame elements, thus differing from RC confined masonry structures in that the contribution of the infill panels to lateral resistance is limited, conferring only to the RC frame elements the main role of resisting earthquake loads. In general, RC infilled frames performed satisfactorily, apart from a few cases listed in the following paragraphs. Hospital and schools of RC infilled construction are described in Section 10.

One of the worst collapses associated to RC infilled frames was that of the Embassy Hotel, located in Pisco, following the formation of a soft storey mechanism (Figure 5.26); prior to the earthquake, the structure had been expanded with additional floors. The collapse was responsible for several casualties and at the time of the survey the structure had been demolished and removed (Figure 5.27). A building adjacent to the hotel was severely damaged, as reflected by the failure in shear of several columns at the first storey with practically no shear reinforcement (Figure 5.28).

Figure 5.26 Collapsed Embassy Hotel in Pisco (Photo Prof. M. Blondet, PUCP, www.eeri.org/lfe/images/peru_coast_photos)

Figure 5.27 Severely damaged RC infilled frame next to the collapsed Embassy Hotel

Figure 5.28 Detail of column failure in shear of the building structure of Figure 5.27

In Figure 5.29 a four-storey RC infilled structure that collapsed after developing a soft storey mechanism is shown, possibly due to the reduction of flexural capacity in the column from the first to the second storey, or to deficient detailing of the beam-column connection as shown in Figure 5.30.

Figure 5.29 Four-storey RC infilled frame in Pisco showing soft storey collapse at 2nd floor

Figure 5.30 Detail of column failure from the building shown in Figure 5.29

Examples of buildings under construction are shown in Figure 5.31 and Figure 5.32: the first figure shows an irregular vertical geometry arrangement that caused extensive yielding of the column at the second, soft storey; whereas the second figure shows a five-storey building with flat-slab beams running in the direction parallel to the street and that may had suffered extensive damage if it had not been properly detailed.

Figure 5.31 Six-storey RC infilled frame in Pisco with vertical irregular geometry showing soft storey damage

Figure 5.32 Five-storey RC building frame with flat-slabs under construction in Ica

All the RC infilled frame structures described above (with the exception of the flat slab structure) failed for one or more of the reasons listed in Section 5.1.3 (factors that make non-engineered RC infilled structures vulnerable to earthquakes). It may also be possible to assert that the deficiencies in earthquake resistance were more due to the absence of qualified engineers and appropriate controls during construction than to old designs, as demonstrated by the damages sustained by newly constructed buildings.

Back calculation of spectral accelerations at Pozo Santo

During the field visit, the EEFIT team found several RC billboard structures inifilled with clay bricks: one near the Paracas National Reserve (Figure 5.33), which suffered practically no damage, and one at Pozo Santo, approximately 25 km southeast of Pisco, which collapsed (Figure 5.34) and is used in the present report to perform back calculations to determine the ground accelerations sustained at the site. It is worth mentioning that the adjacent structures located at Pozo Santo suffered heavy damage, including a church (Figure 5.40) and several one-storey adobe structures.

Figure 5.33 RC infilled frame billboard near the Paracas National Reserve

Figure 5.34 RC infilled frame billboard that collapsed at Pozo Santo

The geometry of the billboard at Pozo Santo was measured on site: a 250 mm thick, 7 m in length and 4.7 m in height rectangular section of clay bricks bounded by 250 mm deep RC elements along the perimeter, supported by four 250x250 mm cross section 1.05 m free standing RC columns (Figure 5.35); in the longitudinal direction the columns were linked by a stiff 500 mm deep RC beam.

Figure 5.35 Overall view of the collapsed billboard at Pozo Santo, showing four 250x250 mm 1.05 m RC columns

Figure 5.36 Detail of the RC columns of the Pozo Santo billboard, showing 12 mm diameter steel rebars with practically no confinement

The collapse mode of the billboard shows that failure took place at the boundary between the top of the free standing columns and the longitudinal deep beam, suggesting that the damage of the structure started in the longitudinal direction (in-plane) followed by overturning of the structure in the transverse direction (out-of-plane)[4]. From the geometry, materials and collapse mode of the structure, it is possible to infer the spectral accelerations that occurred at the site. This is done by computing the base

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[4] Had the collapse been triggered in the transverse, out-of-plane direction, failure would have occurred at the base of the columns, where bending moment is maximum.

shear associated to the development of the flexural capacity at the top of columns, assuming that the longitudinal beam is infinitely stiff and the inflection point is located at 1/4 of the height of the columns with respect to the base, reflecting the condition of a flexible foundation.

The flexural capacity[5] of the column is calculated as 18.7 kN-m, assuming a concrete compressive strength f_c of 25 MPa and a steel yield strength f_y of 420 MPa (60 ksi steel), with steel rebars 12 mm in diameter located at the four corners of the cross section (see Figure 5.36); the concrete covers vary between 40 mm and 20 mm (the larger cover is used in the bending moment calculation).

By dividing the flexural capacity of one column by 0.75 times its free height (equal to 0.79 m), and by multiplying the result by four columns, a base shear of 94.7 kN is obtained for the structure in the in-plane direction. By dividing the base shear by the total mass of the structure, equal to 16,000 kg (calculated assuming a clay brick density of 1,800 kg/m^3, a RC density of 2,500 kg/m^3, and neglecting the mass contribution of the free standing columns), a spectral acceleration of 0.60g is obtained.

In order to relate the spectral acceleration causing failure in the in-plane direction with the response spectrum of the earthquake ground motions at the site, it is necessary to obtain the mode of vibration of the structure in the longitudinal direction, which is computed from the stiffness of the structure and the mass of the billboard used in the base shear calculation. The stiffness of the structure was calculated assuming a Young modulus E_c of 30 GPa and a cracked moment of inertia of the columns equal to half their gross moment of inertia, resulting in a stiffness equal to 11,5700 kN/m. Based on these assumptions the first mode of vibration in the longitudinal direction is equal to 0.074 s.

The elastic 5% response spectrum predicted by the Atkinson and Boore (2003)[6] equations at Pozo Santo for stiff soil conditions shows that the periods for which spectral accelerations can induce failure in the in-plane direction are between 0.15 and 0.43 seconds (Figure 5.37), the lowest bound not being too dissimilar from the value of 0.074 s obtained from the above calculations.

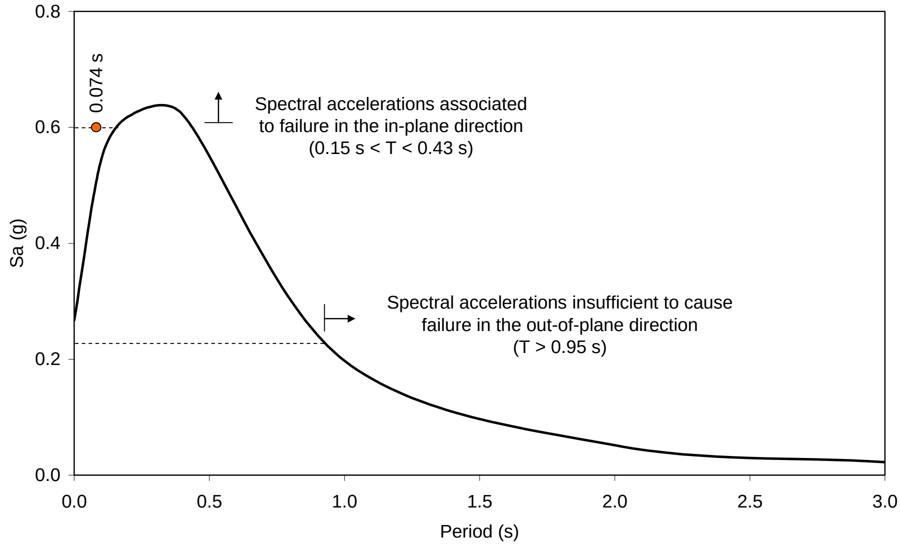

Figure 5.37 Predicted 5% response spectrum at Pozo Santo, using Atkinson & Boore (2003) equations with NEHRP class C (stiff soil) site conditions.

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[5] Shear failure was not considered as a possible cause of collapse, as the shear capacity of each column, computed according to EC2 with no contribution of shear reinforcement, is equal to 42.5 kN, requiring a shear span of 0.44 m, shorter than that considered in the calculations, for shear to command with respect to bending in the failure mechanism.

[6] The Atkinson and Boore (2003) equations predict the response spectrum based on magnitude, epicentral distance and soil conditions, and were used following the good results obtained in predicting the response spectrum of the ground motions recorder at the ICA2 station (See Figure 1.9).

In spite of the longer lever arm (3.83 m, at 2/3 of the total height of the structure) and higher period of vibration (on the order of 0.2 s) of the structure in the transverse direction, the fact that failure was not triggered in the out-of-plane direction may be explained by an elongation of the period due to rocking of the foundation to values above 0.95 s, that together with the associated energy dissipation, may had resulted in spectral accelerations below 0.12g[7] (Figure 5.37), which is the minimum spectral acceleration that would had induced failure at the base of columns in the transverse direction.

The back analysis shows that the ground motions recorded by the accelerometers located in the affected area (i.e., ICA2 station) are compatible with the damage sustained by the billboard, and that in the absence of base acceleration recordings, the collapse or failure of simple structures can be used to derive an estimate of the ground motions at the site, provided that reliable attenuation functions are available at the site.

5.2.4 Steel

Not many steel structures were found in the area, the few cases corresponding to warehouses, sheds and adjacent installations to industrial plants (see Section 9).

Since the team did not have access for a close inspection to these structures – located in industrial plants – it is not possible to make a conclusive statement whether any structure had suffered from local buckling or extensive yielding. The only case where damage was observed was to a truss structure in the Port of San Martín, where one member showed overall buckling without compromising the stability of the structure. Otherwise, the EEFIT team did not observed any global collapses of steel structures.

5.2.5 Prefabricated

As for the steel structures, not many prefabricated structures were found in the area, being the most common type those corresponding to industrial warehouses. No particular damage was observed on these structures during the field mission.

5.3 Churches

Figure 5.38 Location of the collapsed church in Pisco after demolition and debris removal

Figure 5.39 Typical collapse of a *quincha* vaulted roof of a church in Zúñiga

The large majority of churches surveyed during the field mission sustained considerable damage after failure of the roof (Figure 5.39 and Figure 5.40), longitudinal walls (Figure 1.1) and tower bells (Figure

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[7] 0.12g is obtained by multiplying 0.6*g* by the ratio of the lever arms in the longitudinal and transverse directions (0.79 m /3.83 m). When working with the 5% damped spectra, this value is increased by a factor of 1/0.55, where 0.55 is the maximum reduction of the 5% elastic spectra allowed by EC8 to account for higher levels of damping; the 5% damped spectral acceleration thus obtained is equal to 0.22*g*.

5.41), causing not only a large number of casualties, but also an important loss in the cultural heritage of the region (see Section 12.3.2).

The church of San Clement of the Compañía de Jesus, in front of the Plaza de Armas in Pisco, collapsed during a mourning service at the time of the earthquake event, causing the single largest death toll of any structure during the earthquake (Figure 5.38).

The deficient performance of these structures calls for an extensive effort of earthquake performance assessment and upgrading, where required, of those churches that did not collapse or where only lightly damaged during the earthquake event.

Figure 5.40 Church front remains of a collapsed church at Pozo Santo

Figure 5.41 Tilted bell towers of a church next to Plaza de Armas in Ica

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6 Performance of Bridges

Written by Emily So, University of Cambridge / Fabio Taucer, Joint Research Centre

Reviewed by Prof. Robin Spence, University of Cambridge

The description of the performance of bridges has been divided in the present chapter into road and pedestrian bridges. Overall, bridge structures performed quite well during the earthquake, with the exception of the Huamaní Bridge in San Clemente, described in Section 6.1.1, and a footbridge bridge described in Section 6.2.

6.1 Road bridges

Stretches of the Pan-American Highway, Peru's main coastal artery, were interrupted due to landslides and ground settlements (see Section 3.2) north of Chincha Alta, and to damages sustained by the San Clemente Bridge at the crossing of the Pisco river; journey times from Lima to Pisco were reported to have increased from 3 to 8 hours in the aftermath of the disaster. At the time of the EEFIT field visit, all landslide and ground settlement related damages had been repaired, while an alternative temporary route across the dry bed of the Pisco river had been constructed next to the Huamaní Bridge.

In spite of the low number of bridge structures present in the visited areas along the coast and in the valleys of the Ica region (i.e., the terrain arid and mostly flat, with low hills and sand dunes), the EEFIT team observed about 10 road bridges of various sizes, which, with the exception of the Huamaní Bridge, performed quite satisfactorily, as shown in Figure 6.1 and Figure 6.2 by two undamaged bridges at two crossings of the Ica river in the city of Ica.

Figure 6.1 First RC bridge crossing the Ica river in the city of Ica

Figure 6.2 Second RC Bridge crossing the Ica river in the city of Ica

6.1.1 Huamaní Bridge in San Clemente

The Huamaní Bridge in Clemente Bridge is a five span reinforced concrete motorway bridge located at km 228 along the Pan American Highway linking the town of San Clemente to Pisco, with a total length of approximately 150 m (Figure 6.4). The two main roadways of the earthquake affected area, namely the Pan-American Highway and the Carretera los Libertadores, cross at the town of San Clemente (Figure 6.3).

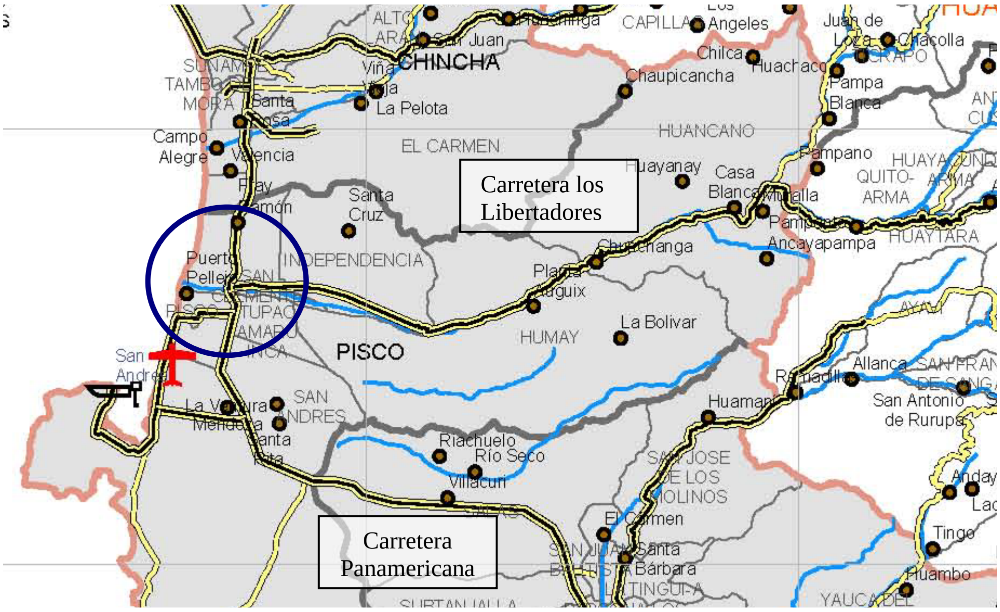

Figure 6.3 Road network around the earthquake affected area, showing the Pan-American Highway and the Carretera los Libertadores, crossing at the town of San Clemente (Source: www.reliefweb.int)

The superstructure of the bridge is continuous, with pinned connections symmetrically located at the second and fourth spans. The bridge deck, 0.3 m thick, is supported by three 0.6x1.3 m RC girders running in the longitudinal direction and connected by transverse beams. A relative displacement of 10 cm was observed between the two portions of the superstructure at the south pinned connection, resulting in local damage to the deck from the pounding action (Figure 6.5). Slightly lower displacements, of approximately 5 cm, and local damage, were observed at the north pinned connection. Underlying utility pipes running in the longitudinal direction of the bridge showed transverse displacements at the pinned connections, whereas the south section of the deck revealed a permanent clockwise rotation (vertical positive axis), damaging the west parapet of the south abutment (Figure 6.6). The failed portion of the abutment showed large rounded aggregate, which could have compromised the strength of the concrete of the abutment (Figure 6.7). No damage was observed on the surface of the deck itself, or on the longitudinal girders supporting the bridge, apart from some minor cracking of the traverse beams.

Apart from the abutments, the largest damage sustained by the bridge was at the second northernmost pier, where both parapets, each with a section varying from 0.55 to 1.3 m in the transverse direction and 1.2 m in the longitudinal direction, failed in shear in the transverse direction (Figure 6.8). The main reinforcement (12 mm diameter rebar spaced at 0.35 m) of the parapets showed insufficient shear reinforcement and confinement (8 mm diameter links spaced at 0.22 m), and was sheared off at the level of the bearings supporting the deck (Figure 6.9). The damage to the parapet may have been caused after pounding from the exterior longitudinal girders, resulting from sliding of the superstructure, supported over steel roller bearings, in the transverse direction with respect to the pier.

From the damage sustained by the parapet of the second northernmost pier, it may be possible to back calculate the spectral accelerations sustained at the site of the bridge, based on the force that induced sliding of the roller bearing with respect to the pier. By assuming a static coefficient of friction between steel and concrete equal to 0.45, the calculated spectral acceleration equals 0.45g, which is compatible with the spectral accelerations given in Figure 1.9 for the ICA2 station at the low periods of vibration (on the order of 0.1 seconds) of the bridge in the transverse direction.

The bridge piers, 0.19 m high above the ground and with a section of 0.12 m in the transverse direction showed no damage. Apart from the damage observed at the parapets of abutments and piers, and pounding of the deck at pinned joints, the remaining parts of the bridge appeared to be in good condition. The EERI team that visited the area 3 days after the earthquake reported evidence of liquefaction at three piers of the bridge and in the surrounding area (EERI, 2007).

The bridge was initially opened with a single lane functioning after the main event, but further cracking subsequent to an aftershock resulted in closure of the bridge, leading to the construction of the alternative crossing through the dry bed of the river. The Minister of Transportation and Communication (MTC) informed on 18 September 2007 that repair of the bridge may have required 45 days of reconstruction works (OCHA SR18, 2007).

Figure 6.4 Huamaní Bridge along the Pan-American Highway

Figure 6.5 Huamaní Bridge: relative displacement between bridge sections at hinge location

Figure 6.6 Huamaní Bridge: shearing off of the west parapet at the south abutment

Figure 6.7 Huamaní Bridge: large size round aggregate used in the concrete of abutments

Figure 6.8 Huamaní Bridge: damage of parapets at the second northernmost pier.

Figure 6.9 Huamaní Bridge: parapet reinforcement detailing at the pier.

6.2 Footbridges

The second bridge that was closed is a pedestrian 80 m long suspension bridge located in the mountainous area west of Lunahuaná at the crossing of the river Cañete. The bridge collapsed after boulders falling from an adjacent slope that sheared off one of the RC towers. Similar footbridge suspension bridges were present in the area and were still in service, in spite of poor detailing of the RC elements supporting the cables, as evidenced in the footbridge that collapsed. Many of these columns showed very little, if any, shear reinforcement, with excessive concrete covers.

Figure 6.10 Pedestrian bridge crossing the Cañete river damaged by rock fall.

Figure 6.11 Reinforcement detailing of the RC tower of the collapsed footbridge.

6.3 References

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7 Performance of Ports and Harbours

Written by Fabio Taucer, Joint Research Centre

Reviewed by Paolo Negro, Joint Research Centre

The region affected by the disaster is characterised by a long coast facing the Pacific Ocean where two among the most important ports of Peru are located: El Callao and Puerto de San Martín.

The activities of the port of El Callao, serving Lima, were not affected by the earthquake; however, damage associated to poor soil conditions was reported in the areas adjacent to the port.

The port of San Martín is located in Punta Pejerrey in a peninsula a few kilometres south of Paracas, next to the National Park of Ballestas (Figure 7.1), constructed over a geological formation of plutonic rocks (P-pgr, ‘porfido granítico’) of the Batolito de San Nicolás, as shown by the Geological map of the Pisco Department prepared by the ‘Instituto Geológico Minero y Metalúrgico of Peru’ (Figure 7.2; Ingemmet, 1979).

The port of San Martín serves as the main node for exporting fish and agricultural products of the Ica region. In the aftermath of the disaster, a Mexican hospital-ship and three warships from the Peruvian Army carrying 1,500 tons of medicine, water, and fuel, as well as medical personnel, were sent to the port of San Martín (OCHA SR3, 2007), which had been set by the Peruvian Civil Defence as one of the two emergency posts (the other being at the Pisco Air Force Base) for receiving and organizing assistance (OCHA SR12, 2007).

Figure 7.1 Location of Port of San Martín (www.earth.google.com)

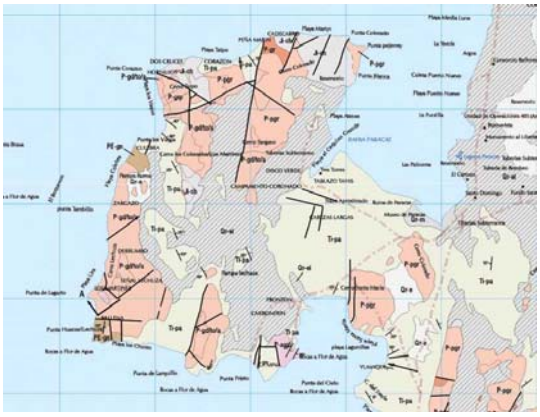

Figure 7.2 Geological map of the Pisco Department, Port of San Martin at Punta Pejerrey (www.ingemmet.gob.pe)

The visit to the port of San Martín revealed that the access to the dock structures was severely damaged (Figure 7.3), resulting from failure and settlement of the underlying soil, composed of a conglomerate of angular stones of up to 150 mm in size, mixed with sand (Figure 7.4). The access area at the south end of the port showed extensive cracking (with deep cracks widths up to 50 mm) and settled approximately 1.2 m with respect to the dock structure and to an adjacent warehouse, both of which did not suffer much damage. Two watch towers (located at each end of the port) toppled due to failure of the ground and of the supporting RC column (Figure 7.5); one electric transformer next to the warehouse also toppled after failure of its support (Figure 7.6). Punching of the pavement from piles supporting the access area on the northern part of the port was also observed (Figure 7.7). It was reported by the employees of the port that most of the damage took place after the strongest aftershocks, with continuous settlement of the ground taking place during the weeks following the main earthquake event.

Most of the damage suffered by the port of San Martín was due to the poor characteristics and compaction of the material used to fill the access structures to the dock; the fill material may had been extracted from the nearby shore, which was present along the beaches surrounding the port.

The dock structure, an 18 m wide reinforced concrete 0.55 m thick slab supported on 600 mm diameter circular steel piles spaced at 4 m (Figure 7.8), did not suffer major damage, however, due to failure of the access structures it could not be used immediately after the earthquake. The use of the port as an emergency centre for receiving assistance became possible only when a temporary access for trucks was constructed by levelling with sand and gravel the settlement that had occurred between the access and the dock (Figure 7.9). However, major repairs will be needed to restore full operation of the port.

The supporting infrastructure adjacent to the port suffered only minor damage, such as minor buckling that was observed in a braced steel latticed structure; large steel tanks did not suffer major damage and remained operational (Figure 7.10).

Other minor dock structures were surveyed in the area of Paracas, one at the waterfront which showed settlement of the dock (Figure 7.11), and a jetty at a Yacht Club south of Paracas that had sustained damage after longitudinal hinging of the steel piles at the connection with the pile cap in the longitudinal direction (Figure 7.12). The damage to these structures may compromise the development of the tourist activity of the area, as many boats depart from Paracas to visit the nearby National Reserve.

Figure 7.3 Port of San Martín: paved access 1.2 m settlement with respect to the dock and warehouse

Figure 7.4 Port of San Martín: fill material of the paved access to the dock structure

Figure 7.5 Port of San Martín: toppled RC watch tower (south end)

Figure 7.6 Port of San Martín: toppled electric transformer

Figure 7.7 Port of San Martín: pile caps punching through the paved access (looking north)

Figure 7.8 Port of San Martín: RC dock structure showing steel piles

Figure 7.9 Port of San Martín: temporary access to the dock at the north end.

Figure 7.10 Port of San Martín: adjacent steel tanks showing no damage

Figure 7.11 Dock structure in Paracas

Figure 7.12 Jetty structure at Yacht Club in Paracas: top hinging of steel piles

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8 Performance of Utility Systems

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The description of the performance of utility systems is divided into water distribution and wastewater, electric distribution, gas/liquid fuels and telecommunications.

8.1 Water distribution and wastewater

According to the National Sanitation Authority (SUNASS), the water supply status six days after the earthquake main event was as follows (OCHA SR7, 2007):

- Cañete: water supply 100% in the towns of San Antonio, Chilca, Cerro Azul, Quilmaza, Calando and Lunahuaná; water was supplied through tankers in San Luis (70%) and Imperial (80%).
- Chincha: water supply had been restored 100% in the towns of Pueblo Nuevo, Tambo de Mora, Chincha Baja, Alto Larán and partially restored (70%) in Chincha Alta and Grocio Prado; water was supplied by tankers in the towns of Sunampe and El Carmen.
- Pisco: water supply network supplied 5% of population, while 95% of the supply was channeled through cistern trucks.

Twelve days after the earthquake, water service through regular pipeline networks in Ica had been totally repaired and working at 100% of its capacity. In Chincha and Cañete, 80 % of the water was supplied through the water distribution network, while in Pisco the percentage was at only 15% (OCHA SR12, 2007).

The city of Pisco receives water from a filtration plant located 18 miles away in the east direction; pipeline damage along the transmission line into the town reduced the flow from 18,000 litres/minute to 10,000 litres/minute following the earthquake. The chlorine disinfection system at the operations centre in Pisco was also damaged by the earthquake. Bottled water was shipped in through the Port of San Martin immediately after the earthquake. In the city, a robust water tank tower (1200 m^3 of water reservoir) supported by a RC frame structure (Figure 8.5) was still functional after the earthquake and was being used to deliver water by means of truck cisterns to the city.

The EEFIT team visited several concrete water towers and some were noted as damaged and no longer operational; the team did not visit any dams, nor was damage reported in any similar structures in the affected region.

8.1.1 Water towers

In Guadalupe, the team passed near to a concrete water tower which seemed to have suffered little damage, but upon further inspection it revealed systematic cracking. The water tower, built in the 1980's, is a 20 m high concrete structure supported by a central hollow cylindrical reinforced concrete member (3-4 m diameter) and 6 slender 35x25 cm RC columns on the perimeter (Figure 8.1). Damage was observed at the central support: at the base, a crack running all the way around the perimeter (possibly coinciding with non-staggered splicing of the reinforcement) (Figure 8.2), while at the top, cracking was observed just below the tank structure, probably due to punching or excessive shear. Although the slender columns shared only a small portion of the lateral load (most of the seismic lateral forces were taken by the stiffer, central cylindrical element), signs of uplifting were observed at their base. The tank was reported to be empty at the time of the earthquake and was declared unusable after it leaked when filling the tank again.

Figure 8.1 Water tank near Guadalupe.

Figure 8.2 Flexural crack running around the perimeter at the base.

In San Juan, a small town 10-15 km away from Guadalupe, one out of two water towers close to the main square was severely damaged (Figure 8.3). Upon closer inspection it was found that the two tanks were built at different periods of time, the undamaged, higher tank being of newer construction. The older tank showed cracks at the level of an infill wall built at the base (Figure 8.4) and at the connection with the main body of the tank. After closer inspection, it was found that there were no stirrups and splicing was made at the joints. The fact that the newer tank did not suffer damage is a very good demonstration that good earthquake performance can be achieved by following current design standards.

Figure 8.3 Water towers in San Juan (older tank in the background).

Figure 8.4 Damaged column next to infill wall, joint showing insufficient reinforcement.

During the field visit, many other tanks, as the one shown Figure 8.6 were still functional with no visible damage.

Figure 8.5 Water tower in Pisco.

Figure 8.6 Water tower near Guadalupe.

An interview that the EEFIT team held at the *Universidad Pontificia Católica del Perú* in Lima with Prof. Daniel Quiun Wong revealed that upgrading of some civil infrastructures had been undertaken prior to the earthquake, as exemplified by a project were Prof. Quiun had been involved for the retrofit, after the earthquake of 1996, of a water tower in Pisco built in the ’60s; the retrofit consisted mainly in jacketing the RC columns.

8.1.2 Wastewater

On 6 September (22 days after the earthquake), the World Health Organization (WHO) and the Pan American Health Organization (PAHO) reported that the sanitation system of Pisco had vastly collapsed, especially in the main water collection tracts, and that an estimation of the status of the water pipelines would had been only possible in the following two weeks (OCHA SR14, 2007).

Although the wastewater treatment plant of Pisco was not damaged, it was not operational, due to lack of power after failure in the electricity transmission lines. Local NGOs provided latrines in and around the main squares of Pisco, however these were already overfilling and proving hazardous. Scarce information was available on the availability of sanitation facilities in smaller towns and rural areas.

8.2 Electricity distribution

Most of the electricity produced in the area affected by the earthquake is produced from hydro power, which is transmitted through high voltage lines from the Andes to a substation in Independencia District, about 12 miles inland from the Pacific coast; no apparent damage to this substation was observed. Electric power from the Independencia substation is distributed through lower voltage lines to Pisco, Ica, and Paracas; three line supports failed in the line serving Paracas/San Andrés.

The buildings housing the electrical substations in Pisco were unaffected and undamaged and 90% of the town’s electrical service was restored at the time of the team’s survey. Power company personnel indicated that substations were operational within a few days. Some problems were reported in Cañetes and Tambo de Mora, as electrical pylons and telecommunication towers had toppled due to liquefaction and foundation failure, yet to be repaired five weeks following the main earthquake event. Although most of the electricity service had been restored at the time of the field visit, OCHA had reported disruptions in both electricity and communications in the first weeks following the earthquake[1].

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[1] (OCHA SR8, 2007): “…The Minister of Energy and Mining reported that in Chincha 60% of street lights and 40% of domestic supply are working normally. In Ica, 95% of street lighting and 50% of domestic power supply are working, while water supply is totally restored. In Pisco, electric power is currently reaching 30% of street lighting and 15% of homes. Power service is improving by the day and it is expected to be totally operational in 10 to 15 days, except in Pisco where it could take a little longer (20 days)…”

8.3 Gas/Liquid fuels

There is no gas distribution system in the affected area, as gas is distributed in bottles. A gas duct runs from the Andes to the Ica region, the gas being liquefied at a facility in Pisco and then loaded onto ships at an offshore facility. No damage was reported at any of these facilities (See Section 9).

8.4 Telecommunications

According to the Earthquake Engineering Research Institute report (EERI, 2007), the telecommunications hardwired system failed during the earthquake. Cell phone systems were functional by 21 August 2007; additional portable call centres were set up at the main square in Pisco.

8.5 References

EERI (2007) “Learning from Earthquakes – The Pisco, Peru, earthquake of August 15, 2007”, *Earthquake Engineering Research Institute*, Special Earthquake Report, www.eeri.org.

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OCHA Situation Report 14 (2007) “Peru Earthquake Report No. 14”, *United Nations Office for the Coordination of Humanitarian Affairs*, 6 September.

9 Performance of Industrial Buildings

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An important number of industrial facilities are located along the coast from Lima to Paracas, taking advantage of the proximity to the Pan-American Highway and of the main ports near Lima and Pisco (Figure 9.1). During the survey the team observed a handful of offshore platforms for processing and distributing natural gas and its condensates from the Camisea Natural Gas Project; no damage was reported or observed in these installations.

Figure 9.1 Industrial facilities along the coast near Pisco

Figure 9.2 Toppled RC prefabricated perimeter walls and undamaged steel tanks along the coast near Pisco

The EEFIT team also passed nearby the main steel production plant of the Corporación Aceros Arequipa S.A., in the vicinity of Pisco. According to the New Zealand Society of Earthquake Engineers reconnaissance team (NZSEE, 2007), the plant normally runs three shifts totalling 1200 staff, mostly from Pisco. The plant was affected for 4 days following the earthquake, due to disruption to electrical power and staff shortages during the first days; there were no associated injuries. By the fourth day production was back to 50% and by the sixth day to 100%. The NZSEE team reported very little damage to the buildings and the plant.

Along the coastal routes there were also numerous plants, including steel plants, fertilizer/fish processing plants, an air separation plant, oil storage and refining facilities, and units processing fish flour and fish oil. The EEFIT team did not visit these facilities but had been told by locals that no damage had been reported, even though work had been suspended due to a break in the fishing season (damage to the fishing industry related to the Tsunami affected 17,000 families, see Section 4). Most of the damage to infrastructure observed by the team on the coastal region was to boundary walls and to a few steel trussed structures (Figure 9.2); no damage was observed on the steel tanks. There was also no reported damage to the irrigation canals for agriculture.

In general, the industrial activity suffered more from the shortage of personnel that had to cope with the disaster than from the actual damage of the infrastructure.

9.1 References

NZSEE (2007) “Observation Diary - Peru Earthquake of 15 August 2007”, *New Zealand Society for Earthquake Engineering Inc*, www.nzsee.org.nz.

10 Performance of Hospitals and Schools

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During the field visit, the EEFIT team put particular importance on the survey of damaged schools and hospitals, as their serviceability in the aftermath of an earthquake is crucial for adequate emergency operations and post-earthquake recovery.

A feature that was common to both hospitals and schools in the visited areas is that most of the structures that were damaged were either of masonry construction in combination with some type of reinforced concrete structure, or as in the majority of cases, corresponded to RC infilled frames built between the 1960's and up to the 1980's, prior to modern earthquake resistant construction norms.

According to preliminary assessments of the Peruvian Government (6 September 2007), 14 hospitals were destroyed, and 103 were affected in the area (OCHA SR14, 2007). Figure 10.1 shows a public structure for the supply of health related services that suffered severe damage; the structure was of RC construction in combination with brick masonry. The large damage sustained may hade been caused by an irregular geometry in plan and to the presence of large window openings at the second storey; the building was being evacuated at the time of the survey; however, it was not clear whether the structure would had been demolished or repaired.

Figure 10.2 shows a new hospital built prior to the earthquake that exhibited adequate performance, next to the remains of an older part of the hospital which was severely damaged and demolished after the earthquake.

Figure 10.1 Public health structure being evacuated in Pisco

Figure 10.2 New hospital, built prior to the earthquake, next to a previously existing one that was severely damaged and demolished in Pisco

The school infrastructure was severely affected in the region: in Ica 80 schools were reportedly damaged with more than 154 temporary prefabricated classrooms needed after the disaster, while in Chincha 36 education centres with 324 classrooms were required to restore school activities (OCHA SR8, 2007).

The EEFIT team visited several schools that suffered damage in Ica and Pisco, most of which were closed due to extensive damage; no associated casualties or injuries were reported.

Among the many schools visited, the school of the *Gran Unidad Escolar* San Luís Gonzaga in Ica is emblematic, as it showed most of the damage typologies observed throughout the field visit. According to the staff guarding the school premises, the main structure was built in the late 50's, following the construction standards and quality of materials of the time; the date of construction could not be verified against official documents. Many elements were constructed with steel deformed bars, which were commonly used only decades later, suggesting that the complex may be the result of several additions of building units during time.

In general, the structure of the schools visited sustained large levels of damage corresponding either to designs executed before modern standards of earthquake resistant design or to new designs non-conforming to current standards (i.e., low quality of materials and poor inspection), characterised by:

- Large openings at the first storey, with slender, tall columns and rigid roofs/slabs and/or beams, resulting in soft-storey mechanisms with failure at the top of columns (Figure 10.3 and Figure 10.4)
- No compliance with capacity design principles that guarantee that plastic hinges are developed at beam ends, whereas columns remain elastic or near yielding, thus dissipating energy while maintaining structural stability; in fact, in none of the schools visited, cases where beams had developed plastic hinges were observed (Figure 10.3, Figure 10.4 and Figure 10.7).
- Shear failure of columns due to insufficient shear reinforcement (Figure 10.5, Figure 10.6 and Figure 10.8) with respect to flexural capacity.
- Short column shear failure, due to the presence of openings at 3/4 interstorey height for light and air circulation (Figure 10.6).
- Low quality of materials, low strength of concrete and use of poor-quality, large sized stones from river beds as aggregate (abundant all through the coast of Peru) (Figure 10.8 and Figure 10.9).
- Insufficient detailing of reinforcement (Figure 10.8) concerning: lengths and staggering of splicing, development lengths, transverse reinforcement for shear strength and confinement at element ends, small diameter of shear links and stirrups with respect to longitudinal reinforcement, small diameters of longitudinal reinforcement, excessive or insufficient cover of longitudinal reinforcement (Figure 10.9).
- Inappropriate design of expansion joints, leading to damage after pounding at the roof level between independent units (Figure 10.10).

Even though there were no casualties associated to the schools or hospitals that were damaged, had the ground shaking been stronger (i.e., a closer epicentral distance to the affected area) these schools would have certainly collapsed, increasing dramatically the death toll, especially among children.

Figure 10.3 *Gran Unidad Escolar* San Luís Gonzaga: column failure at top end

Figure 10.4 *Gran Unidad Escolar* San Luís Gonzaga: column failure at top end; roof parapet activated a strong-beam-weak-column mechanism

Figure 10.5 Shear failure at the base of a column in a school in Ica

Figure 10.6 *Gran Unidad Escolar* San Luís Gonzaga: short column shear failure

Figure 10.7 Pisco: School building showing failure of column at top end at the second storey, due to insufficient shear reinforcement and activation of a strong-beam-weak-column mechanism

Figure 10.8 *Gran Unidad Escolar* San Luis Gonzaga: column failure in shear due to insufficient shear reinforcement and low quality of concrete

In spite of the fact that most schools were of reinforced concrete construction, in the rural mountain areas many schools were of adobe construction. In the town of San Jerónimo (point No. 2, Figure 3.7) up the valley of river Cañete, the team visited a school constructed out of adobe (Figure 10.11 and Figure 10.12), showing only minor damage, possibly due to attenuation of the ground shaking from the larger epicentral distance and to the better quality of the underlying soil (i.e., rock). Had the ground shaking been larger, this school would have probably suffered extensive damage.

The damage caused by the disaster on the school infrastructure calls for an immediate and urgent need to assess the earthquake performance and associated risk of collapse of all those schools built prior to the enforcement of modern standards of earthquake design and of good construction practice, especially of those schools that were not damaged during the present disaster, and upgrading those showing poor performance and unacceptable risk of collapse.

Figure 10.9 *Gran Unidad Escolar* San Luis Gonzaga: excessive concrete cover, lowering design flexural capacity, and poor concrete quality

Figure 10.10 *Gran Unidad Escolar* San Luis Gonzaga: damage due to pounding at ceiling level

Figure 10.11 San Jerónimo (Cañete river valley): adobe school showing limited damage

Figure 10.12 San Jerónimo (Cañete river valley): Students inside classrooms

10.1 References

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11 Management of the Disaster

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The relief effort was centrally managed by INDECI (Peruvian Civil Defence System - *Instituto Nacional de Defensa Civil*) and was based at the Area 51 Air Base just south of the town of Pisco near the coast. The air strip did not suffer major damage from the earthquake, with only a few superficial cracks evident in the hangar buildings and in the one-storey reinforced concrete building housing the INDECI office. The airstrip was being used for landing supplies from relief organisations. Organisations represented at the base include INDECI, Red Cross, UNDP and UNDAC.

The operations were organised into the following categories:

- Health and mental health
- Logistics
- Coordination
- Agriculture
- Education and security
- Infrastructure

At the air base, the team met with Carlos Valareso, Raul Lareinz, Agustín Basouri and Percy Alvarado, Head of the Coordinating Committee.

At the time of the visit, INDECI was in the process of carrying out damage evaluation, by comparing preliminary damage with actual damage. Out of the 7,000 houses in Pisco, INDECI estimated that 80% had been damaged, with 80-90% being of adobe construction. Mr. Lareinz mentioned that INDECI was in the process of asking people to move back from the shelter camps to their properties where the debris from the collapsed homes had been removed, so that they could establish temporary housing before starting reconstruction.

Figure 11.1 Relief camp in the *Viejo Club Atlético* grounds in Pisco

Figure 11.2 Relief camp at a park in Pisco

INDECI estimated that the city of Pisco would be completely cleared in two and a half months following the earthquake event, costing up to US$7 million, not including demolition costs[1]. The locals were being asked to help and were being paid at a rate US$5 for an eight hour day-shift. The public ministry, in charge of issuing death certificates to those killed in the earthquake, was compensating relatives of the dead with 800 *nuevos soles* (US$253) for each person killed (see Section 12.2).

In Pisco, the team visited two temporary relief camps based at the sites of the *Viejo Club Atlético* (Figure 11.1) and at a local park (Figure 11.2). The tents were supplied by INDECI and each of these facilities housed nearly 50 families. The shelter camps were working at overcapacity, while the adjacent building structures were unusable and hazardous, as these were severely damaged by the earthquake. In addition, many of the relief camps visited by the team were set up next to the premises of public institutions, such as hospitals, schools, sport facilities, impairing their use and resumption of activities (Figure 11.3).[2]

The EEFIT team also noted that there were groups of tents being erected adjacent to a busy road (Figure 11.4) with no proper coordination, amenities or protection, showing that there were no common standards or panning in setting up relief camps. The location of these camps next to important roads or to areas of demolition, with large quantities of dust particles, could cause respiratory diseases in the affected population.

Figure 11.3 Relief camp in premises adjacent to a school

Figure 11.4 Relief camp by the side of the Pan-American Highway in Chincha.

The EEFIT team, during the survey of the installations of the Port of San Martín, visited a large warehouse used by INDECI to store part of the relief material arriving from other areas in Peru and from donor countries and International Organisations[3]. Outside and inside the warehouse (Figure 11.5 and Figure 11.6), large quantities of material were stocked and piled up, waiting for distribution one month after the disaster, such as tents, mattresses, cooking stoves, water and clothes.

In fact, during the visit of the EEFIT team to the region of Castrovirreyna and to the towns and villages near Guadalupe and El Carmen, as well as in rural areas near the town centres of Ica, Chincha and Pisco, it was found that despite some villages being within 20 km of the centre of these cities, not much

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[1] The cleaning and debris removal in the areas struck by the earthquake was carried out by the "Cash-for-work program" (*Construyendo Perú*), with the participation of 8,000 people and a total investment close to US$3.2 million (OCHA SR7, 2007). The Ministry of Labor announced in 21 August 2007 that it would assess a budget increase of the programme to create 2,000 new temporary jobs in Pisco and another 2,000 in Chincha and Ica (OCHA SR11, 2007). INDECI informed that 210,000 m^3 of debris have been removed as of September 15th (OCHA SR18, 2007)

[2] INDECI reported a total of 12,000 distributed tents. The 24 camps located in Pisco were supported with food and other types of humanitarian aid, from which 4,255 families (21,275 persons) benefited (OCHA SR18, 2007).

[3] INDECI received 12,000 tons of humanitarian aid coming from international and national sources (OCHA SR9, 2007). On September 18th, 245 Tons of humanitarian aid and 120 Tons of recycled clothes were stored at the Puerto de San Martín (OCHA SR18, 2007).

aid had reached the local population, which was relying on local resources to set up temporary shelters (Figure 11.7 and Figure 11.8). OXFAM cited the same problems in their assessment reports, saying that many villages away from the main roads had been left unaided; serious security problems were also recorded, with reports of looting and robberies in towns and villages, as well as along some roads immediately after the disaster.

Figure 11.5 Relief stock of water piled up outside the warehouse at the Port of San Martín

Figure 11.6 Tents being stocked inside the warehouse at the Port of San Martín

Figure 11.7 Informal relief camp in rural area near Guadalupe

Figure 11.8 "We need help" sign in rural area near Guadalupe.

Concerning International response, on 28 August, the United Nations and its humanitarian partners launched through UNOCHA a Flash Appeal close to US$37 million, in order to assist more than 200,000 people affected during the six months following the disaster (OCHA SR12, 2007). On 11 January 2008, Relief Web confirmed that US$20 million of international aid had been financed through the United Nations System (ReliefWeb, 2008).

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12 Socio-Economical Aspects

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Reviewed by Prof. Robin Spence, University of Cambridge

The review of the data gathered during and after the field mission concerning socio-economic aspects is presented in the following, addressing issues related to the causalities of the earthquake, social welfare, and economic aspects related to industry and tourism.

12.1 Casualties from the earthquake

As reported in Section 1, the official death toll at the time of preparing this report stands at 519, with 1,366 injured (OCHA SR21, 2007), with more than 150 people killed from the collapse of the roof of the San Clemente church of the Compañía de Jesús in Pisco during a funeral service. Considering the magnitude of the event and the high vulnerability of the building stock, the number of casualties, excluding those associated to the collapse of the church, can be considered to have been relatively low. One of the possible reasons cited for this is the fact that the ground motion was characterised by two portions of strong shaking separated by a relatively calm portion lasting 30-40 seconds, allowing people to escape their homes, mostly one-storey high, before collapsing. Another reason is the time of day when the earthquake occurred, when most people are awake (for those living in adobe houses who had time to escape) and/or outside their homes, either on transit or working in safer engineered building structures, such as banks, commercial areas and industrial plants.

Another reason that may explain the low number of casualties, in spite of the mass devastation such as that suffered by the city of Pisco, with 11,017 collapsed houses (OCHA SR18, 2007), is that most houses were one-storey high, with light roofs mostly made of *quincha* (see Section 5.1.1) typical of the desert climate of the region, which at the time of collapse may had inflicted minor threats to the life of occupants with respect to heavier roofs of houses located in more adverse (rain, cold weather) climates.

In order to explore these hypotheses and further investigate the causes of injuries, the team enlisted Astrid Tolmos (Univ. of Ica) to carry out a questionnaire survey of survivors of the earthquake. This is an area in which one of the team members, Emily So, has concentrated much of her current research.

12.1.1 Casualty Survey

In all, 115 questionnaires were carried out in the area of Chincha Alta and Pisco and the surrounding towns and villages. The thinking behind the design of the questionnaire was simple: it needed to record what happens to a survivor of an earthquake from the moment the earthquake happens to the time of the interview, and the factors contributing to survival. The key relationship explored is the causal pathways of injuries, seeking out links between types and severity of injuries and their causes. It was anticipated that survivors would provide data on the following:

a. The physical location of the survivor (whether inside or outside of a building)

b. Aspects of human behaviour in response to the earthquake

c. Physical damage to structures and likely cause

d. Causes of death and nature and extent of injury to survivors (themselves and others with them)

e. Search and rescue efforts

f. Treatment of injuries

g. Infrastructure and communication disruption

h. Condition of the survivor, and hopes and concerns for the future

Figure 12.1 A survivor at Chincha Alta being interviewed at her shop

Figure 12.2 Participants of the survey sitting outside their temporary housing in the village of Grocio Prado

The survey questionnaire introduced the research aims and sought informed consent, all in the local language. The lead questions were open-ended and carefully ordered to give survivors the opportunity to tell their stories to an empathetic and active listener, and these were recorded in field notes. This meant preparing the interviewer to focus on the humane side of the story, before asking detailed questions about the buildings, their injuries and the aftermath of the disaster. From here the interview sought factual responses to more specific questions. All interviews were carried out in person and interviewers were visiting homes and temporary housing of survivors.

There are some obvious limitations to the dataset produced from the questionnaires as a representative sample of those affected, as the number of people interviewed corresponds to a small sample compared to the number of people affected by the earthquake. However, some key findings from this event can be drawn from the survey and are presented in the subsequent paragraphs (see Table 12.1).

Table 12.1 Main characteristics of the earthquake and survey conclusions

Mag	**Time**	**Casualties**	**General Terrain**	**Survey conclusions**			
				Main type of building stock	**Main type of injuries**	**Contribution to survival**	**Wait before help arrived**
7.9	18:40	519	Flat, desert	Adobe	Minor cuts and bruises, fractures	“Help of God”, ability to move (2-phase motion)	Average wait was 1 day.

The results from the survey show that for people inside buildings at the time of the earthquake, nearly all deaths and injuries were directly caused by building collapse as assumed by models such as HAZUS (FEMA, 1999) and the Cambridge Casualty Model (Coburn and Spence, 2002). In this earthquake, the survey showed that a significant number of people survived in completely collapsed buildings: of those in collapsed dwellings (43% of the buildings surveyed), none of the inhabitants were reported to be killed and this supports the observation in the field that people were able to get out before their dwellings collapsed. What the surveys have highlighted in terms of evasive action is that people who were able to get out of their dwellings during the earthquake also knew what earthquakes were (>80% of respondents that got out from their dwellings had knowledge of earthquakes). This is an area still under assessment at the moment, but brings about interesting questions of climate, culture and knowledge as contributors to the proportion of occupant entrapment in collapsed buildings.

In examining respondents with injuries, for those in buildings, it was conclusive that most of the more severe injuries were caused by structural collapses and less severe injuries were caused by failure of non-structural elements or by falling of contents. However, the questionnaires also show that serious injuries can be caused by non-structural elements as well, which may occur in collapsed or non-collapsed buildings. There were a much higher percentage of respondents with lower and upper extremity fractures than what shown by the overall statistics posted by INDECI (22% of reported injuries).

Immediately after the earthquake, INDECI posted on their website a list of 1,284 hospitalised injuries from the earthquake. These ranged from cuts and bruises to fractures, and also included pneumonia and post disaster trauma. The injuries were neither gender specific nor were there an apparent vulnerable age group affected. Over half of the hospitalised victims were from Pisco and approximately 20% from the Chincha Province. The EEFIT team was told during the visit that many injuries from the more remote villages were not treated in hospitals but in medical tents in temporary camps and therefore not included in these official figures.

12.2 Social welfare

Even though the death toll was almost two orders of magnitude lower than that caused by the 31 May 1970 7.9 magnitude Chimbote earthquake in Northern Peru, which killed over 70,000 people[1], the 15 August 2007 earthquake affected over 200,000 people[2] in one of the country's most economically prosperous areas.

In the immediate days following the earthquake, the lack of water and proper sanitation systems, lack of shelter and the presence of dust in the air from debris of the collapsed houses raised the risk of respiratory infections and other health problems. Damage to sewage lines and latrines left thousands of people without proper sanitation, increasing the risk of gastro-intestinal diseases.

Figure 12.3 Affected dwellers piling their belongings outside their collapsed houses in Guadalupe

Figure 12.4 Temporary accommodations in Pisco (made of steel/ aluminium sheets)

The EEFIT team observed that in the visited area, especially in the main cities, many people were walking around aimlessly, in many cases guarding the few belongings and possessions they were able to save from the wreckage of their homes, setting up temporary shelters in front of what had been their

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[1] "Although the earthquake itself caused much death and damage, severe losses were also caused by a *huayco* (an Inca word for avalanche) which swept down the steep slopes of the Cordillera Blanca from the Nevados Huascarán into the Callejón del Huaylas, a steep valley paralleling the coast. Yungay and thousands of its residents were buried under tens of feet of mud, earth, water, boulders, and debris". "On May 31, the earthquake and its side-effects damaged more than 70 percent of the buildings in the valley city, and took an estimated 20,000 lives" (USGS, www.earthquake.usgs.gov)

[2] "…40,035 families [were] rendered homeless and a further 30,542 families have been affected…200,000 people who have been directly affected by the earthquake" (Peru Earthquake Flash Appeal, 24 August 2007, *United Nations Humanitarian Consolidated Appeal Process*, www.ochaonline.un.org)

homes (Figure 12.3). As a result, the active population, especially single mothers, was not able to carry out their daily activities and jobs to economically support their families.

In response to the strains caused by the disaster on the population, the Peruvian Government announced grants to each family whose home was destroyed, as well as money for funeral expenses and the injured[3], allocating US$82.3 million for the reconstruction of the affected areas (see Section 13). However, the large scale of the destruction suggests that rebuilding Pisco and Chincha may cost much more, let alone the surrounding villages which at the time of the survey had seen very little of relief and aid. The shortage and deficiencies of aid distribution had caused discomfort and anxiety to the population, which gathered in the main squares of towns and villages to request aid to the Government (Figure 12.5 and Figure 12.6).

Figure 12.5 People gathering at the Plaza de Armas in Pisco

Figure 12.6 Riot police on standby by the main square of Pisco during a demonstration

In addition, there were problems of schooling, hospital care and security. During informal interviews of the EEFIT team with the local population, it was common to hear that people had lost their homes and that all they had were insecure tents or temporary make-shift shelters (Figure 12.4). Most children were at home or at relief camps, as most schools were not functioning and parents had to look after them. In most of the towns the team reported people clearing in appalling dusty conditions, salvaging adobe bricks and in some cases starting reconstruction. There is, however, interest within the locals to build with earthquake safe houses and many had enquired about seismic resistant adobe housing.

12.3 Economic

12.3.1 Agricultural, fishing and industrial activities

The economic activity was also affected by the earthquake. The region of Ica is one of the most important agricultural centres of Peru, producing and exporting asparagus (Figure 12.7) and other crops such as fruits and grapes (Figure 12.8) for the production of wine and spirits[4]. The costal area is also a

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[3] The Peruvian Government approved on 17 August 2007 a compensation fund providing US$312 per family for each dead member and US$1,875 per family to reconstruct destroyed houses (OCHA SR3, 2007); on 21 August 2007 approximately US$ 190,000 were transferred to INDECI to support the victims' families burial activities (OCHA SR7, 2007). On 28 August, the first 800 soles (US$253) checks were disbursed to cover the costs incurred by family members accompanying the injured to Lima for medical attention (OCHA SR12, 2007). Approximately, US$7.6 millions were transferred to the Ministry of Women and Social Development in order to procure food through the World Food Program (OCHA SR6, 2007).

[4] According to the Ministry of Trade and Tourism, on 22 August 2007, agro-exports in the emergency area had recovered to 70% of their pre-earthquake capacity. Economic activity in the area was expected to gradually regain full capacity as power supply was being restored. In the textile sector, the main companies located in Ica and Chincha had also restarted their activity, although not at 100% (OCHA SR8, 2007).

very important centre for processing and exporting fish related products[5]. As described in Section 9, most of the agricultural and industrial infrastructure had not been damaged during the earthquake.

Figure 12.7 Asparagus crops in the Ica region

Figure 12.8 Grape vineyard near Guadalupe

During the first week following the earthquake, AIR worldwide (www.air-worldwide.com), a Boston-based catastrophe modelling firm, estimated that insured losses, hitting mostly the commercial sector, would not had been over US$1 billion. This figure may underestimate the actual economic losses sustained, as the industrial and agricultural sector had a slow recovery of production to full capacity in the weeks following the disaster resulting from shortages of staff that had to cope with the disaster.

12.3.2 Tourism

Figure 12.9 XVII century chapel in Hacienda San José near El Carmen with damaged bell tower.

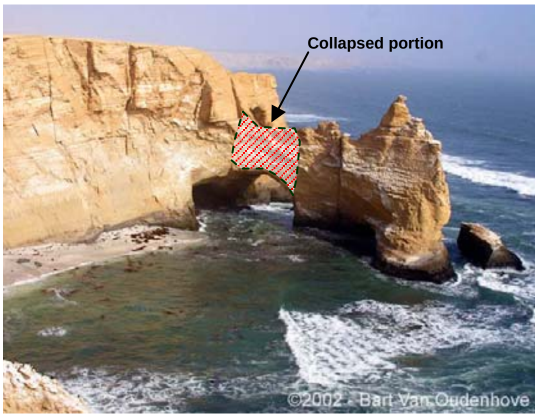

Figure 12.10 La Catedrál natural rock formation in Paracas National Reserve (from www.tierra-inca.com)

In terms of tourism, although not as popular as Machu Picchu or the Nazca Lines (the latter also located in the Ica region farther away from the epicentre and not sustaining damage), the Ica region was affected by the fact that many of the historic churches had collapsed. According to the National Culture Institute, the event badly damaged at least 173 churches, monuments and historic buildings, with about one-third completely destroyed. In particular, the 329-year-old colonial Hacienda San José, outside the city of Chincha, suffered from partially collapsed walls, but was largely intact (Figure 5.13), saved by its wooden roof and the collapsed bell tower of its XVII century chapel (Figure 12.9). The *hacienda*

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[5] On 26 August 2007, traditional fishers of Ica received help from the Ministry of Production to resume their activities. The Ministry provided nets and other fishing equipment. As a result of the earthquake, docks and other fishing infrastructure in San Andrés, Laguna Grande, Lagunillas, Chaco and Tambo de Mora were damaged (OCHA SR11, 2007).

(farmstead) was declared a national monument in the late 1960s and was under renovation to resume as a resort hotel serving local tourists.

A natural rock formation, known as the “Catedral”, a major tourist attraction in Peru located in the Paracas National Reserve, had collapsed into the sea during the earthquake (Figure 12.10).

In Pisco, the five-story Embassy Hotel ‘pancaked’ onto its ground floor (see Section 5.2.3) killing 15, while all other hotels in the area had only suffered minor damage, with a few exceptions that had major cracking and were closed for repairs during the EEFIT team’s visit.

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13 Reconstruction Issues

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As mentioned in Sections 11 and 12, emergency relief had not been very effective in rural areas, especially in the mountains, where families that had lost their homes were starting reconstruction using adobe bricks (Figure 13.1) from the previous existing houses that collapsed.

Most of the reconstruction was taking place using either traditional techniques of adobe construction (Figure 13.2), in the case of the more poor families, or non-engineered techniques for the construction of reinforced concrete confined masonry houses, in the case of families with higher economic means (Figure 13.3 and Figure 13.4).

Figure 13.1 Adobe bricks ready for use in reconstruction in Chincha Alta

Figure 13.2 Reconstruction of an adobe wall using traditional techniques in El Carmen

Figure 13.3 Reconstruction taking place in Chincha Alta

Figure 13.4 Reconstruction using RC in Chincha Alta without adequate technical assistance

The reconstruction of adobe houses was mostly observed in rural areas, while that of non-engineered RC frame and RC confined masonry houses was typically observed in urban centres, resulting in both cases in highly vulnerable constructions to earthquake hazard, thus re-establishing the same high risk present before the earthquake event.

‘Self’ reconstruction of non-engineered houses may be seen as a way for the local population to cover immediate shelter needs and the deficit resulting from insufficient resources (both in budget and timing) of the Government to finance the reconstruction of engineered houses. Therefore, some kind of assistance and control aimed at increasing the quality and earthquake resistance of the rebuilding of houses not assisted directly by the Government would be desirable to diminish the risk to future, similar earthquake events. This type of objective can only be achieved by implementing a comprehensive program that involves the participation of institutional organizations, NGO's, Universities, and most important, the active participation of the local population.

13.1 National response

On 28 August 2007, the Peruvian Congress discussed and approved a law to create a special, new autonomous Fund for the Reconstruction of the South (FORSUR) in charge of the reconstruction of the areas affected by the earthquake (OCHA SR11 and SR12, 2007), building upon the successful experience s achieved by the Reconstruction Fund for the Coffee Region (FOREC, *Fondo para la Reconstrucción del Eje cafetero*)[1] of the areas damaged in Colombia after the January 1999 earthquake. To this end, the Peruvian Government planned on 24 August 2007 to earmark 260 millions of *nuevos soles* (US$82.3 million) to FORSUR by the end of 2007 to lead the reconstruction process in coordination with ministers, regional presidents and local authorities (OCHA SR10, 2007).

A supplementary credit of US$31.6 million was authorized on 29 August by the Peruvian government for the reconstruction of public infrastructure (OCHA SR6, 2007).

On 28 March 2008, FORSUR transferred to the mayor of Chincha the amount of 722,200 *nuevos soles* (US$228,400) for relocating the 440 families that had lost their homes in the district of Tambo de Mora in the areas affected by liquefaction; to prevent the construction of new houses, a memorial park for the victims of the 15 August earthquake will be built in the affected area (www.peru.com, 28/03/08).

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[1] Rather than using a centrally-directed approach, this program adopted an innovative, decentralized method relying on community organizations in the municipalities. For housing reconstruction, FOREC gave subsidies rather than carrying out the construction itself. NGOs were contracted to manage the reconstruction effort in 32 zones in coordination with municipal and regional governments. These measures were so successful that in 2000 the United Nations awarded FOREC the Sasakawa Prize, which honours entities that prevent or lower the risk of natural disasters (World Bank, 2007).

14 Conclusions

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From the findings of the mission, the following set of conclusions may be drawn:

1. The entity and magnitude of the disaster caused by the earthquake event was the result of a combination of several factors:
   - The large magnitude, shallow depth and intermediate[1] epicentral distance of the main event to the affected area (i.e., Hazard).
   - The high vulnerability of traditional earth constructions (adobe, or a combination with *quincha*, masonry and/or RC) and reinforced concrete (RC) infilled frames non-conforming to modern earthquake resistant construction standards (i.e., Vulnerability).
   - The location of building structures and constructions on poor quality soils susceptible to liquefaction and to ground failure, as well as in areas exposed to Tsunami. In mountain areas, rural houses constructed on or near slopes without proper consideration of the risk associated to landslides and/or falling of boulder debris (i.e., Urban Planning).
   - Difficulties in managing the emergency after the disaster[2] (i.e., Disaster management).
2. In spite of the large number of destroyed houses (58,581) and affected population (200,000), the number of casualties that resulted from the earthquake disaster was comparatively low (519 deaths), due to three main factors: the long duration of the earthquake event with an intermediate portion of low level ground motions that allowed dwellers to escape, the fact that most adobe houses were single storey with light roofs – typical of arid climates –, and the time of the day (18:40, local time), when most people are awake and out of their homes.
3. Traditional earth structures, in particular those of adobe construction, designed without the inclusion of any kind of reinforcement[3], and without the consideration of earthquake resistant concepts[4], are susceptible to collapse in a sudden, brittle manner, causing the deaths/injuries of their occupants and the complete loss of the housing structure.
4. Structures built according to current standards for earthquake resistant design, such as 1 to 6 storey RC confined masonry buildings, performed satisfactorily with minimum levels of damage for the levels of ground motions induced in the affected areas.
5. Schools and hospitals built prior to current standards of earthquake resistant design sustained high levels of damage, due to insufficient strength, ductility, appropriate detailing and unfavourable

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[1] The city of Pisco and Chincha Alta were located at 70 and 50 km from the epicentre, respectively; a larger and more devastating disaster would have resulted had the epicentre been located at a closer distance to these two cities.

[2] During the visit to the Port of San Martín, large stocks of emergency material (tents, water, furnaces, clothes) where stored without being distributed, almost one month after the earthquake event. Many of the emergency camps and shelters visited were overcrowded and located at open air premises next to schools and hospitals, some of which had suffered severe damage, thus preventing their repair and further re-establishing of activities.

[3] Typical reinforcement consists of bamboo rods running into the walls, or a steel or polyester net plastered and attached onto the exterior and interior surfaces.

[4] Earthquake resistant concepts consist of regular geometries, small openings, short unsupported lengths of walls, stocky walls and rigid roof/floor diagrams.

global geometries (soft storeys, short columns), as well as due to the low quality of construction materials.

6. Earth structures (one storey adobe or combined with *quincha* at the second storey) designed for earthquake resistance and built by the NGO's and International Agencies present in Peru, with the participation of universities and research institutions, prior to the earthquake event, performed satisfactorily.

7. Most of the attention in emergency relief was focused in the largest cities (Ica, Pisco and Chincha Alta), while rural, remote areas, especially along the valleys running up the Andes, were facing delays in receiving emergency relief.

8. As the reconstruction process led by governmental institutions had not commenced at the time of the field mission, part of the affected population had already started reconstruction, in general without qualified assistance. In rural areas with higher levels of poverty, the adobe bricks from the fallen houses were being reused for reconstruction following traditional techniques, thus re-establishing the same level of high risk that existed prior to the earthquake event.

9. During informal interviews, the affected population showed a high level of receptiveness, expressing their concern in reconstructing earthquake safe houses, different from those that collapsed, and in adopting and following any guidance that could be given by external sources for earthquake safe construction. In particular, it is important to mention the awareness of the population resulting from the good performance shown by the earthquake resistant adobe houses that were built before the earthquake event (see (6)).

10. The Peruvian Civil Protection (INDECI), the Delegation of the European Commission in Peru and PREDECAM (*Apoyo a la Prevención de Desasters de la Comunidad Andina*), expressed strong interest in the results of the EEFIT field mission, namely conclusions and recommendations, which were regarded as valuable in the process of planning and assisting the reconstruction phase.

15 Recommendations

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From the list of conclusions given in Section 15, it is possible to draw the following set of recommendations, aimed mainly to assist the reconstruction phase with the objective of reducing the earthquake risk in the affected area:

1. Where reconstruction is carried out by adopting current standards of design and modern construction technologies (e.g., reinforced concrete (RC) confined brick masonry), attention should be placed in guaranteeing a good quality of construction and earthquake resistant designs, by ensuring adequate levels of inspection and review of the proposed designs.

2. All the schools and hospitals in the Province of Ica designed prior to current standards of earthquake design, including those that did not sustain considerable levels of damage, should be assessed for adequate performance and, if needed, upgraded.

3. The upgrading of structures, including those that suffered damage during the earthquake event, in particular schools and hospitals, should be carried out by qualified engineers, using the support of national and international norms (e.g., Eurocode EN 1998-3: Assessment and retrofitting of structures).

4. The successful performance of RC confined brick masonry buildings, which are becoming the main typology of ‘modern’ buildings in Peru, should be assessed more in detail, especially with regards to the effective levels of ground motions to which they were exposed during the earthquake, assessing their performance until collapse and recognising the levels of construction quality present in the area.

5. The successful performance of the upgraded, and of the new earthquake resistant designed adobe houses described in Section 5.2.1, suggests that further research should be promoted in order to produce consolidated guidelines for the assessment, retrofit and design of adobe structures (see (10)). Cost analysis studies should be carried out in order to determine the feasibility of investing in upgrading the existing adobe building stock most at risk.

6. All the reconstruction should take place in land with adequate soil conditions, relocating those structures built on soil that suffered from liquefaction effects. If reconstruction takes place in areas prone to liquefaction, the underlying soil should be upgraded and stabilised after performing a cost-benefit analysis with respect to the solution of relocation. This activity requires adequate urban planning through the involvement of the Municipalities, using the available data on soil conditions and risk maps (including Tsunami) prepared by the Civil Protection and Universities in Peru.

7. It is very important that timely action is taken in the aftermath of the disaster to assist the reconstruction of safe earthquake resistant adobe houses in distant rural areas, where, owing to the difficulties of Governmental Institutions in providing support, families start the reconstruction of adobe houses following traditional techniques, thus re-establishing the high level of seismic risk existing prior to the earthquake event.

8. It is recommended that the support towards reconstruction in rural, remote areas, as described in (6), involves the participation of the affected population, by creating awareness on the basic principles of risk mitigation, and by identifying local leaders that can be trained and act as conveyors of the principles of earthquake resistant design of adobe houses[1].

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[1] Based on the experience from previous earthquake disasters, effective communication is vital for reconstruction, such as setting up small groups for demonstration activities addressing adequate practices for earthquake safe reconstruction (using for example, simple leaflets adapted to the local population) and training of local builders.

9. The process described in (8) can only be successful by means of an effective collaboration of:

    - NGO’s and International agencies, that have a long experience in the field of reconstruction through the development of projects that account for socio-economical aspects and the participation of local communities;

    - Universities and research centres, that possess the technical expertise related to the design, upgrading and construction of earthquake resistant houses;

    - Official institutions, through the Municipalities, in charge of urban planning for the correct location of reconstruction projects, as well as for giving financial and legal support to the reconstruction activities;

    - International Institutions, such as the European Commission, PREDECAN (*Prevención de Desastres en la Comunidad Andina*), the World Bank, ISDR, USAID, etc., that can effectively contribute with additional funds and that can advice to the Governmental Institutions on the management of the reconstruction process.

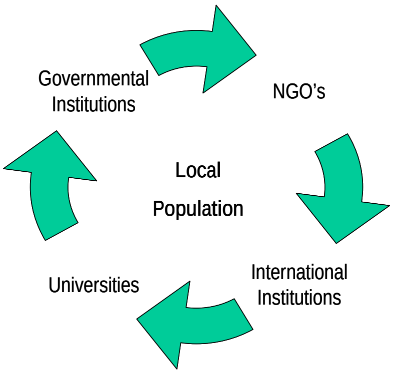

Figure 15.1 Reconstruction process: Collaboration between local population and external actors

10. In view of the fact that the building stock in Peru, especially in rural areas and away from large urban centres, is mostly composed of adobe houses, it is recommended that the Peruvian Construction Standards are updated to reflect the latest techniques for the construction of earthquake resistant adobe houses and the upgrading of existing ones.

Figure 15.2 A sustainable reconstruction process should lead to the transition from temporary shelters built after the disaster to earthquake resistant designs using local materials and workmanship (Photos from Cañete river valley near Huangáscar)

European Commission

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Abstract

A field reconnaissance mission was led to the areas affected by the disaster caused by the Magnitude 7.9 earthquake event of 15/08/2007 near the city of Pisco in Peru. The main objectives of the mission were to collect data and make observations leading to improvements in design methods and techniques for strengthening and retrofit, and to assist the phase of reconstruction. The mission focused on the behaviour of non-engineered structures, in particular those of adobe constructions. The findings of the mission confirmed that most of the damage was observed on adobe houses constructed with traditional non anti-seismic techniques which either collapsed or nearly collapsed, causing 519 deaths, 1,366 injuries and more than 58,000 houses destroyed. The mission also confirmed that buildings constructed according to modern earthquake resistant design standards performed with no evident damage. All the parties contacted during the mission, especially the EC Delegation, showed particular interest in the results of the present mission report, which will be taken into consideration when planning the reconstruction phase, especially of the most distant rural areas, where close collaboration between the Governmental Institutions, International Organizations, Universities and NGO's, will be needed to assist the population for the adoption of earthquake resistant designs in the reconstruction of the destroyed houses.

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