

**THE PISCO (PERU) EARTHQUAKE OF 15 AUGUST 2007**  
**NZSEE Reconnaissance Report, June 2008**

**David Hopkins, Darrin Bell, Rafael Benites, James Burr,  
 Craig Hamilton and Rudolph Kotze**

**TABLE OF CONTENTS**

Summary .....	113
1 Introduction .....	113
2 The earthquake .....	114
2.1 History of earthquakes in the area .....	114
2.2 Tectonic setting .....	115
2.3 Hypocentral parameters .....	116
2.4 Key features .....	116
2.5 Strong Ground Motion .....	120
2.6 References .....	123
3 The affected areas .....	123
4 Emergency Response .....	124
4.1 Emergency Communications .....	124
4.2 Reconnaissance .....	124
4.3 Six Critical Needs .....	125
5 Geotechnical .....	128
5.1 Geotechnical overview .....	128
5.2 Slips .....	130
5.3 Liquefaction .....	135
5.4 Microzonation studies .....	140
5.5 Tsunami .....	141
6 Buildings .....	142
6.1 Introduction .....	142
6.2 Seismic Design Standard .....	142
6.3 Building Practice .....	143
6.4 Lima .....	145
6.5 Building Performance in Lima .....	148
6.6 Epicentral region .....	150
6.7 Building performance in epicentral region .....	151
6.8 Analysis of Damage Levels .....	168
6.9 Industrial Structures .....	171
6.10 A New Zealand Perspective .....	175
7 Lifelines .....	175
7.1 Telecommunications .....	175
7.2 Transport networks and facilities .....	175
7.3 Marine (ports, shipping, fishing) .....	181
7.4 Energy supply and distribution .....	184
8 Social and Economic Impacts .....	185
8.1 Social impacts .....	185
8.2 Economic impacts .....	185

9	Key lessons and implications.....	185
9.1	General .....	185
10	Implications for the 4 R's of Emergency Management.....	186
	Acknowledgements.....	187

## Appendices

Appendix A.....	188
Recommendations for future reconnaissance visits.....	188
Appendix B – Team Members and Mission Objectives.....	189
Appendix C – Acknowledgement and Contact List.....	191

## List of Tables

Table 1: Recorded Accelerations (Amax).....	122
Table 2: Evolution of Peruvian Seismic Standards.....	163
Table B1: Reconnaissance team members and responsibilities.....	189

## List of Figures

Figure 1. Tectonic setting .....	114
Figure 2. Central section of subduction zone.....	115
Figure 3. Areas of primary slip.....	116
Figure 4. Earthquake context.....	117
Figure 5. Earthquake records.....	118
Figure 6. Rupture analysis.....	119
Figure 7. Spatial distribution of aftershocks.....	120
Figure 8. Location of strong motion instruments in Greater Lima.....	121
Figure 9. Records from Parcona (PAR) station.....	122
Figure 10: Map of affected areas.....	123
Figure 11: Aerial view of Pisco showing worst-damaged areas.....	125
Figure 12: USAR casualty record on San Clemente Cathedral, Pisco.....	126
Figure 13: Damage to hospital treatment room in Ica Regional Hospital.....	126
Figure 14: Camp at Ica.....	127
Figure 15: Immunisation tents in Chincha Alta.....	128
Figure 16: Extract from Pisco geological map.....	129
Figure 17: Typical desert landscape.....	130
Figure 18: Rock slide above road in Andes foothills.....	131
Figure 19: Failure of cut slope.....	131
Figure 20: Reactivation of scree slope.....	132
Figure 21: Typical embankment failure as a result of liquefaction.....	132
Figure 22: Low embankment failure.....	133
Figure 23: Damage to the Huamani Bridge southern embankment.....	134
Figure 24: Larger slip on Pan American Highway.....	135
Figure 25: Sand ejecta beside Pan American Highway.....	136
Figure 26: Surface cracking from liquefaction.....	136
Figure 27: Ejecta around bridge abutments.....	137
Figure 28 Liquefaction-induced offset to wall in Paracas.....	138
Figure 29 Ground subsidence in wharf shed at Port San Martin.....	139
Figure 30: Liquefaction damage at Las Lagunas.....	139
Figure 31: Microzonation map – Pisco.....	140
Figure 32: Microzonation map - Ica.....	141
Figure 33: Tsunami run-up details.....	141
Figure 34: Boats washed up by tsunami in Paracas.....	142
Figure 35 Peru – Zones used for seismic design.....	143
Figure 36 Confined Masonry Building.....	144
Figure 37 Infill Masonry Brick.....	144
Figure 38 Confined Masonry Construction.....	144
Figure 39 Adobe House Construction.....	145
Figure 40 Lima - Modern High Rise Buildings.....	146

Figure 41	Lima – Older Style Multi-storey Buildings.....	146
Figure 42	CISMID Lima accelerograph stations.....	147
Figure 43	CISMID Lima response spectra.....	147
Figure 44:	Undamaged building Lima.....	148
Figure 45	Miraflores Residential Area.....	149
Figure 46	Miraflores High-rise Commercial Buildings.....	149
Figure 47	Building Impact - Miraflores.....	150
Figure 48	Miraflores Apartment Buildings with diagonal creaking of columns.....	150
Figure 49	ICA2 Spectra.....	151
Figure 50	Pisco Residential Street.....	151
Figure 51	Pisco Cleanup.....	152
Figure 52	Undamaged Buildings - Pisco.....	152
Figure 53	City Centre - Ica.....	153
Figure 54	Street Damage - Ica.....	153
Figure 55	Collapsed church roof - Ica.....	154
Figure 56	Typical Adobe House Damage.....	154
Figure 57	Collapsed Adobe House - Pisco.....	154
Figure 58	Damaged Two Storey Adobe Buildings - Pisco.....	155
Figure 59	Cathedral San Clemente before Earthquake.....	155
Figure 60	Cathedral San Clemente after Earthquake.....	155
Figure 61	Undamaged Confined Masonry Dwelling - Pisco.....	156
Figure 62	Undamaged Engineered Confined Masonry Dwelling - Pisco.....	156
Figure 63	Multistorey Confined Masonry Building - Pisco.....	156
Figure 64	Pisco Confined Masonry Buildings with panel damage.....	157
Figure 65	Diagonal cracking of infill masonry panel.....	157
Figure 66	Brick panel damage - Ica.....	157
Figure 67	First Floor Collapse - Pisco Residential Buildings.....	158
Figure 68	Column Failure - Pisco Residential Building.....	158
Figure 69	Embassy Hotel Damage - Pisco.....	159
Figure 70	Demolished Embassy Hotel - Pisco.....	159
Figure 71:	Commercial Buildings - Ica.....	160
Figure 72	Beach Houses - Paracas.....	160
Figure 74	Pisco Grandstand.....	161
Figure 75	Ica Grandstand.....	161
Figure 76	Water Tower - Pisco.....	162
Figure 77	Cracked Tie Beams - Pisco Water Tower.....	162
Figure 78	Damaged School - Canete.....	163
Figure 79	Column Damage - Canete.....	163
Figure 80	Damaged School - Ica.....	163
Figure 81	Column Damage - Ica.....	164
Figure 82	Infill wall damage - Ica.....	164
Figure 83	School Constructed to New Standard - Pisco.....	164
Figure 84	New Standard School Detailing – Pisco.....	165
Figure 85:	Glass damage at an Ica school.....	165
Figure 86:	Spandrel separation at an Ica school.....	166
Figure 87:	Undamaged school – Ica.....	166
Figure 88:	University stadium Ica - no significant damage.....	167
Figure 89	Regional Hospital – Ica.....	167
Figure 90	Short Column Failure - Ica Regional Hospital.....	168
Figure 91	Operation preparation areas - Ica Regional Hospital.....	168
Figure 92	Unsecured Building Plant - Ica Regional Hospital.....	169
Figure 93	Ica, Llolleo and 1170 spectra compare.....	169
Figure 94	Ica, El Centro and 1170 spectra compared.....	170
Figure 95	ICA2:NS:1.0.....	170
Figure 96	El Centro:N:1.5.....	170
Figure 97	Llolleo:N:1.0.....	171
Figure 98	System Cumulative Total Energy.....	171
Figure 99	Cumulative Hysteretic Damping Energy.....	172
Figure 100	Steel Portal Warehouse, Port of San Martin.....	172
Figure 101	Acero Arequipa Steel Plant.....	174
Figure 102	Tank Damage - Pacific Blue Oil.....	175
Figure 103	Oil Terminal - Pisco.....	176
Figure 104:	Typical bridge on Carretera los Libertadores (Route 24a).....	176
Figure 105:	Huamani Bridge on the Pan American Highway at San Clements.....	177
Figure 106:	Superstructure damage.....	177
Figure 107:	Damage to restraining walls.....	178
Figure 108:	Rock falls on Route 24a.....	178
Figure 110:	Tsunami damage to pier on Paracas coast.....	179
Figure 111:	Structural damage to pier.....	180

Figure 112: Wharf damage - Port San Martin .....	180
Figure 113: Settlement behind wharf.....	181
Figure 114: Settlement of backfilled areas behind wharf.....	182
Figure 115: Wharf operation delivering emergency supplies to Pisco area .....	183
Figure 116: Ica waste water network.....	184
Figure 117: Ica water supply zonation.....	184
Figure B1: Reconnaissance team members .....	190

*List of Abbreviations*

CDEM	Civil Defence Emergency Management
CERESIS	Centro Regional de Sismologia
CISMID	Centro de Investigaciones Sismicas y Mitigacion de Desastres
ECC	Emergency Communications Centre
EERI	Earthquake Engineering Research Institute (California)
GIS	Geographical Information Systems
IGP	Instituto Geofisico de Peru
INDECI	Instituto Nacional de Defensa Civil
LATE	Local Authority Trading Enterprise
MM(I)	Modified Mercalli (Intensity) - a measure of earthquake shaking intensity
MTC	Ministry of Transport and Communications
NEIC	National Earthquake Information Centre (US)
NZS	New Zealand Standard
NZS1170	New Zealand Standard for Structural Design
NZSEE	New Zealand Society for Earthquake Engineering
OCHA	United Nations Office for the Co-ordination of Humanitarian Affairs
PVC	Polyvinylchloride - a plastic
SEDAPAL	Peruvian state-owned water company
UNDAC	United Nations Disaster Assessment and Co-ordination
UNICEF	United Nations International Childrens Emergency Fund
USAR	Urban Search and Rescue
USGS	United States Geological Survey
VHF	Very High Frequency

## SUMMARY

The Mw 8.0 Pisco earthquake struck at 6.40pm local time with an epicentre offshore about 150 km south of Lima. At least 519 people were killed, and over 1,300 injured. Over 38,000 homes were destroyed and more than 100,000 were made homeless. 14 hospitals were destroyed and many other facilities damaged. The city of Pisco was worst affected with serious damage to the majority of adobe buildings. Other cities and towns nearby suffered similar damage to a lesser extent, depending on the distance from the epicentre. The capital Lima was not seriously affected, although there was some minor damage to buildings.

Strong ground motions were felt for over two minutes. In this subduction earthquake a tsunami was generated and affected tens of kilometres of coast.

The New Zealand Society for Earthquake Engineering Society (NZSEE) sent a 6-person reconnaissance team to Peru. The team spent three days in Lima meeting with key authorities and four days in the field observing some of the earthquake-affected area. This report describes the team's observations and comments on the implications for earthquake engineering practice.

Highlights of the event in the eyes of the team were:

- The long duration of the event – over 2 minutes of strong shaking
  - The unique geotechnical context – no rainfall and sandy soils
  - Significant liquefaction damage to roads and buildings
  - Poor performance of adobe construction
  - Generally good performance of reinforced concrete brick infill – but there were major collapses.
  - Good performance of some unreinforced masonry buildings
  - Widespread use of shear walls in major buildings in Lima
  - Engineered structures generally performed well
  - Damage to parts of Pan American Highway due to liquefaction
  - Minimal damage to a major steel mill, designed to international standards
  - Collapse and/or overload of telecom systems for up to four hours following the event, isolating Pisco and Ica
  - Water and waste water systems and storage were seriously affected in Pisco, and significantly in Ica
  - Port St Martin, serving Pisco, was seriously damaged but functional
  - Coordination of overseas / international aid needs careful consideration as part of response planning.
  - Management of response resources is critical.
  - There were significant tsunami effects which were variable in height up to 10 metres.
  - Relatively minor damage to architectural finishes and building services can render hospitals non-functional.
- Survival of industrial facilities was important in reducing social impact by saving jobs.
  - The best of Peruvian earthquake engineering is international standard.
  - The development of earthquake-resistant standards in schools over the last three decades has paid dividends with modern designs performing well.

## 1 INTRODUCTION

The New Zealand Earthquake Engineering Society (NZSEE), through its President, Michael Pender, and Reconnaissance Team Organiser, Andrew King, activated its Reconnaissance Scheme and sent a 6-person team to Peru following the magnitude 8.0 Pisco earthquake of 15 August 2007.

One aim of NZSEE visit was to learn from the earthquake and so improve knowledge and practice in New Zealand for building earthquake-resistant infrastructure and resilient communities. Another aim was to show support to earthquake professionals in Peru who have achieved so much over the last few decades and who continue to push for further and more widespread mitigation measures.

The team consisted of David Hopkins (David Hopkins Consulting, Wellington) (leader), Darrin Bell (Connell Wagner, Wellington), Rafael Benites (GNS Science, Wellington), James Burr (Tonkin and Taylor, Auckland), Craig Hamilton (Wellington Regional Council), and Rudolph Kotze (Transit New Zealand, Wellington). The team selection covered the range of disciplines of particular interest.

The team left New Zealand on 25 August and returned on 4 September, spending a week in Peru – three days in Lima and four days in the Pisco area. The team was joined in Lima by Roberto Chavez of Lima who acted as guide / interpreter / facilitator for visits in Lima and in the field.

Prior to departure from New Zealand contact was made with the Peruvian ambassador to New Zealand who, together with the NZ Honorary Consul in Lima, facilitated contacts in Lima. Meetings were held in Lima with key authorities, including Ministries of Foreign Affairs, Transport and Communication, Education, Housing, and Health, the Lima Municipality, National University of Engineering, Catholic University of Peru, Geophysical Institute of Peru. These meetings provided much background information already gained from the field as well as an indication of the impact and response of the various sectors.

This report presents the observations of the team and the key lessons and implications evident from the reconnaissance mission. This consists mainly of what the team saw, but material from other sources has been included to provide the context and improve understanding of the implications.

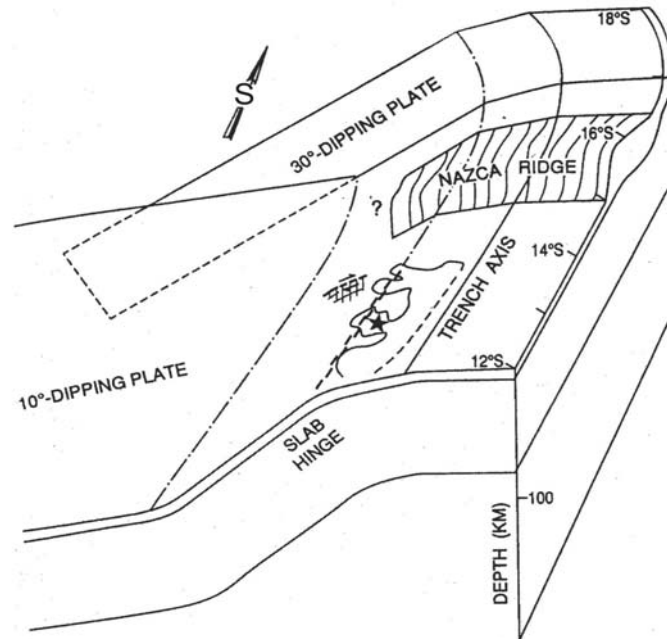
## 2 THE EARTHQUAKE

### 2.1 History of earthquakes in the area

The Peruvian seismic zone marks the boundary between the South American and the Nazca plates, and the continuation of the Peru-Chile trench (Figure 1), where the Nazca plate subducts under the South American Plate at about 8 cm/yr.

This process of plate convergency is responsible for the high seismic activity in the region, producing about 60 earthquakes of magnitudes  $M \geq 4.5$  at depths less than 60 km, per year. It is also responsible for the great, historical earthquakes documented in the last four centuries, of estimated magnitudes up to  $M 9.5$ .

### Subduction along the Peru-Chile Trench



**Figure 1. Tectonic setting**

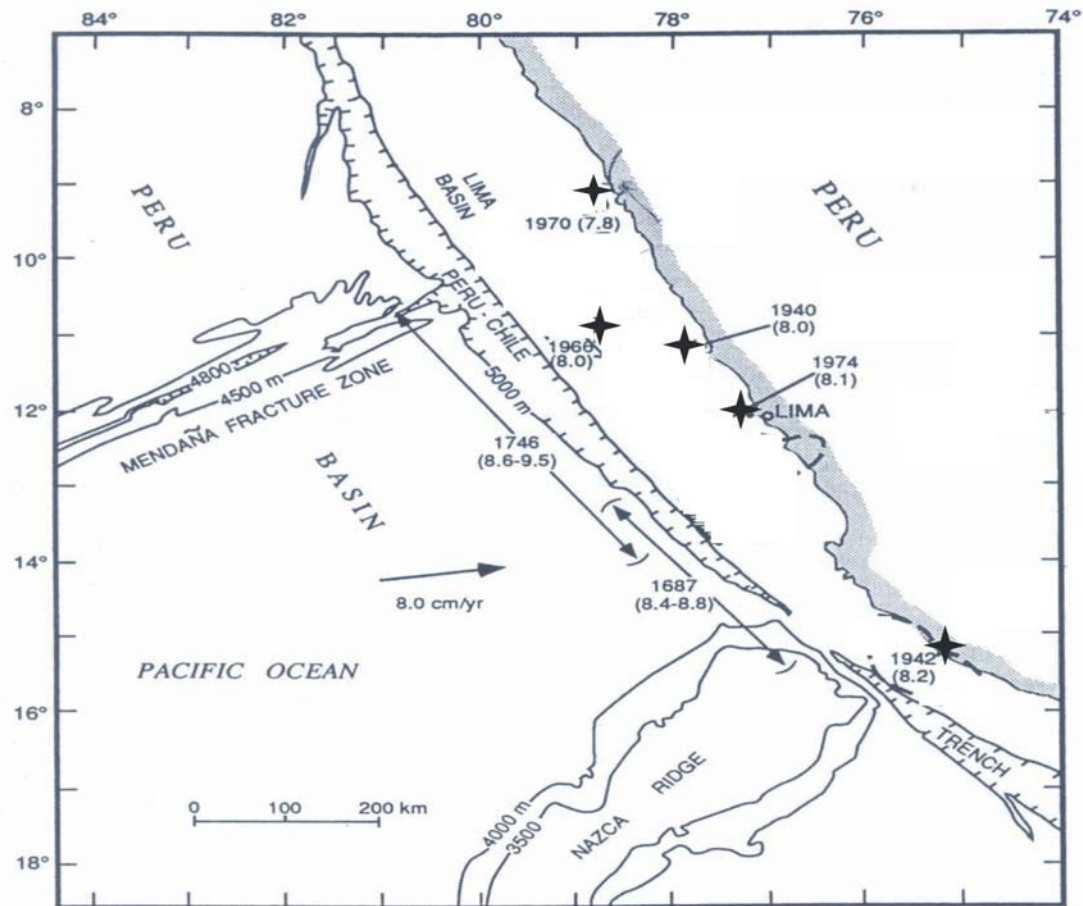
*Schematic view towards the South of the Nazca Plate subducting underneath the South-American Plate, along the Peru-Chile Trench. The shallow-dipping part of Nazca Plate is between slab hinge, where it is strongly coupled with its more steeply dipping northern part, and the Nazca Ridge, where it undergoes a smooth change of dipping angle, from 10° E to 30° E (from Langer and Spence, 1995).*

Typically, subducting plates dip between 8° and 10° until depth between 20 – 40 km, then increase their dip for depths in the range 30° – 70° before descending into the mantle. The subduction beneath central Peru, however, is rather peculiar: It dips typically down to a depth of about 100 km, then becomes horizontal for 500 km eastward, then again increases its dip descending into the mantle. This geometry connects the downdip extrapolations of both the Carnegie Ridge and the Nazca Ridge, whose buoyancy is considered the main contribution to the low angle subduction (Langer and Spence, 1995).

Most studies on the seismicity of Peru agree that the pattern of great historical earthquakes in the region show the existence of three seismically distinctive zones corresponding to the segmentation of the Nazca Plate subducting under Peru (Hasegawa and Sacks, 1981, Langer and Spence, 1995). These are bounded by the intersections of the Carnegie Ridge, at about 00-30 S, the Mendana fracture zone, at about 100 S, and the Nazca Ridge, at 150 S, with the Peru-Chile trench. Of these, the central segment, between the Mendana fracture zone

and the Nazca Ridge, exhibits highly irregular recurrence of great earthquakes, involving both large inter-plate underthrusting earthquakes and intra-plate normal fault earthquakes. It also shows irregularity of the rupture lengths, location of epicentral zones and timing (Dorbath et al. 1990). The details of seismic occurrence, tsunami generation and damage for this zone is available for the last 450 years (Silgado, 1985). Researchers have estimated rupture lengths between 70 km and 350 km for major earthquakes since the one in 1586 ( $M 8.1$ ) and corresponding average seismic slip in the range between 3 and 5 cm per year, accounting for about 50% of the total rate of convergency. The complexity of the rupture pattern associated with the major earthquakes in this zone is illustrated in Figure 2 (Langer and Spence, 1995) where the estimated rupture area for the event in 1746 ( $M$  between 8.6 and 9.5) covers the combined rupture areas for the 1966 ( $M 8$ ) and 1940 ( $M 8$ ) earthquakes, plus a big part of the 1974 ( $M 8.1$ ) earthquake. Prior to the 1940 earthquake, this zone shows no occurrence of major earthquake for almost 200 years.

## Tectonic Setting of the August 15 2007 Pisco earthquake



**Figure 2. Central section of subduction zone**

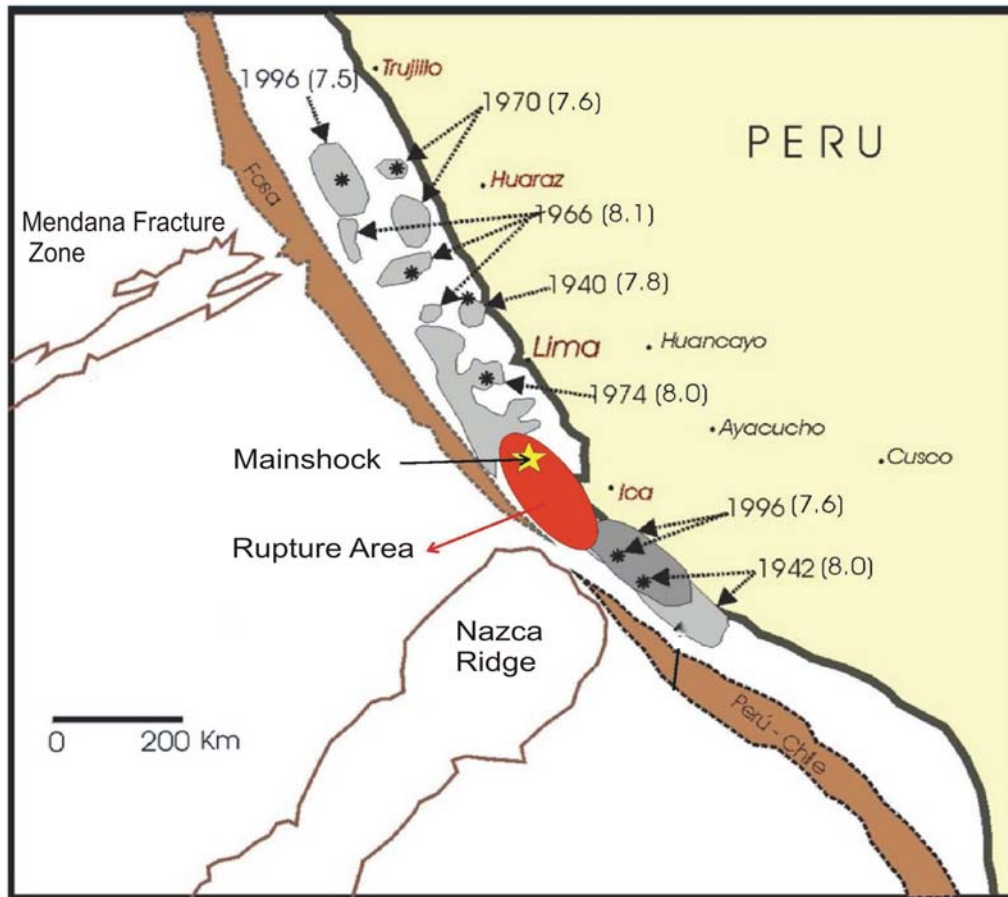
**Including the Mendana Fracture Zone and the Nazca Ridge, where a series of large earthquakes of M 7.8 – 9 occurred since 1687. Bracketed arrows depict approximate rupture lengths of the indicated events (from Langer and Spence, 1995).**

The Northern segment shows no important seismic activity except for only one major event in 1619 (M 7.7 - 8.0) with an estimated rupture length between 100-175 km, and with no tsunami generation. According to the chronicles of the time, this event caused severe damage in the city of Trujillo. The Southern segment shows more regular patterns of seismicity since the earthquake in 1582, of estimated magnitude between 7.7 and 8.0, the first documented earthquake in Peru. Great earthquakes in this zone have often generated local tsunamis, with heights ranging between 2 m and 14 m. The earliest well known is the event in 1604, of M 8.7-9.0, which ruptured along 450 km and generated a tsunami of height between 10-15 m (Dorbath et al. 1990). The latest is the June 23 2001 M 8.2 earthquake, in the city of Arequipa, which ruptured an area of 370 km x 70 km and generated a tsunami of local height about 10 m (Stirling et al. 2003). As pointed by Dorbath et al. (1990), the cumulative slip in this zone during the last 400 years is about 30 m, which accounts for almost the total displacement due to plate convergence. Also, the seismicity at the borders of the Central and Southern segments with the

Nazca Ridge shows three great events, the 1942 (M 8.2) and the southern tip of rupture of the 1687 event, suggesting that most of the convergence in this region is taken by aseismic slip.

### 2.2 Tectonic setting

The August 15 2007, M 8.0 Pisco, Peru earthquake (or Pisco earthquake) occurred in the Central segment of the Peruvian seismic zone, described above, at about 60 km west of the city of Pisco (Figure 3). It ruptured an area of about 170 km x 130 km, covering the Southern part of the rupture area of the 1974 (M 8.1) earthquake, and extending up to the northern side of the rupture area of the 1942 (M 8.2) and the 1996 (M 7.7) earthquakes. This spatial extent was identified by Tavera and Bernal (2005) as a "seismic gap", associated with the possible occurrence of a large earthquake, as well as by Robinson et al. (2003) by calculating the distribution of Coulomb shear stress along the coast, due to eight large earthquakes.



**Figure 3. Areas of primary slip**

*The shaded areas represent the approximated areas of primary slip for the indicated historical events. The red area is the estimated extent of the rupture area of the 15/08/07 Pisco earthquake. This occurred in the seismic gap predicted by Tavera and Bernal (2005).*

The depth of the event, about 40 km, and its focal mechanism solution (below) defined the Pisco earthquake as an interface event, similar to those of 1940, 1942, 1966, 1974, 1996 and 2001, as shown in Figure 4(a) (Tavera and Bernal, 2005). Tavera and Bernal also report that a peculiar feature, not confirmed yet, of the Pisco earthquake was that it may have had a precursor event on 11 August 2007, at about 19:18 UTC, of magnitude M 4.1. The epicentre of this event was at about 77 km NW of Pisco, followed in time by about 40 small aftershocks, as shown in the seismicity map in Figure 4(b).

### 2.3 Hypocentral parameters

The values below have been obtained from the Geophysical Institute of Peru (IGP), USGS and NEIC, all referred in Tavera and Bernal, 2005.

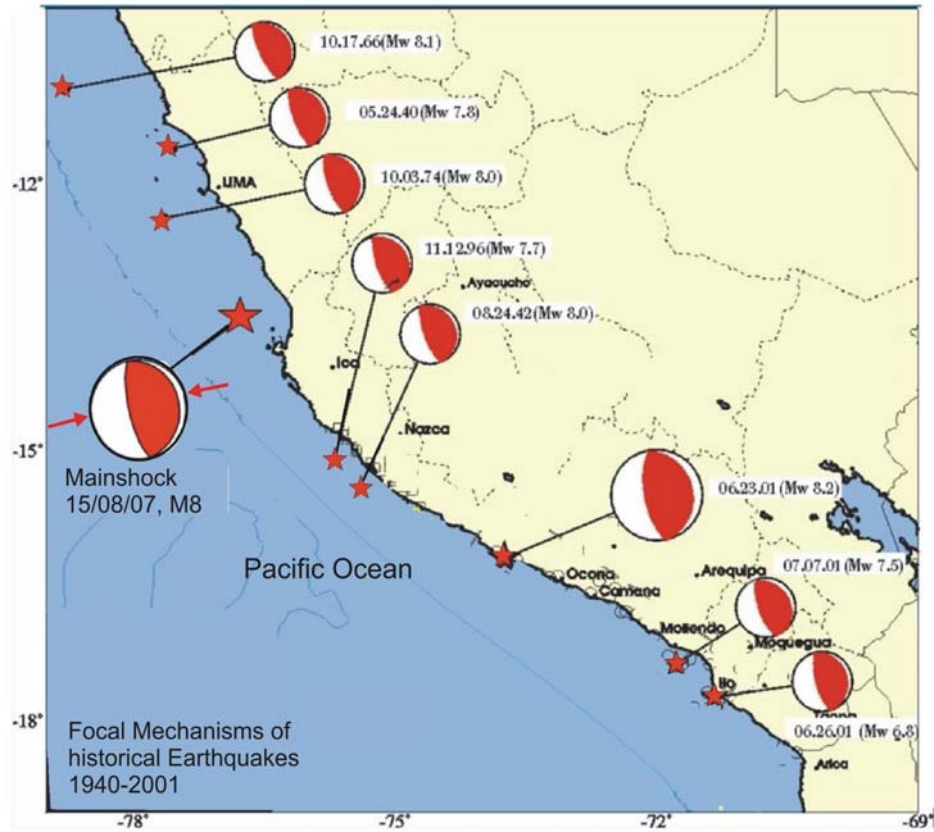
The hypocentral parameters of the Pisco earthquake are:

- Time: 23:40:40.56 UTC
- Location : 13.357 S, 76.521 W
- Depth: 40 km (IGP)
- Magnitude: Mw = 8.0 (USGS), 7.9 (IGP)

- Seismic Moment: 1.2 times  $10^{21}$  N-m (NEIC)
- Maximum Intensity: VII (MM) in areas of Pisco, Chincha and Canete.
- The focal mechanism of the Pisco earthquake correspond to a thrust fault, with nodal planes defined by  $\varphi_1 = 311^\circ$ ,  $\delta_1 = 14^\circ$ ,  $\lambda_1 = 119^\circ$ ,  $\varphi_2 = 161^\circ$ ,  $\delta_2 = 78^\circ$ ,  $\lambda_2 = 83^\circ$  (IGP), where  $\varphi$ ,  $\delta$  and  $\lambda$  denote strike (with respect to North), dip angle and rake angle, respectively.

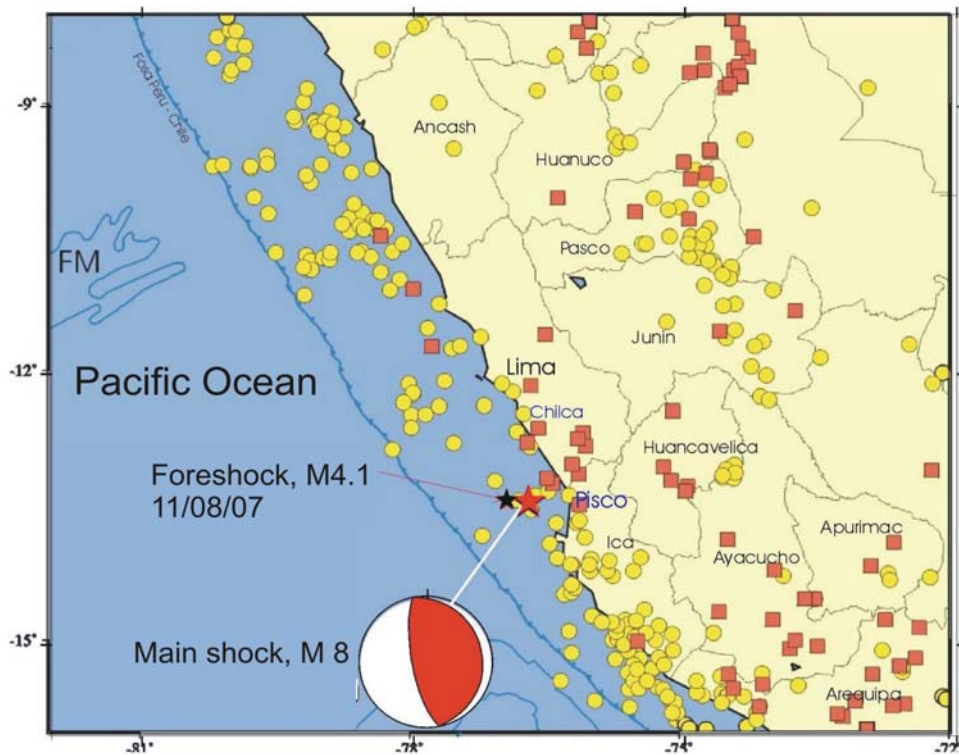
### 2.4 Key features

The rupture duration of the Pisco earthquake is of about 210 seconds, with the rupture front exhibiting South-East directivity (i.e. towards Pisco) and an average velocity of about 1.4 km/s. This unusual duration and rather low rupture velocity, which is just within one third of the rupture velocities observed for events of similar size, reveals a complex rupture process. The seismic waveforms at all stations that recorded the earthquake show the arrival of two groups of primary waves, corresponding to two distinctive rupture fronts and separated about 70 s in time. These are identified as R1 and R2 in the displacement records of, for example, station ANMO, USA, in Figure 5.



(a)

*Focal mechanisms of great earthquakes that occurred in the central and southern sections of the subduction zone in Peru. Note that all of them exhibit almost the same dominant (thrust) mechanism.*

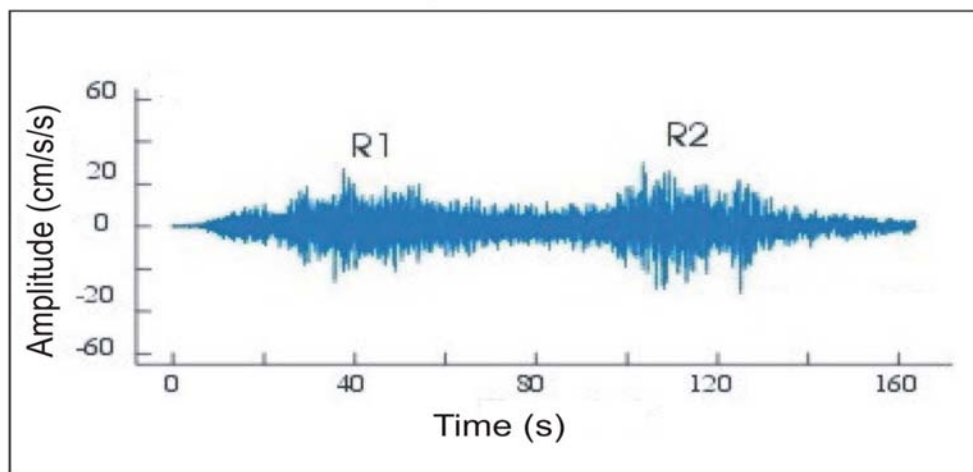


(b)

*The seismicity for  $M > 4$  corresponding to the central and southern sections of the subduction. Circles represent depths less than 60 km, and squares depths from 61 to 350 km.*

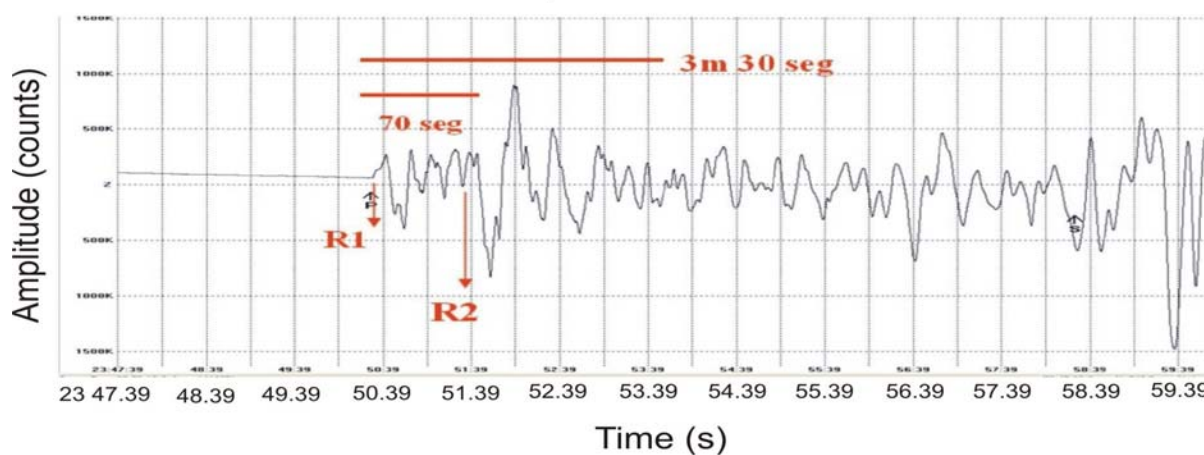
**Figure 4. Earthquake context**

Station MAY, strong motion  
166 km from Epicenter



(a)

Station ANMO (U.S.A.), Displacement  
6040 km from Epicenter



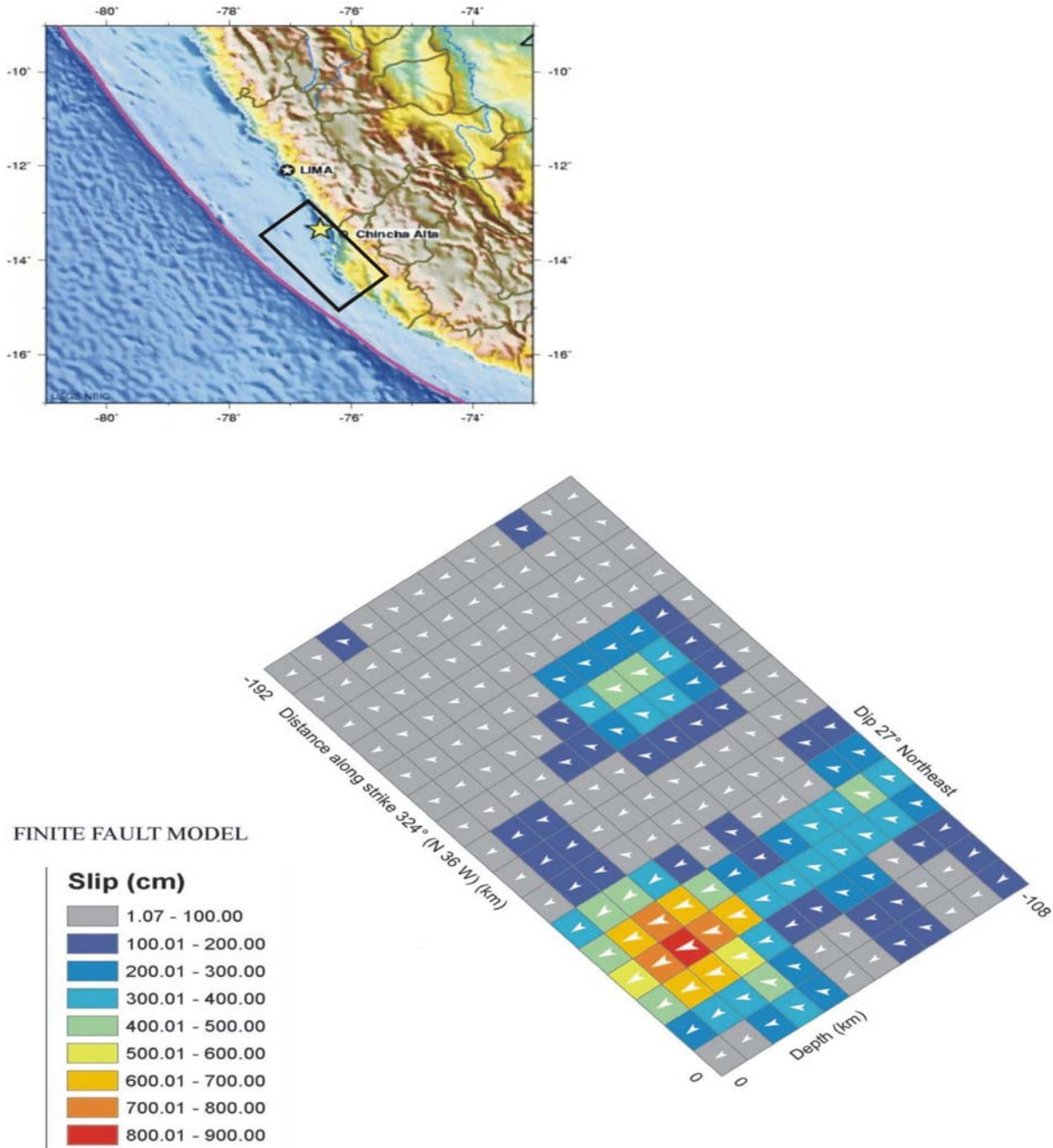
(b)

The sub-events recorded at two different stations from the epicentre, (a) Station Mayorazgo, Lima (Geophysical Institute of Peru) acceleration record, (b) Station ANMO, U.S.A. displacement record (from Tavera, 2007).

**Figure 5. Earthquake records**

A fault slip inversion on a fault area of  $192 \times 108 \text{ km}^2$  (determined by aftershock distribution) performed by USGS (Chen Ji from the university of California at Santa Barbara and Yehua Zeng, from NEIC) using teleseismic data shows that the rupture is, in effect, composed of two main slip events at points separated about 100 km within the fault, as shown in

Figure 6. The first one is down dip the fault, with a maximum slip of 3 to 4 m. The second is shallower, close and underneath the Independence Bay, south of the Paracas peninsula, with maximum slip between 8 - 9 m. This location is within the area of observation of a tsunami with heights of up to 5 m.

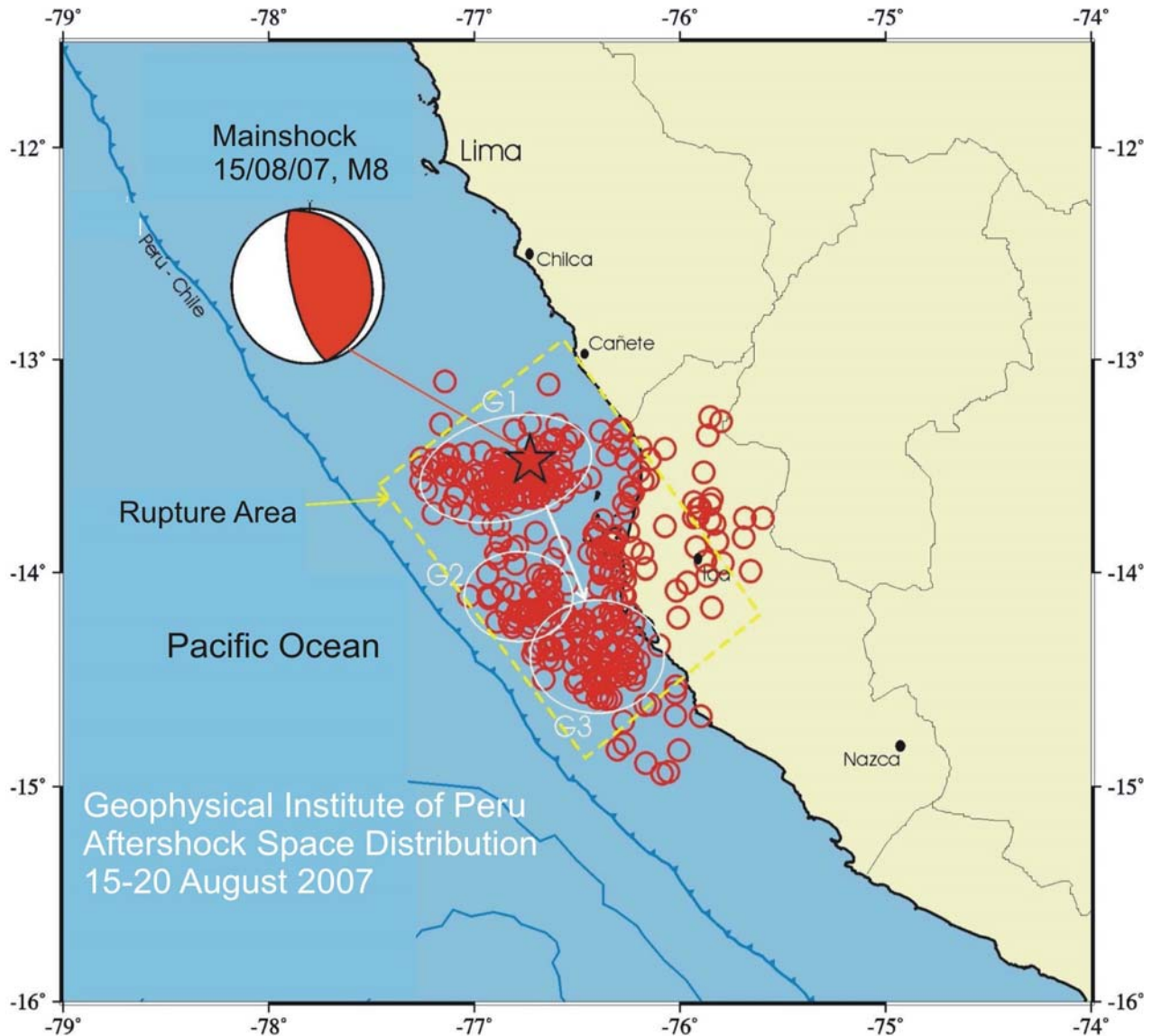


**Figure 6. Rupture analysis**

*Finite fault slip history inversion of the 15/08/07 Pisco earthquake. The fault area is depicted in the top figure. Note the appearance of two slip events, the larger towards the South and closer to the surface than that in the earthquake initiation point.*

A striking feature is revealed by the distribution of the aftershocks of the Pisco earthquake, reported by Tavera et al., 2007. Figure 7 shows the epicentres of 355 of those, of  $M \geq 3$ , and depths less than 50 km, projected upon a fault area  $150 \times 100 \text{ km}^2$ . It is observed that these aftershocks group into three main groups, G1, G2 and G3, the first around the hypocenter of the main shock, and the other two towards the south of the Paracas peninsula. It is clear from the epicentre location that

the energy has propagated mainly towards the south, in a process that could have been unilateral or bilateral. These coincide, roughly, with the slip inversion reported by the USGS, and can be associated with the presence of strong elastic heterogeneities within the fault, or “asperities”, or areas where the slip is relatively large as compared to other parts of the fault, and responsible for the generation of strong ground motion.



**Figure 7. Spatial distribution of aftershocks**

*This shows aftershocks of  $M > 3$  which occurred within 6 days after the 15/08/07 Pischo earthquake. Note the nucleation of events in about the same areas as those where maximum slip has occurred.*

## 2.5 Strong Ground Motion

The Pischo earthquake has been registered by a total of 15 strong motion instruments of the IGP, CISMID (Centro de Investigaciones Sísmicas y Mitigación de Desastres), SEDAPAL (the state owned water company) and CERESIS (Centro Regional de Sismología). Almost all the instruments are deployed in Metropolitan Lima; there is one near Pischo

(PCN, about 120 km South-East of the epicentre), and one in Ica (GUA) which, unfortunately, has not registered the earthquake due to instrument failure. Figure 8 shows the locations of the strong motion instruments as well as a general description of the soils on which they are deployed, and Table 1 shows the maximum accelerations recorded at each component.

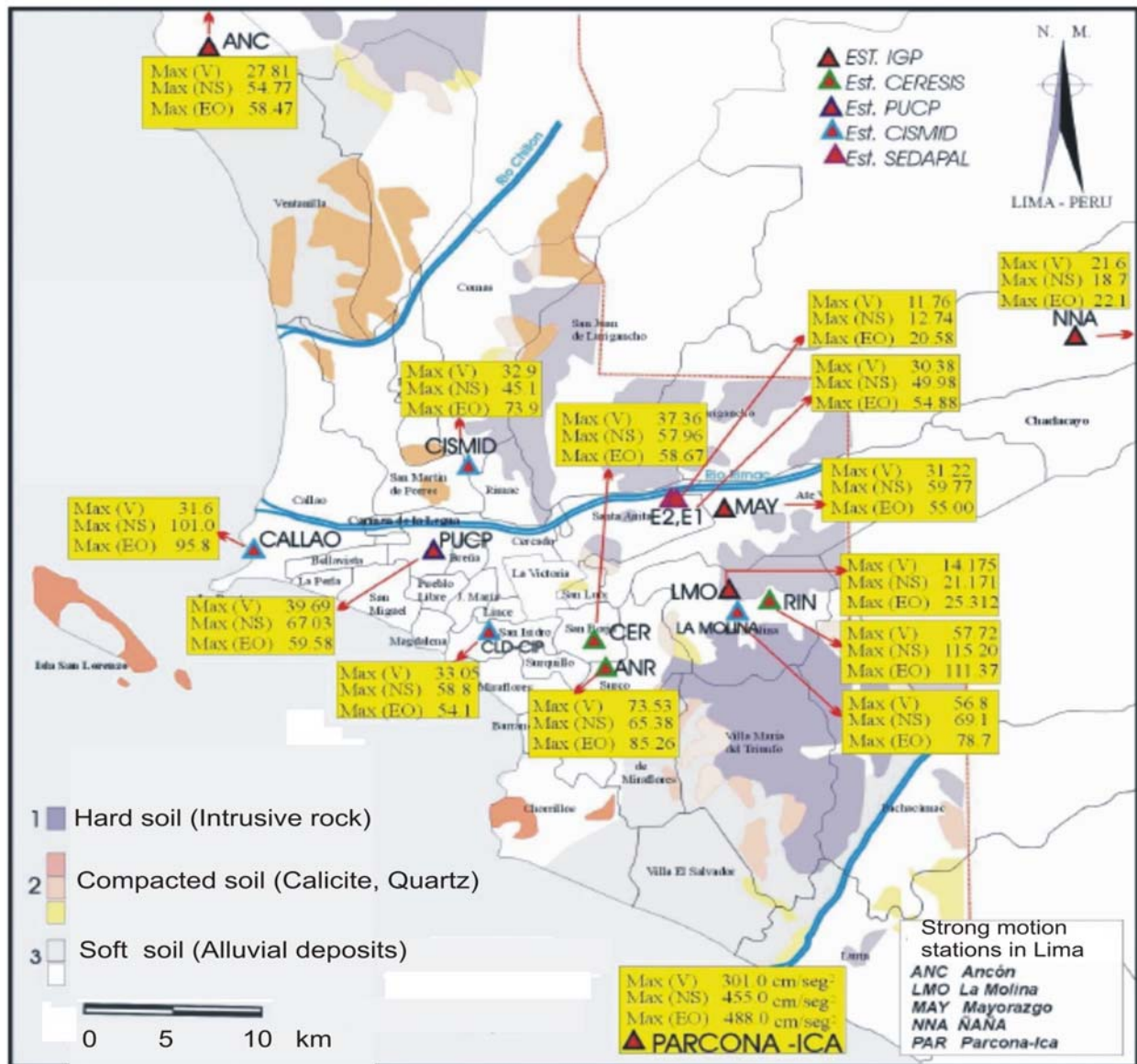


Figure 8. Location of strong motion instruments in Greater Lima

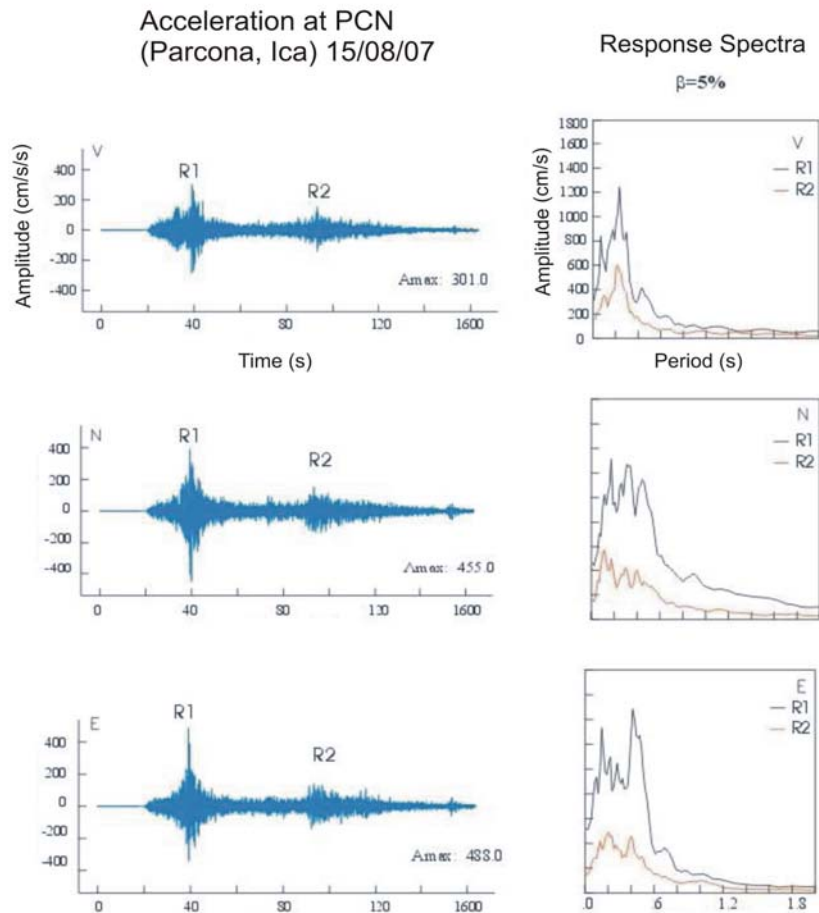
For each station, the maximum values of recorded acceleration for the three components are given within a yellow rectangle. The type of soils is indicated by the colours on the bottom left corner of the figure. The Parcona (PAR) station, in the city of Ica, is the closest to the earthquake epicentre, and is outside the scale in this map.

**Table 1: Recorded Accelerations (Amax)**

Station	Station Code	Acceleration (cm/sec <sup>2</sup> )		
		Vertical	North-South	East-West
IGP	PCN	301.0	455.0	488.0
	MAY	31.2	59.7	55.0
	ANC	27.8	54.7	58.4
	LMO	14.2	21.2	25.3
	NNA	21.6	18.7	22.5
CERISIS	RIN	57.7	111.0	
	ANR	73.5	65.2	85.3
	CER	37.3	58.0	58.7
PUCP	PUCP	39.7	59.6	67.0
CISMID	CISMID	32.9	45.1	73.9
	CLD-CIP	33.1	58.8	54.1
	La Molina	56.8	69.1	78.7
	Callao	31.6	101.1	95.8
SEDAPAL	E1	30.4	50.0	54.9
	E2	11.8	12.7	20.6

An example of acceleration recording is shown in Figure 9, for the PCN station, near the epicentre, for each component and corresponding response spectra. A dominant feature in these

accelerograms is the presence of the groups of primary waves R1 and R2, described above.

**Figure 9. Records from Parcona (PAR) station**

The acceleration recorded at the Parcona (PAR) station, for the three components. The response spectra has been calculated for each of the slip events R1 and R2.

## 2.6 References

Dorbath, L.A., Cisternas, A. and Dorbath, C. (1990). Assessment of the size of large and great historical earthquakes in Peru, *Bull. Seism. Soc. Am.* **80**, pp 551-576.

Hasegawa, A. and Sacks I.S. (1981). Subduction of the Nazca Plate beneath Peru as determined from seismic observations, *J. Geophys. Res.* **86**, pp 4971-4980.

Langer C.J., and Spence W. (1995). The 1974 Peru Earthquake Series, *Bull. Seism. Soc. Am.* **85**, pp 665-687.

Silgado, E., (1985). *Destructive earthquakes of South America 1530-1894*, Earthquake Mitigation Program in the Andean Region, Vol 10, CERESIS, Lima, Peru, 328 pp.

Stirling, M., Langridge, R., Benites, R. and Aleman, H. (2003). The Magnitude 8.3 June 23 2001. Southern Peru

Earthquake and Tsunami: Reconnaissance Team Report, *Bulletin of the New Zealand Society for Earthquake Engineering* **36**, 189-207.

Tavera, H., Bernal I., Strasser F.O., Arango-Gaviria M.C., Alarcon, J.E. & Bommer, J.J. *Ground Motions Observed During the 15 August 2007 Pisco, Peru, Event*, Submitted to the Bulletin of Earthquake Engineering, 7 April 2008.

Tavera H. and Bernal I. (2005). *Distribucion especial de areas de ruptura y lagunas sismicas en el borde oeste del Peru*, Boletin de la Sociedad Geologica del Peru, No. 6, Volumen Especial No.6 Alberto Giesecke Matto, pp 89-102.

Tavera H., Bernal, I. and Salas, H. (2007). *El Terremoto de Pisco del 15 de Agosto, 2007 (7.9 Mw)*, Departamento de Ica, Peru (Informe Preliminar), Instituto Geofisico del Peru, pp42.

## 3 THE AFFECTED AREAS

The significant effects of the earthquake were generally confined to the area within 20 kilometres from the coast, extending 100 km north from the epicentre to Lima and for a

similar distance to the south. The principal places of interest for earthquake effects were Lima, Pisco, Chincha and Ica as shown in Figure 10.



*Figure 10. Map of affected areas*

Lima, the capital of Peru is a sophisticated large city with buildings ranging from basic dwellings to modern multi-storey hotels, offices and apartment buildings. Infrastructure, similarly, ranges from modern and sophisticated to basic.

In common with many cities it has seen remarkable population growth, especially in the last 30 years - 300,000 in the 1930s, 3,500,000 in the 1970s and over 8 million in 2005. Much of the recent growth has been due to an influx of people from mountain villages and it is reported that about 50% of Lima's

population live in “shanty towns”. Buildings in these shanty towns are frequently up to three storeys in adobe or concrete block. Construction details are unknown. Many older government buildings of stone masonry or adobe reflect the Spanish influence of Lima’s past, while the more modern buildings reflect up-to-date knowledge of earthquake resistant design principles. Flat roofs are a feature of many residential houses and low-rise apartment buildings – rainfall in Lima and the coastal region is minimal.

Pisco, a coastal city about 100 km south of Lima, has a population of around 120,000. Annual rainfall, again, is minimal, but this southern area has many more sunshine hours than Lima. Pisco, which was founded in 1640, was once considered by the Spanish as a possible place for the capital city. Pisco is served by a port near Paracas and has an air force base immediately to the south. Residential, small commercial and government buildings are predominantly of adobe construction, including some notable churches, and hotels. A few more modern buildings of up to six storeys are of reinforced concrete frame with masonry infill. Pisco has a number of holiday residences and is a popular stop for tourists en route from Lima to Nazca, Arequipa and Chile to the south.

Founded in 1563, Ica is a city of 260,000 people to the south east of Pisco, located on the Ica River, about 400 m above sea level. Between Ica and the coast is 40 kilometres of sand dunes and desert. The range of building types is similar to Pisco’s but includes more modern and larger buildings. Ica is an important agricultural region where grapes, cotton, asparagus, olives and other produce is grown.

Significant industries in the Ica region include a world-class steel mill, large fish oil processing plants and a modern gas liquefaction plant.

## 4 EMERGENCY RESPONSE

### 4.1 Emergency Communications

#### 4.1.1 General

The ability of responding agencies to communicate verbally is critical in any emergency response. The ability to transfer data is equally as important given the reliance on information management tools and Geographic Information Systems (GIS) and the demand for sharing the intelligence of responding agencies to aid decision making.

The increasingly changing nature of technology and the advances being made by responding agencies in utilising technology, means that response procedures, processes and systems are constantly evolving and being updated to ensure that when required, emergency communications work.

Similar to New Zealand Civil Defence Emergency Management (CDEM) agencies, Instituto Nacional de Defensa Civil (INDECI) in Peru, has a number of communication systems in place utilising various technologies.

#### 4.1.2 Radio

In Ica the INDECI authorities lost telephone and internet based communications during the initial stages of the response and utilised VHF radio, powered by a generator, to communicate with other responding agencies.

The Ministry of Health used the same radio network, but some of the radios were reliant on mains electricity and as such were inoperable when the power was down. Those on battery power could be used.

The Ministry of Transport and Communications used their own radio network to communicate with their work crews and were able to communicate impact assessments of road damage on the main routes and establish where key communication outages had occurred. This system used battery power and was therefore operable.

Whilst the radio systems enabled verbal communication they are limited in data transfer capacity, an issue that has been highlighted through a number of significant exercises in New Zealand. Many CDEM agencies are using advances in technology to overcome this limitation, but understanding and robustness of this technology are critical discussion points before the limited budgets of these agencies are committed.

#### 4.1.3 Satellite

Like many of the CDEM agencies in NZ the INDECI authorities in Ica did not have access to satellite technology. Télécoms Sans Frontières assisted local response agencies by deploying an emergency crew of telecom specialists which installed two satellite based Emergency Communication Centres (ECC) offering voice, fax and internet access nationally. INDECI officials and the international response agencies were able to utilise this technology which added value to the response.

Télécoms Sans Frontières also installed satellite equipment at the key logistical area at Pisco harbour. Over 3500 MB of data was transferred and 100 hours of voice communications were used in 35 days.

Emergency communications were not restricted to the responding agencies. Telefónica and Télécoms Sans Frontières established calling operations for affected communities who wanted to contact family and friends to say “I’m alive” but could not use the damaged infrastructure.

The use of satellite technology is becoming a more cost effective option for communicating and many CDEM agencies in New Zealand are exploring how this can be applied to suit their needs and overcome the data transfer issue. This is not restricted to the traditional responders like Police and Fire. Many lifeline utilities that understand their responsibilities under the Civil Defence Emergency Management Act 2002 now utilise satellite technology in their own response arrangements at the very least to enable verbal communication.

### 4.2 Reconnaissance

Establishing the impact of an earthquake on a large geographical area such as Pisco, Ica or requires the co-ordination of information from many different agencies.

Early aerial reconnaissance gives response agencies an initial snap shot of the key geographical areas where further ground reconnaissance maybe required or an indication of where aid and resources will need to be deployed.

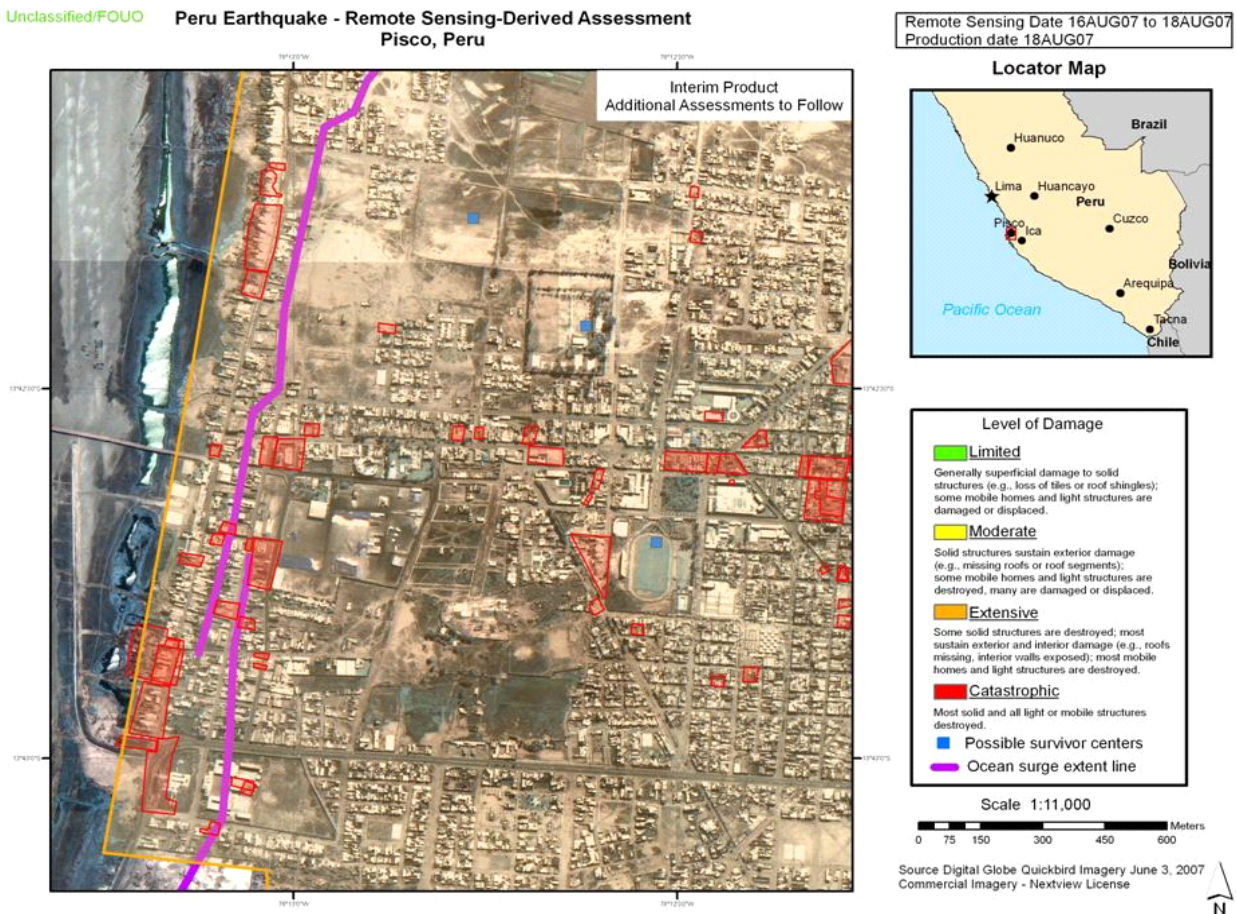
Ground reconnaissance will not only support aerial reconnaissance but it will also provide response agencies with the detail required for the essential decision making to save and protect life, property and the environment.

INDECI established a series of aerial reconnaissance sweeps on 16 August. These were used to give response agencies, both nationally and internationally, an indication of the scale of the event and where the critical areas of impact were.

Local knowledge was used to support the aerial reconnaissance, with INDECI volunteers being deployed to

the suburbs where suspected damage would be highest. In Ica, the authorities divided the city into six sectors and deployed staff and volunteers to a particular sector based on the needs established from this early ground reconnaissance.

Figure 11 shows the impacted areas in Pisco with possible survivor centres and ocean surge extent lines. This shows how satellite technology can be overlaid with the intelligence gathered from aerial and ground reconnaissance.



**Figure 11. Aerial view of Pisco showing worst-damaged areas**  
Photo courtesy INDECI Pisco

The Ministry of Transport and Communications deployed crews at 04:00 on 16 August to establish the damage to the major routes and the communications nodes. The Ministry of Health was concentrating on establishing the impact of the earthquake on their hospitals and medical facilities so they could make decisions on where to treat the injured and where to deploy field hospitals. However, they needed intelligence from the Ministry of Transport and Communications to make decisions on the movement of the injured, and from the Ministry of Education to determine which schools could be used as places for treatment.

The water companies concentrated on the impact on the supply system and reservoirs while the power companies focussed on establishing where power failures had occurred. Both of these critical elements helped with the decisions of other agencies on the deployment of staff or resources. This highlights that all agencies emergency services responsibilities need to understand their dependencies on other agencies for service delivery and also how co-ordinated reconnaissance can be mutually beneficial.

#### 4.3 Six Critical Needs

The six critical needs is a method of taking key components of disaster response and using them as focal points for tackling

an overwhelming event like an earthquake. Each critical need is not considered in isolation, but in conjunction with the others due to the interdependencies existing between them. Analysis of the situation for the Pisco earthquake follows.

##### 4.3.1 Urban Search & Rescue (USAR)

By the time the team arrived at Pisco and Ica some 12 days after the earthquake, USAR teams had long been stood down. However, monitoring of the situation provided a snap shot of the scale of USAR response by the national and international community.

Peruvian authorities relied on the international urban search and rescue community to support the national USAR response by supplying additional resources, both manpower and equipment.

Through the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), USAR teams from around the globe contributed to the response either by providing personnel on location, on standby or in monitoring roles. The United Nations Disaster Assessment Coordination (UNDAC) team on the ground in Peru was able to co-ordinate teams where necessary with assistance from INDECI.

These are not new lessons for New Zealand as arrangements are in place to assist UNDAC teams with the coordination of

international USAR response. However, the lesson is one of local responding agencies understanding the capabilities of national and international USAR teams whilst ensuring that the transmission of intelligence, generated by the local response, assists in the deployment of USAR teams.

Figure 12 shows the USAR team's record of casualties in the collapse of San Clemente Cathedral in Pisco where 148 people lost their lives, a reminder of the nature of the search and rescue activity.



*Figure 12. USAR casualty record on San Clemente Cathedral, Pisco*

#### 4.3.2 Treatment and movement of the injured

The early reconnaissance and impact assessments carried out by the Ministry of Health quickly established that medical facilities and hospitals in the affected areas were limited in capacity, not only for providing continued treatment of

existing patients, but also in their ability to provide treatment to those injured in the earthquake. Figure 13 shows damage to a hospital treatment room which has rendered it unusable to treat the injured.



*Figure 13. Damage to hospital treatment room in Ica Regional Hospital*

In Ica the regional hospital and in Chincha the main hospital was only partially operating. Because of the overwhelming emergency demand the continued care of existing patients was compromised. In Ica and Chincha, potable water and electricity outages rendered hospitals to 60% functionality. In Pisco, the main hospital was unusable due to collapsed walls.

The Ministry of Health built into their response arrangements contingencies for moving and treating the injured. On 16 August health teams of 50 doctors, 30 nurses, 20 ambulances

and a mobile operations centre were sent to Chincha and Ica. For the severely injured, an air bridge was established between affected areas and the capital Lima, where fortunately the medical facilities and hospitals were undamaged. By 21 August, 650 wounded had been transferred to Lima for treatment. INDECI have reported that the total number injured for this event was 1,366.

### 4.3.3 Health

The Ministry of Health used exercises to refine response arrangements. These were aimed at both health sector response arrangements and co-ordinated arrangements requiring the assistance of other agencies. These refined arrangements were used during this event.

The President was quoted as saying in on 16 August that all doctors should be on standby and all health services would be free of charge to those that needed it. This was supported by the Ministry of Health who declared that a state of alert was in place for all hospitals and asked all medical personnel in Peru to be on standby.

The Ministry of Health immediately stated the specific medical supplies that would be required and this is evident from the OCHA situation report 2 issued on 16 August 2007. This intelligence, identified through exercises, enabled the international response community to respond quickly and put in place the logistical requirements to get the medical resources to the appropriate locations.

Although unknown during the initial stages of the response, the impact on the health sector was significant as 103 hospitals were affected and 14 were destroyed. By 19 August, situation reports acknowledged the quality of the impact assessments coming from the health sector. This intelligence supported the early decision making before (?) the extent of the impact was more fully known.

The health sector not only have a role to play in assessing and supporting hospitals and medical facilities, but they also have a significant role in public health related issues, such as disease control and nutritional assessment at the welfare camps. The actions taken by the health sector to address these issues were much more effective as a result of the response exercises.

### 4.3.4 Welfare

INDECI reports that 58,581 houses were destroyed by the earthquake. This left thousands without basic welfare components, shelter, food, the facilities to cook food and a source of quality water. Some of the displaced people would have been taken care of by family or friends but the majority looked to the Peruvian authorities to assist. In Pisco alone, 24 camps were set up to shelter 21,275 people.

A visit to a camp in Ica (Figure 14) demonstrated the work that had gone into providing the means for people to survive. The camp had a number of latrines to provide for sewage disposal. These were regularly maintained by a local contractor to ensure that they did not become a health risk. The camp had a number of 2,500 litre water containers that were topped up by local water tankers filled from the city's water towers. The authorities had contracted local delivery companies to deliver food to the camps, thus using local resources and aiding local recovery.



*Figure 14. Camp at Ica*

Army personnel were located at the camp in Ica. Security following the earthquake did become an issue and army personnel were deployed to mitigate any risk of looting or violent unrest. By basing themselves at the camp they provided security to this particular camp.

The nature of this event and the associated impacts dictated that many international agencies would be required to support the Peruvian response. This meant that logistical arrangements needed to be effective in getting the humanitarian aid to these camps and other locations at the appropriate time. Some indication of the complexities and the enormity of the logistical role are evident by the large quantities of tents, blankets, folding beds, mattresses, sheets, food, clothing,

generators, hygiene kits, cooking utensils and bottles of water quoted in the situation reports published by response agencies. Indeed, logistical arrangements became a focal point for discussion between INDECI and the UNDAC team so that clear systems could be identified and put into place to manage the supply and distribution of relief supplies.

### 4.3.5 Sanitation

The sewage systems in Pisco, Ica and elsewhere were affected by the earthquake and a number of disruptions were evident throughout the impacted areas.

Latrines were set up at the welfare camps to provide the first barrier to prevent disease. Health authorities identified this as

a key risk and were ready to respond. Whilst these provided short term relief, health authorities continued to discuss this method of sewage disposal given the challenges of maintenance, cleaning and effective disposal.

Debris from the collapsed buildings was enormous. Many of the affected streets showed piles of rubble, either through demolition or as a direct result of the earthquake. Debris, mainly adobe rubble, was pushed into the street ready for loading onto one of the many trucks. The short term destination of the debris was one of the many large, barren open spaces available in or near the urban areas.

By 15 September INDECI reported 210,000 m<sup>3</sup> of debris had been removed. Authorities now face decisions on what to do with the debris in the long term. There is a high risk that the temporary sites will become a dumping ground for refuse and create a public health hazard.

The Peruvian Health authorities quickly established a number of public information messages regarding health risks. Due to the collapse of water and sewage systems, on 17 August

public information on the prevention of communicable diseases such as acute respiratory infections and diarrhoea was broadcast. 150,000 flyers on prevention of pneumonia, diarrhoea and other likely ailments were distributed in affected areas and a number of programs were broadcast on local radio throughout Ica on health issues.

Driving the public information were the continual epidemiological studies and nutrition assessments that provided the health authorities with the data on public health issues such as E.Coli and Salmonella. Whilst the utilisation of the communal kitchen system to provide food for the affected communities proved effective, concerns about food-transmitted diseases remained and the situation monitored(?).

A number of vaccination centres (Figure 15) were established in many suburbs, with the services free of charge. The vaccinations that were administered were dependent on the intelligence from the studies and assessments being undertaken. For example, in late September a yellow fever vaccination programme was established specifically for Ica.



*Figure 15. Immunisation tents in Chincha Alta*

#### 4.3.6 Restoration of lifelines

Understanding the impact on engineering lifelines is essential in determining logistical arrangements for the deployment of humanitarian aid and prioritisation for the restoration of essential services such as water supply, sewage disposal or electricity supply. Many of the Peruvian lifelines were affected during this event, which required co-ordination of information and response arrangements. Section 9 discusses these impacts in more detail.

## 5 GEOTECHNICAL

### 5.1 Geotechnical overview

The geology of the near coast area from Chincha Alta south to Paracas is described in published geological maps as comprising recent Quaternary aged marine, alluvial and aeolian deposits. The source of these alluvial deposits is the Andes, which are located directly to the east. An extract from the Pisco geological map is shown in Figure 16. Based on the observations during the site reconnaissance, the alluvial

materials are typically sandy gravels while the aeolian deposits are a relatively uniformly graded fine sand with some/minor silt. No observations of the marine deposits were made. A few outcrops of Tertiary Pisco formation rock are shown adjacent to the Rio Pisco and this rock was observed on the north abutment of the Huamani Bridge. The rock comprises a white thinly bedded mudstone/siltstone with subvertical jointing along the bedding.

The area directly south of Paracas encompassing the peninsula is shown as comprising Quaternary aeolian deposits, Tertiary Paracas formation, Jurassic Chocolate formation and various Palaeozoic granite units. None of these deposits was observed in any detail although much of the ground surface in this area was covered in sand and small gravels. The Port (Puerto General San Martin) located at the north east corner of the peninsula is underlain by one of these granite units although the majority of the port is on fill, presumably sourced from these adjacent materials.

What makes the area particularly unusual from a New Zealand context is that it is a desert with little or no regular rainfall. Figure 17 shows a photo of the typical landscape in the area.





*Figure 17. Typical desert landscape*

## 5.2 Slips

The earthquake caused numerous slips in the affected area and the team observed some of these, particularly around the road network as these were easily recognisable and accessible. We were made aware of some of the slips in the area by other agencies, including Ministry of Transport and Communications, the Geophysics Institute and CISMID.

The slips that the team is aware of can be broadly grouped into three main types as follows:

- Rock slides in the foothills of the Andes to the east of the main affected area,
- Small embankment failures caused by liquefaction in the flat Quaternary areas,
- Larger scale landslides near the coast by Chincha Alta.

These slips are discussed in more detail below.

### 5.2.1 Rock Slides

A large rock slide was observed by the team on a cut slope above Route 24a running from San Clemente up to the foothills of the Andes. The rock is a strong sandstone with variable joint spacing from 10 mm to over 1 m. The rock has at least one unfavourable joint orientation dipping out of the cut face. The debris from this slide varied from small gravels up to boulders of around 2 m in diameter. The slide had destroyed the steel “W” crash barrier and closed the road with

boulders visible several hundred metres away at the toe of the slope. While the road was open during our inspection, the slope was still quite unstable with constant small debris falling and many large blocks with open joints looking ready to fall. This slide is shown in Figure 18.

The Ministry of Transport and Communications (MTC) gave us information on many other rock slides further up the valleys. Many of these are also falls from cut faces above the roads (see Figure 19). However, at least one appears to be the reactivation of a large scree slope slide (see Figure 20).

### 5.2.2 Small Embankment Failures

We observed numerous small road embankment failures on the Pan American Highway between Cerro Azul and Pisco. These failures were caused by liquefaction of the underlying soils and were typically located where the road was carried by a low embankment crossing a shallow valley with higher groundwater levels. The embankments were less than 3 m high and the slips generally appeared to extend back to no further than the centreline. Figure 21 shows one such typical embankment failure. Power poles running along the sides of the embankments were also damaged by the slips and many poles were leaning or had been replaced. In one location we noted a laterally extensive and several meter high failure in the adjacent natural sandy slope.



*Figure 18. Rock slide above road in Andes foothill*

s



*Figure 19. Failure of cut slope*  
*Photo – Ministry of Transport and Communications*



**Figure 20. Reactivation of scree slope**  
Photo – Ministry of Transport and Communications



**Figure 21. Typical embankment failure as a result of liquefaction**  
Photo – Ministry of Transport and Communications

Numerous sand boils and surface cracks were observed in these areas and confirmed the presence of liquefaction. The ejecta from the sand boils was a fine sand with no more than a trace of silt. The cracking was confined to within the shallow dry crust at the surface but was laterally extensive in some cases.

Liquefaction-induced embankment failures were observed on the section of Pan American Highway. This section of road that runs along at a low level near the coast north of Chincha

Alta is founded on recent marine deposits and has a high groundwater level due to its proximity to the sea. These embankments were less than one metre high but were still affected with lateral spreading and some vertical displacement, typically along the centreline as shown in Figure 22. The steeper sandy slopes above the road had numerous very shallow failures. These appeared to be restricted to the crust at the ground surface.



**Figure 22. Low embankment failure**  
Photo – Ministry of Transport and Communications

The most significant liquefaction damage observed was to the embankment leading to the southern abutment of the Huamani Bridge. We were informed that vertical displacements of up to 1 m were recorded in this approximately 4 m high embankment. The damage to the road can be seen in Figure 23. The failure of this embankment and therefore loss of

passive resistance may have been responsible for the damage to the upper part of the bridge's southern abutment wall. The toe of that southern abutment wall shows signs of movement out towards the river with the riprap at the base having clearly recently moved.



**Figure 23. Damage to the Huamani Bridge southern embankment**  
 Photo – Ministry of Transport and Communications

### 5.2.3 Larger Landslides

The team briefly observed a larger scale slip located on the Pan American Highway north of Chincha Alta as the road drops to the coastal plain. The slip occurred in a fill embankment over a deep gully, took out one lane of the road and left a steep scarp along the centreline as shown in Figure 24.

The EERI reconnaissance team observed a large scale liquefaction-induced seaward displacement of a marine terrace along the coastline north of Tambo de Mora<sup>1</sup>. The block is approximately 3 km long by 1 km wide with a maximum vertical offset of 3 m and cracks up to 1 m wide. Sand ejecta were observed inside many of these cracks.

The northern boundary of this failure is adjacent to the slip observed in the Pan American Highway discussed above and it is possible that the damage to the road is part of or at least affected by this larger failure.

---

<sup>1</sup> “Learning from Earthquakes, The Pisco, Peru Earthquake of 15 August 2007”, EERI Special Earthquake Report, October 2007.



**Figure 24. Larger slip on Pan American Highway**  
 Photo – Ministry of Transport and Communications

### 5.3 Liquefaction

In addition to the road embankment failures we observed many other instances of liquefaction in the area affected by the earthquake during our reconnaissance trip and are aware of other locations that we were unable to see. Many areas are quite susceptible to liquefaction due to the nature of the soils (alluvial sandy gravels and aeolian sands) and the high groundwater conditions near the coast and rivers.

#### 5.3.1 Pan American Highway

The liquefaction resulting in the small Pan American Highway embankment failures is discussed the previous section. As noted in that section there were numerous sand boils in these locations and the streams of ejecta running from the boils could be clearly seen on the ground surface. Extensive cracking of the surface crust was also observed, in some cases this crust was 200 to 300 mm thick and the subsequent crack could be up to 100 mm wide, although it was generally much smaller than this. The ejecta and crustal cracking can be seen in Figure 25 and Figure 26 respectively.



*Figure 25. Sand ejecta beside Pan American Highway*



*Figure 26. Surface cracking from liquefaction*

Liquefaction damage was observed in one section of the road leading from the Pan American Highway to the town of Pisco. Again this was a low lying section of road with high groundwater. The damage comprised cracking and a step in the road pavement. The road was still operable but vehicles needed to slow down and avoid the worst areas. It is likely that other sections of local roads in similar circumstances were affected by liquefaction damage.

Some liquefaction was noted at the Huamani Bridge. The damage to the southern abutment approach embankment is

described above, but in addition some sand boils were observed around two of the foundations as shown in Figure 27. The most damaged pier had several sand boils around it and the next pier north had two boils. The ejecta consisted of clean fine to medium sand. No vertical displacement was observed in the bridge and no sand boils were seen in the open areas between the piers or upstream and downstream of the bridge. The sand boils around the piers are therefore considered to be the result of the lateral movement of the bridge foundations forcing the sand up through the surface.



*Figure 27. Ejecta around bridge abutments*

### 5.3.2 Pisco and Paracas

The towns of Pisco and Paracas suffered from liquefaction damage in the areas directly adjacent to the sea. In Pisco this appears to be confined to cracking and settlement damage to pavements and the settlement of the ground around a buried sewage pumping station. In Paracas the liquefaction caused extensive cracking and settlement damage to the promenade

and small seawall along waterfront. The team observed settlement and lateral spreading damage to several roads and houses close to the coast including a 300 mm longitudinal offset to a wall running perpendicular to the coast (see Figure 28 ). Two wharves were damaged in Paracas with structural failure at the pile heads, probably due to reduced resistance to lateral loads caused by liquefaction of the underlying soils.



*Figure 28. Liquefaction-induced offset to wall in Paracas*

### 5.3.3 Port San Martin

The largest single area of liquefaction damage we observed was at the Port (Puerto General San Martin). The port is located at the north eastern corner of the peninsula and the majority of the flat port land has been created by placing fill into the sea. This fill is constrained at its outside edge by a concrete retaining wall running along the rear of the wharf structure. The two ends of this fill platform are unrestrained.

The team noted extensive damage to the port pavements due to liquefaction. These pavements include large hexagonal concrete slabs and asphalt surfaces. The damage comprises up to 1 m vertical settlement of the fill and cracking of several hundred millimetres width and up to 1 m deep. The settlement and crack widths increase in magnitude towards the sea and wharf structure. The wharf pile foundations appear to have coped well with the earthquake motion and also the lateral loads imposed by the liquefied soils behind the retaining wall. Without this retaining wall the damage to the pavement would have been significantly greater as could be seen from the much larger movement and damage along the ends of the port where the fill is unrestrained.

The ground settlement in the flexible asphalt occurred as a relatively constant grade in the final surface from the inshore

side to the wharf side, whereas the concrete slabs were left with a stepped profile between each slab. The maximum step observed was approximately 200 mm.

Numerous sand boils were observed all over the pavements with ejecta from the boils and most of the cracks almost covering the surface in some places. The ejecta comprised fine uniform sand with very little silt and one area of fine gravels, all being the fill materials in the underlying port reclamation.

Wharf storage sheds are located on the liquefied fill areas of the port. These are steel portal structures supported on concrete filled steel piles, presumably founded below the fill. One of these buildings was located near the wharf in the area of greatest ground movement and the adjacent ground settled by up to 500 mm as well as suffering significant horizontal displacement. Refer Figure 29. Figure 29 Some gapping was observed in the soils around the top of these piles indicating that the piles had moved laterally in relation to the ground. However, the piles and their connections to the concrete ground beam appeared to be in good condition as did the sheds themselves, indicating that the earthquake ground motions and the liquefied soil movements had little detrimental effect on these pile foundations.



*Figure 29. Ground subsidence in wharf shed at Port San Martin*



*Figure 30. Liquefaction damage at Las Lagunas*  
*Photo courtesy Alfonso Rey*

### 5.3.4 Other locations

The team was made aware of liquefaction damage at other locations. One of these caused considerable damage to four houses in the area known as Las Lagunas. This is an up market subdivision around 70 km south of Lima set around a lake, thereby providing a source of water to increase liquefaction potential. Refer Figure 31. The damage comprised extensive settlement and lateral spreading resulting in large cracks and differential movement in the houses. Based on the photos we saw, at least some of these damaged houses will need to be demolished.

The EERI reconnaissance team also observed significant liquefaction induced settlement in the coastal town of Tambo de Mora. They report instances of up to 900 mm settlement in buildings in that area.

### 5.4 Microzonation studies

The potential for damage from liquefaction is well understood in this area of Peru and both the towns of Pisco and Ica have had microzonation studies undertaken for them. The studies

are based on SPT results from boreholes around the towns and each of the reports included a hazard map indicating the areas at highest risk. These maps are shown in Figure 32.. The zones shown in these figures are based on the allowable bearing capacity for shallow foundations.

The Pisco map provides values from 1 to 3 kg/cm<sup>2</sup> (100 to 300 kPa) and the Ica map provides values of 0.5 to 2 kg/cm<sup>2</sup> (50 to 200 kPa). Superimposed on these microzonation maps are the areas of significant building damage in each town. The Pisco microzonation correlates well with damage - most of the affected buildings being within or adjacent to Zone III, the most susceptible to liquefaction. The damaged buildings in Zone II are near the coast and the damage here may be the result of higher groundwater levels and damage by the tsunami.

The Ica correlation is not as evident with most of the damaged buildings being in Zone 2 rather than the highest risk area of Zone 3. However, Zone 2 contains the older and commercial part of the town and Zone 3 is comparatively free of development, as can be seen in the Figures.

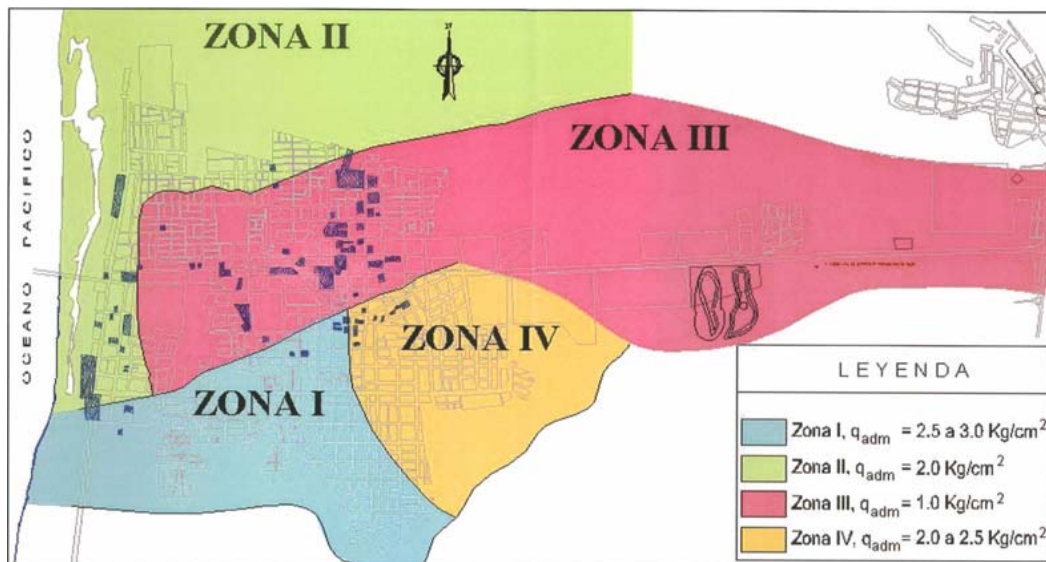


Figura N° 3: Zonificación Geotécnica de la Ciudad de Pisco

Figure 31. Microzonation map – Pisco

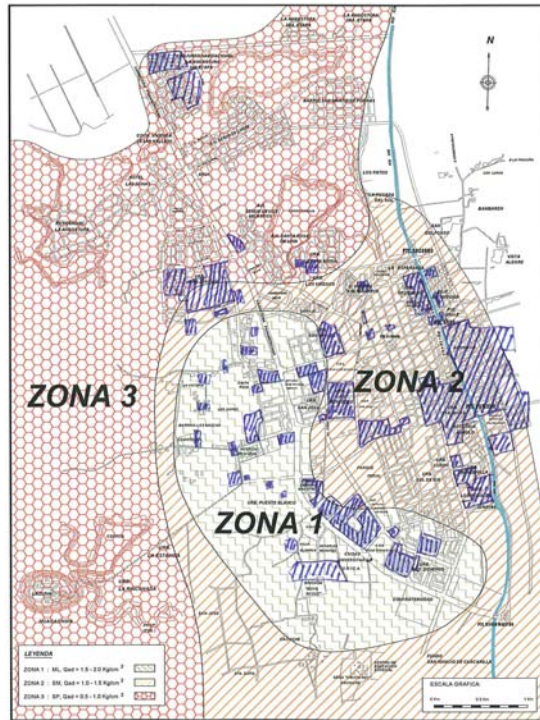


Fig. Nº 1: Zonificación Geotécnica

Figure 32. Microzonation map – Ica

5.5 Tsunami

The earthquake was centred near the coastline and the resulting tsunami arrived quickly (10 to 20 minutes) with only minimal warning times for the coastal inhabitants. Most areas received warnings or understood the potential danger but even so there were several deaths caused by the tsunami.

The team observed the tsunami damage in Cerro Azul, Pisco and Paracas and received some detailed run-up and damage

records from Dr Ronald Woodman of the Instituto Geofísico, who had made a special personal study of tsunami effects in the Paracas area. Refer Figure 33. In Cerro Azul a hotel had tsunami water over the patio area adjoining the beach and through the foyer, corresponding to a level of at least 2 m above mean sea level.

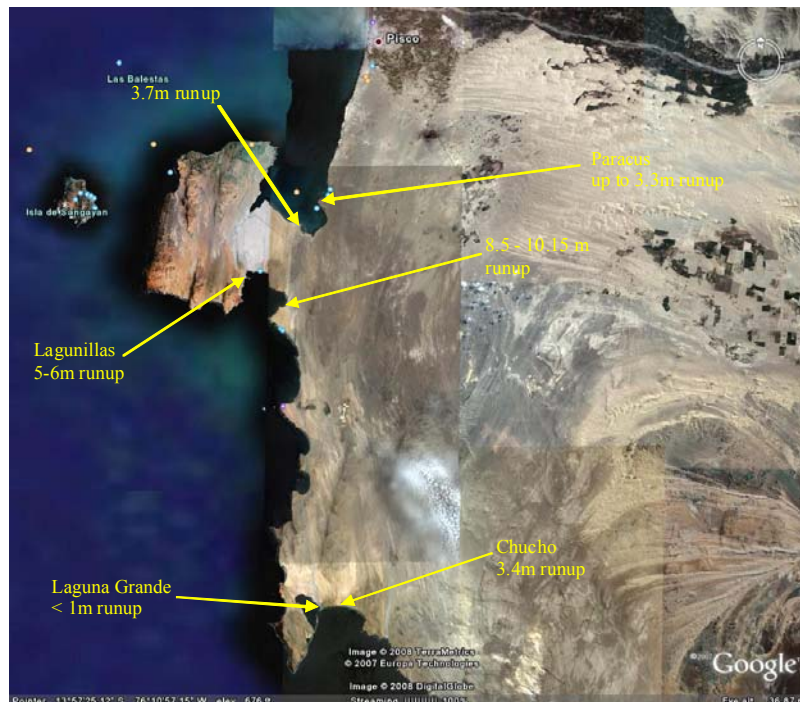


Figure 33. Tsunami run-up details

In Pisco and Paracas the tsunami washed boats up into the streets and flooded low lying buildings near the coast. Refer Figure 34. In Paracas, we measured a water mark 1.2 m above floor level on the wall of a shop on the main promenade. A resident stated that the tsunami wave was 3 m high through his house which is located approximately 20 m from the sea. Just to the south of Paracas where the coastline ground profile rises up at around 30°, the run-up was recorded at heights of around 3.3 m to 3.7 m above mean sea level.

In Pisco water marks were observed about 1 m above floor level on some concrete houses set back 30 m from the sea. Many of these houses had broken windows at low levels which were probably caused by the tsunami.

The tsunami was significantly larger to the south of the peninsula, with run-up heights of up to 10 m recorded around the bay formed by the southern part of the peninsula. In Lagunillas a 5 to 6 m high wave destroyed buildings on a small narrow point and three deaths were reported. In Laguna Grande some 30 km south of the peninsula no damage was reported to the fishing village which sits on a sandspit around 1 m above sea level. However, in Chucho around 1.7 km away, a 3.4 m run-up was recorded. This significant difference may be due to the large lagoon adjacent to Laguna Grande.



*Figure 34. Boats washed up by tsunami in Paracas*

## 6 BUILDINGS

### 6.1 Introduction

A review of the performance of building structures is presented in two sections.

The first section covers the capital city of Lima. Lima has a large population and has a significant number of buildings designed to modern seismic standards. The peak levels of earthquake shaking in Lima were comparable to serviceability levels in New Zealand? high seismic zones or ultimate design levels in low seismic zones.

The second section covers the area closest to the epicentre, the Department of Ica. There was a high level of structural damage in this area. The level of earthquake shaking in the Department of Ica was comparable to ultimate design levels in high seismic zones. There were reports of some significant

ground shaking and damage in inland regions, in the mountainous area east of the Ica District but the reconnaissance team did not visit these more remote areas due to time constraints and accessibility.

### 6.2 Seismic Design Standard

Design practices for Buildings are specified in Technical Building Standards, which form part of the National Building Code of Peru, administered by the Ministry of Housing and Construction. The Technical Building Standards set out the minimum provisions for limit state design. Seismic design provisions are provided in Technical Standard of Building E.030, Earthquake-Resistant Design (Norma Técnica E.030, Diseño Sismo Resistente), Lima, April 2nd 2003.



*Figure 35. Peru – Zones used for seismic design*

The design philosophy of the Peru Seismic Design Standard is similar to that of the Seismic Standards of New Zealand and the USA. The provisions of the Peru Standard are similar to those of USA standards.

Peru is divided in three seismic zones, as shown in the Figure 35.

The coastal region (Zone 3) has the highest seismic hazard, with a nominal peak ground acceleration of 0.4g and peak seismic coefficients varying from 1.0g for rock sites to 1.4g for flexible soil sites.

### 6.3 Building Practice

The principal form of construction for modern buildings in Peru is reinforced concrete frames infilled with masonry. These are structures constructed with brick masonry walls with slender reinforced concrete beams and columns (commonly 200 mm square) that ‘confine’ the brick. Floors

and roofs are typically a reinforced concrete slab cast onto hollow clay bricks (effectively forming a rib profile). In many cases hollow bricks are used, particularly for infill panels. Buildings are typically one to two storey, but it appears that it is common practice to add additional storeys when required: - column stubs and reinforcement are often left protruding from the roof slab for this purpose. Residential confined masonry buildings typically have a high ‘solidity ratio’ (area of wall per floor area), with few and small openings.

The Peruvian seismic loadings standard, E.030, specifies an effective ductility of 2 ( $R = 3$ ) for confined masonry structures. Significantly this was reduced from the 1997 edition of the standard, which specified an effective ductility of 4 ( $R = 6$ ). The design of confined masonry structures is prescribed by the Technical Standard E.070, (Norma Técnica E.070 Albañilería). This includes provisions for seismic design, with structural form and design parameters limited by seismic zone. Required solidity ratios are specified as a function of the E03.0 seismic parameters.



**Figure 36. Confined Masonry Building**



**Figure 37. Infill Masonry Brick**



**Figure 38. Confined Masonry Construction**

Reinforced Concrete is used for the construction of larger commercial and residential structures. Older buildings were commonly featured reinforced concrete frames with masonry infill panels (a common form for older hospital and school buildings). More modern buildings feature wider use of reinforced concrete shear walls. Floors slabs are typically insitu reinforced concrete. The seismic loadings standard, E.030, specifies effective ductilities of 4 to 6 ( $R = 6$  to 8) for reinforced concrete structures. The design of confined masonry structures is prescribed by the Technical Standard E.060, (Norma Técnica E.060 Concreto Armado).

In rural areas and towns a large number of houses are of adobe construction. There are also a significant number of large older adobe buildings, including some impressive churches and municipal building. Adobe houses are typically single storey structures with mud brick external walls and mud covered cane internal partitions (quincha). Roofs are typically flat and formed by wooden joists covered by fibre matting, perhaps plastered with mud. Larger buildings typically have an adobe lower level and quincha upper level.



**Figure 39. Adobe House Construction**

The design of adobe structures is prescribed by Peru Technical Standard of Building E080, Adobe (Norma Técnica E.080, Adobe) December 1999.) This includes seismic provisions, with a base seismic coefficient of 0.2g for high seismic areas (Zone 3). Significantly the standard restricts the use of Adobe construction in soft soil areas. The standard specifies structural requirements including return walls, foundations, bamboo reinforcement, and roof ties. The Catholic University of Peru is actively researching and developing seismic systems for Adobe buildings.

From the review of Peru Technical Standards and discussions with government ministries and Technical Institutes it is apparent that Peruvian seismic design standards are to a high International Standard. However discussions with government and municipal authorities indicate that there are significant issues in the implementation of the standards to achieve compliance. A high percentage of building structures are uncertified.

## **6.4 Lima**

### **6.4.1 General**

In Lima, the capital of Peru, there is a wide range of buildings from basic single-storey dwellings to sophisticated modern multi-storey hotels, offices and apartment buildings. Infrastructure, similarly, ranges from modern and sophisticated to basic.

Lima has a history of earthquakes. The most significant event in modern times was the 1974 M8.1 Lima earthquake, with the epicentre just off the coast of Lima. Discussions with residents indicated that significant earthquake occurred relatively frequently. There was a high awareness of earthquakes, both with respect to safety and damage. Damage of non-structural components, particularly cracking of plaster is a common occurrence in earthquakes.



*Figure 40. Lima - Modern High Rise Buildings*



*Figure 41. Lima – Older Style Multi-storey Buildings*

#### 6.4.1 Earthquake shaking in Lima

Lima is located approximately 150 km from epicentre. As detailed in section 2, there are a number of recording stations around Lima with recorded peak ground accelerations between 0.06g and 0.10g. The region was assessed as having experienced shaking equivalent to MM V on the Modified Mercalli scale.

Data records for four recording stations in Lima were provided by the Peru Geophysics Institute and CSMID:

- CSM: (CISMID Universidad Nacional de Ingeniería) Zone 1 soil; dense, stiff gravel deposits
- CDL-CIP: (San Isidro): Zone 1 soil; dense, stiff gravel deposits
- MOL: La Molina (East of Lima): Zone 2 Soil: shallow soil overlying the denser Lima Conglomerate. (we understand there may have been some local topography effects in these records)
- CAL (DHN): (Callao – port area to the west): Zone 3 -4 Soil: soft soil deposits

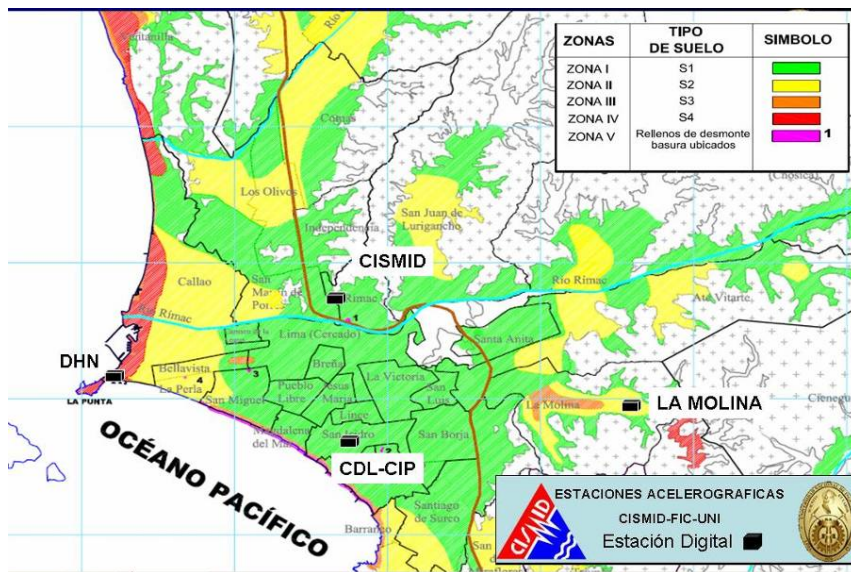


Figure 42. CISMID Lima accelerograph stations

Response spectra generated from the Lima records are presented in Figure 43. These figures provide comparisons of the record spectra with Peruvian and New Zealand Design Hazard Spectra. Relevant New Zealand spectra with a zone factor of 0.1 are plotted. These nominally represent a 1 in 25

year event in Wellington and a 1 in 500 year event in Auckland. There are representative of serviceability level and design level events respectively. Peruvian design spectra plotted are scaled by a factor of 0.25, the New Zealand scale factor for 25 year event.

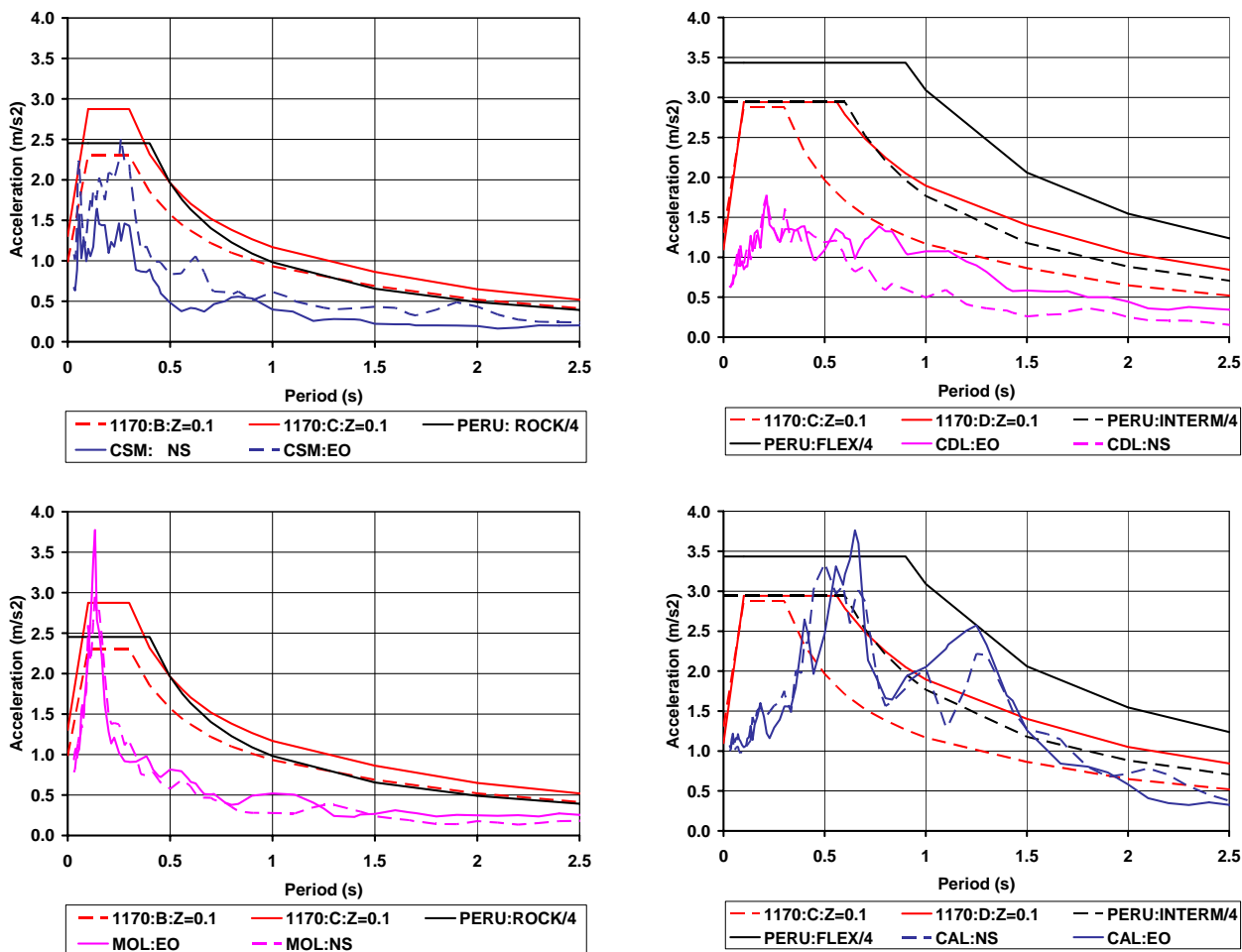


Figure 43. CISMID Lima response spectra

The spectra comparisons illustrate the following:

- CSM record response for mid and long periods are approximately 50% of the design spectral values for NZS1170 rock & shallow soil sites and Peru rock & very stiff soils. Peak spectral values for short periods are approach the design spectra values.
- CDL record responses are approximately 50% of the design spectral values for NZS1170 soft soil sites (Peru intermediate soil sites). Peak spectral values for mid and long period are similar NZ1170 rock and intermediate spectral values.
- MOL record responses are approximately 50% of the design spectral values for NZS1170 rock & shallow soil sites (Peru rock & very stiff soils) with the short period resonant peak similar to NZS1170 rock and intermediate spectral values.
- CAL record responses approximate NZS1170 soft soil spectra (Peru intermediate soil/ Soft soil), and significantly exceed the spectral values for some periods.

The Spectral plots illustrate a large variation in seismic demand on building structures in Lima, with response levels greatly influenced by site conditions and building frequency. It is evident that while the spectral levels were typically 50% of the Auckland design level or Wellington serviceability level, there were a number of instances in which the design levels were matched or exceeded.



**Figure 44. Undamaged building Lima**

It was reported that a some multi-storey buildings in the Port area of Lima suffered major non-structural damage, partitions and ceilings. Significantly this would be in the region of the Callao recording stations, where the highest levels of acceleration were recorded.

In the downtown area there were reports of windows breaking, but there was little evidence of this. The Lima Municipality reported some damage to historic buildings in downtown area. Conditions of these historic buildings vary. Even though there

## 6.5 Building Performance In Lima

### 6.5.1 Damage Levels

General observations were that the earthquake resulted in a high level of alarm, possibly due to the duration of the event. However, there appeared to be a comparatively low level of damage. Discussions with residents indicated there was minimal non-structural damage when compared with earlier events which were perceived as having a lower level of excitation.

The reconnaissance team observed a relatively wide area of Lima during three days of meetings in Lima. Additionally more detailed inspections were made of the downtown area of Lima and the Miraflores area (neighbouring San Isidro). The team arrived in Lima nine days after earthquake, and it is possible that minor damage such as broken windows could have been repaired.

Generally there appeared to be minimal damage in Lima. General observations while travelling through Lima was that there was no visible damage, even in buildings which would generally be considered vulnerable to seismic motions ; historic structures, unreinforced masonry, buildings with a 'soft' first floor. Refer Figure 44.

is a range of renovation programmes in place, a number were believed to be in a poor condition due to the progressive effects of age and seismic activity.

The most detailed observational survey was carried out in the Miraflores areas, a more affluent residential and commercial areas to the south of the city centre. Typical buildings were residential low rise (two storey) confined masonry structures with flat roof construction. No damage to these buildings was observed.

Miraflores has a number of streets of multi-storey buildings, typically 10 to 20 storey commercial and residential buildings. Commercial buildings appeared to be typically of 70s or 80s construction. A number of the residential buildings appeared

to have been recently constructed. The typical structural form was moment frame across the buildings and shear wall down the sides.



*Figure 45. Miraflores Residential Area*



*Figure 46. Miraflores High-rise Commercial Buildings*

### **6.5.2 Damage to Multi-storey Buildings**

The principal damage observed in the Miraflores area was superficial damage due to pounding (impact) of high-rise buildings in the instances where no or minimal seismic gap was provided. Over a dozen instances of minor damage due to

building impact were observed on Avenida Angamos Este, Avenida Jose Pardo, and Avenida O. Benavides.

Two multi-storey buildings in these streets were observed to have a few missing window panes.



**Figure 47. Building Impact – Miraflores**

There were two observed instances of buildings with structural damage on the Avenida O. Benavides. A 17 storey apartment building had diagonal cracks in columns and beams on the front face for the bottom five floors. A nearby 18 storey apartment building had horizontal cracking in the side shear walls indicating the joint opening. There was also

corresponding cracking of beam column joints on the front face. Both buildings appeared to be new. Comparison with other buildings would suggest construction control or steel anchorage could have been contributing factors to the formation of cracks.



**Figure 48. Miraflores Apartment Buildings with diagonal creaking of columns**

## 6.6 Epicentral Region

### 6.6.1 Overview

The principal area affected by the earthquake was in the Department of Ica, the coastal area adjacent the epicentre. There was major damage in the two main coastal towns in the region, Pisco & Chincha. Significant damage also occurred in

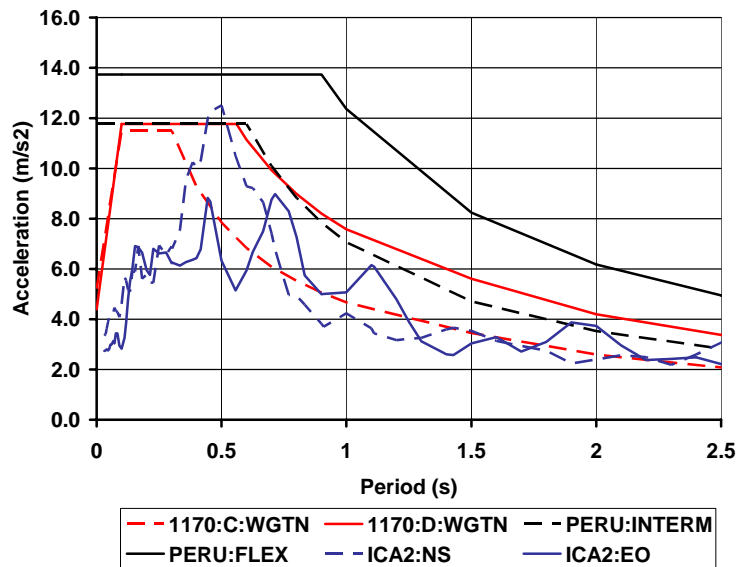
the inland city of Ica, and coastal towns to the north, such as Canete, on the road to Peru. Pisco & Chincha are located 40 – 50 km from the epicentre, while Ica is located 120 km from the epicentre (note that these are the distances to the initiation of the fault rupture – fault propagation was towards Pisco and Ica). Peak ground accelerations of 0.3 to 0.5g were recorded, with an assessed intensity of MM VII. There was a high level of damage in the area, including the collapse or damage of the

majority of adobe buildings. A number of churches, hospitals, and schools in the area suffered major damage.

### 6.6.2 Spectral Characteristics

Response spectra generated from the ICA2 records are presented in Figure 49. This figure provides a comparison of the record spectra with Peruvian and New Zealand Design Hazard Spectra; Peruvian Zone 3 design spectra for intermediate and flexible soil sites, and New Zealand

intermediate and soft soil site spectra for a zone factor of 0.4. The New Zealand Spectra represents a 1 in 500 year event in Wellington. This is representative of the design level event in a region of high seismic hazard. The comparison shows indicates that the earthquake could be considered a design level event for buildings in high seismic regions with vibrations periods over 0.4 seconds.



*Figure 49. ICA2 Spectra*

## 6.7 Building Performance In Epicentral Region

### 6.7.1 Damage Levels

There was widespread destruction of buildings in the coastal towns of Pisco and Chincha. Buildings in these towns were typically simple single storey adobe dwellings. The majority of these adobe buildings were damaged. There were also a number of confined masonry structures, typically two to three stories. Damage of these buildings appeared to be isolated.

Damage was greatest in Pisco, possibly due to ground conditions (refer to geotechnical section). In Pisco many streets were full of rubble. Earthmoving equipment was present, and it was evident that many buildings had been demolished. While it is likely that ground shaking was the principal cause of damage in Pisco, ground subsidence and tsunami would also have been contributing factors, particularly along the waterfront. Houses in some streets in Pisco were relatively undamaged. This may have been because of the structural form, or location (ground conditions were better on the southern side of the town).



*Figure 50. Pisco Residential Street*



*Figure 51. Pisco Cleanup*



*Figure 52. Undamaged Buildings – Pisco*

In Coastal towns to the north of the epicentre, damage was typically confined to toppling of walls of adobe structures or freestanding walls. There were instances of damage to more substantial buildings; for example in Canete a bank and a church built on corner sites in the town centre were damaged, while a local school suffered significant structural and non-structural damage.

There were few settlements in the coastal area to the south of Pisco.

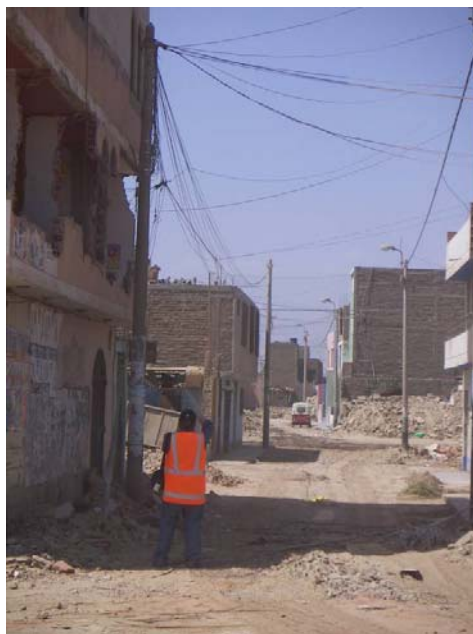
The most significant was the coastal settlement of Paracas, a fishing and resort town. Buildings here were typically of confined masonry or reinforced concrete construction. Damage to structures here appeared to be principally attributable to ground settlement or tsunami.



**Figure 53. City Centre - Ica**

Buildings in the inland city of Ica typically appeared to be confined masonry structures. Significant areas of adobe buildings were apparent on outskirts of the city, and in older areas of the city centre. While Ica was a substantial city there were few modern buildings.

The team observed the collapse of damage to a significant number of residential adobe buildings in Ica. There was also damage to isolated public or commercial adobe buildings, with the most significant damage being to churches and school and hospital buildings.



**Figure 54. Street Damage - Ica**



*Figure 55. Collapsed church roof - Ica*

### 6.7.2 Adobe Structures

Typical adobe buildings were simple single storey dwellings. The majority of these adobe buildings in Pisco were seriously damaged. Large numbers were also damaged in Chincha and Ica. Out-of-plane failure of walls was common. There were a few isolated instances of diagonal cracking of walls indicating

in-plane failure. There were a number of more substantial adobe structures, including two storey commercial buildings and residences. Damage levels of these structures varied. From observation, typical adobe houses were not detailed for seismic actions and were constructed in soft soil zones.



*Figure 56. Typical Adobe House Damage*



*Figure 57. Collapsed Adobe House - Pisco*



*Figure 58. Damaged Two Storey Adobe Buildings - Pisco*



*Figure 59. Cathedral San Clemente before Earthquake*



*Figure 60. Cathedral San Clemente after Earthquake*

The most significant casualty of the earthquake was the Cathedral San Clemente. The dome of the Cathedral collapsed, killing 148 people. The building was principally adobe construction. The corner towers, which had been reinforced with concrete, were the only parts of the church that remained.

### 6.7.3 Confined Masonry Structures

Confined masonry buildings observed were generally undamaged, including buildings that one might expect to be vulnerable to a large earthquake. There were isolated observed instances of out-of-plane toppling of cantilever walls and in-plane cracking and/or loss of masonry infill walls.



*Figure 61. Undamaged Confined Masonry Dwelling - Pisco*



*Figure 62. Undamaged Engineered Confined Masonry Dwelling - Pisco*



*Figure 63. Multistorey Confined Masonry Building - Pisco*



*Figure 64. Pisco Confined Masonry Buildings with panel damage*



*Figure 65. Diagonal cracking of infill masonry panel*



*Figure 66. Brick panel damage - Ica*

Instances of major damage observed in Pisco were;

A four storey residential building, with a ground floor carpark and three levels of dwelling over. The structure supporting the front of the first floor had collapsed. The remaining floors were remarkably intact. A neighbour reported that during the earthquake she has observed a crack in the ground propagating

from the waterfront past the front of the building immediately prior to its collapse.

The 5-storey Embassy Hotel building collapsed and had been demolished. It was reported that 15 fatalities in this buildings. The building behind it, which appeared to be of similar structural form, had significant damage to brick walls



**Figure 67. First Floor Collapse - Pisco Residential Buildings**



**Figure 68. Column Failure - Pisco Residential Building**



**Figure 69. Embassy Hotel Damage - Pisco**  
(Source: Taiki Saito Building Research Institute)



**Figure 70. Demolished Embassy Hotel – Pisco**

As 12 days had lapsed between the earthquake and the site inspection, the observed damage did not necessarily provide an accurate assessment of real damage levels and building

vulnerability (as many seriously damaged buildings had been demolished). Information was available from other reconnaissance teams who were in the region earlier.

The EERI reconnaissance team visited the affected areas 3 days after the earthquake event. They reported that confined masonry with soft stories, relevant irregularities, or bad detailing, collapsed or showed severe damage. The Taiki Saito, Building Research Institute published a brief reconnaissance report four days after the earthquake event. They reported that most of damage in confined masonry buildings was the collapse at parts of concrete casting joints in the upper part of columns and joints between columns and girders. The report showed photos of a number confined masonry buildings which had sustained heavy damage. These were generally soft storey failures.

The observations of these reconnaissance teams therefore indicate that there was more widespread damage to confined masonry buildings than observed by the NZSEE team.

#### 6.7.4 Reinforced Concrete Buildings

There were limited numbers of buildings that would be regarded as reinforced concrete (as opposed to confined masonry). Many of these would have incorporated infill masonry panels.

A number of school and hospital buildings could be regarded as reinforced concrete frame buildings with infill panels. There was damage of these buildings where critical structural weaknesses were present. (School and Hospital buildings are addressed separately in the following section.)

The few modern reinforced concrete buildings observed were undamaged, apart from those subject to ground subsidence.



*Figure 71. Commercial Buildings - Ica*



*Figure 72. Beach Houses – Paracas*

### 6.7.5 Grandstands

The grandstands for the sports stadia in both Pisco and Ica were of reinforced concrete construction. At the Pisco stadium damage had occurred due to differential movement of the suspended seating and the seating supported on grade. The concrete roof structure was undamaged. There was minor

cracking of infill masonry panels. Damage of the Ica grandstand was limited to cracking at the base (due to differential movement) and minor infill panel cracking. There was no damage to the reinforced concrete columns and beams - not even a crack.



*Figure 73. Pisco Grandstand*



*Figure 74. Ica Grandstand*

### 6.7.6 Water Towers

Water storage towers for town supply were inspected in Pisco and Ica. In all cases the tanks and piping were undamaged but there was significant damage to some of the support structures.

In Pisco there was a 1,200 cubic metre tank supported on a robust reinforced concrete frame. The tank was built in the 1960s and suffered damage to columns in a 1995 earthquake. These had been jacketed to about 6 m height. All columns were undamaged, but many of short tie beams between columns had significant cracks. A similar structure was

inspected in Ica. There was only minor cracking to a few beams. This is an older reservoir and due for replacement. It was being run at one-third full as a precaution, pending detailed assessment of the damage.

In Ica inspections were made of two 1,200 cubic metre tanks supported on 200 mm thick reinforced concrete walls. In both cases there were signs of opening of construction joints in the tower structure, though damage was minor. At one of the sites there were signs of opening of construction joints in the tank, resulting in some leaking.



*Figure 75. Water Tower - Pisco*



*Figure 76. Cracked Tie Beams - Pisco Water Tower*

### 6.7.7 School Buildings

The Ministry of Education reported that a significant number of older school buildings were damaged with damage to contents and broken windows.

The reconnaissance team observed a number of older school buildings in Canete, Chinca, and Ica. Buildings were typically 2 to 3 storey reinforced concrete buildings with infill panels and concrete around the stairs. Features of the buildings were short columns and deep spandrels.

Damage was mostly superficial, but at two sites structural damage was observed. At a local school in Canete, there was shear failure of short columns, minor cracking of infill walls and minor impact damage from pounding of adjacent structures. A number of windows were cracked. At San Luis Gonzaga School, cracking of walls and spalling of concrete was sufficient to require repair. One column supporting a canopy had lost all concrete in the core, revealing that there

were no horizontal ties. The main, 3-storey wing had some cracks and significant amounts of glass breakage.

The EERI reconnaissance team reported similar structural form and damage for Educational facilities in Pisco & Ica.

School buildings built or retrofitted since the introduction of new Standards in 1996 performed well. The new buildings were characterised by the incorporation of blade columns or short walls, and well detailed movement joints between the concrete structure and infill panels. A school in Pisco built to the new standard appeared to be undamaged, despite the destruction around.

Table 2, taken from a presentation made Dr Javier Pique, adviser to the Ministry of Education, shows the evolution of Peruvian Seismic standards since 1964. It is evident that standards have been updated to much the same timetable as New Zealand standards have been developed. The regular major earthquakes affecting populated areas have no doubt

acted as a catalyst for Peru, but so too have earthquakes in other countries. The improvement these changes have brought

about is evident in the performance of modern school buildings.

**Table 2: Evolution of Peruvian Seismic Standards**

1964	First project of Peruvian Standard based on SEAOC
1970	First Peruvian Standard nationwide
1977	Second Peruvian Standard (after earthquakes of Chimbote-Huaraz 1970, Lima 1974)
1997	Third Peruvian Standard (After Mexico earthquake 1985, Loma Prieta 1994, Kobe 1995, Nazca 1996)
2003	Revision of 3rd Standard



*Figure 77. Damaged School - Canete*



*Figure 78. Column Damage - Canete*



*Figure 79. Damaged School - Ica*



*Figure 80. Column Damage - Ica*



*Figure 81. Infill wall damage - Ica*



*Figure 82. School Constructed to New Standard - Pisco*



*Figure 83. New Standard School Detailing – Pisco*



*Figure 84. Glass damage at an Ica school*



*Figure 85. Spandrel separation at an Ica school*



*Figure 86. Undamaged school – Ica*



*Figure 87. University stadium Ica - no significant damage*

### 6.7.8 Hospitals and Health Facilities

The Ministry of Health reported that all facilities in Ica and the earthquake affected area were damaged to varying degrees. All hospitals in Pisco were lost, and only two modern “pavilions” survived there. Considerable equipment damage occurred, by power shut-off, by dust and by falling. Lack of building services to create the necessary positive pressure rooms is hampering some activities.

The Ministry of Health noted that new hospital design standards had been introduced and that buildings constructed to the new standards performed well. The new design standards were based on the use of shear walls. The EERI

reconnaissance team reported that three new buildings at San Jose Hospital in Chincha performed very well.

An inspection was made of the Regional Hospital in Ica. Building form and damage was similar to that of older schools. Characteristic buildings were storey reinforced concrete with infill panels featured short columns and deep spandrels. The site inspection showed extensive cracking of infill panels and a few instances of short-column failure. There was considerable damage to non-structural components; partitions, ceiling panels, un-braced contents and equipment. This made many rooms, including operating theatre suites, inoperable. Damage to building plant was also noted.



*Figure 88. Regional Hospital – Ica*



*Figure 89. Short Column Failure - Ica Regional Hospital*



**Figure 90. Operation preparation areas - Ica Regional Hospital**



**Figure 91. Unsecured Building Plant - Ica Regional Hospital**

### 6.8 Analysis Of Damage Levels

Damage to Adobe structures was as expected. Walls were not effectively restrained by the roof and the bond between adobe bricks was minimal in most cases. The damage levels may have been in part due to the long duration of the earthquake, with toppling resulting from progressive movement of bricks,

Confined Masonry structures appeared to have performed better than would be expected given the earthquake magnitude and ground acceleration levels. Failures were principally due to critical structural weaknesses, such as shear failure of short columns, or lack of effective reinforcement anchorage or lapping.

The most common damage was loss of infill walls. It appears that typically diagonal shear cracks were generated due to in-plane action, then the cracked walls would fail out-of-plane. As with Adobe structures, the duration of the earthquake may have contributed to this out-of-plane failure.

One possible reason for the relatively good performance of the confined masonry structures is the high solidity ratio (i.e. high density of walls) typical in Peruvian dwellings. Significantly,

confined masonry structures had insitu concrete floors and roofs providing good structural diaphragms.

The structural damage to modern reinforced concrete buildings in the Department of Ica, and the non-structural damage in Lima were much lower than expected given the earthquake magnitude and ground acceleration levels.

Some explanation for the lower than anticipated damage levels can be found through a more detailed investigation of the earthquake records and spectra. A comparison was made of the time-history record and response spectra for the ICA2 Pisco record with those of other earthquake events of similar level and subsoil conditions. For this purpose, response records for the El Centro (USA) and Lolleo (Chile) earthquakes were selected (courtesy of GNS Science, Wellington). The records have been scaled so that the peak accelerations and response spectra levels approximate those of the ICA records.

One significant feature illustrated by the ICA2 response spectra is that the high response levels were typically in mid-to high period ranges. The effect on Peruvian buildings,

which are typically stiff low period structures, is therefore likely to be reduced when compared to events with high

response levels in the low-period range.

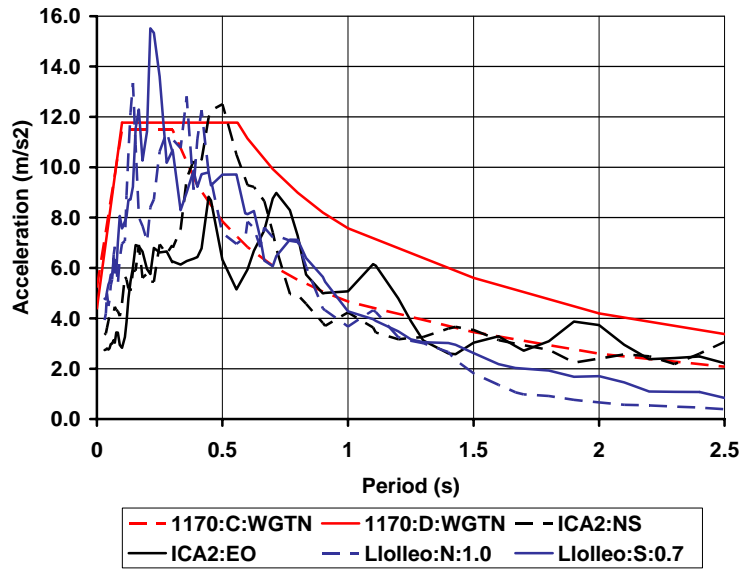


Figure 92. Ica, Lollole and 1170 spectra compared

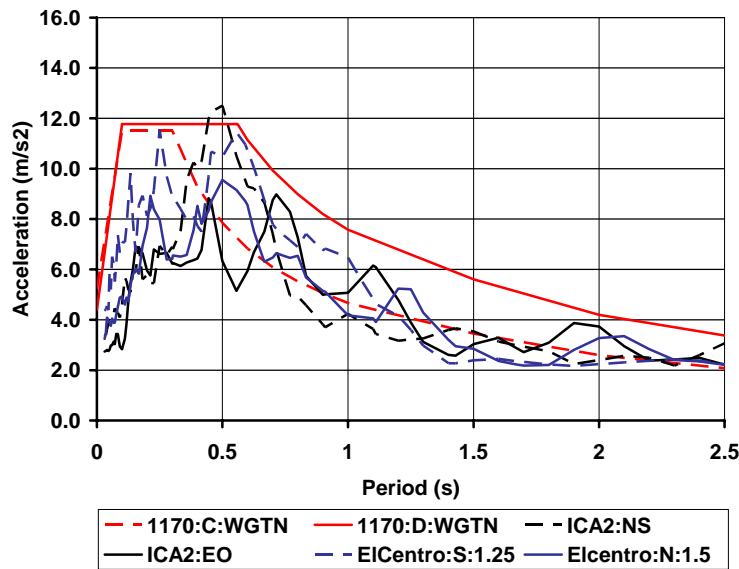
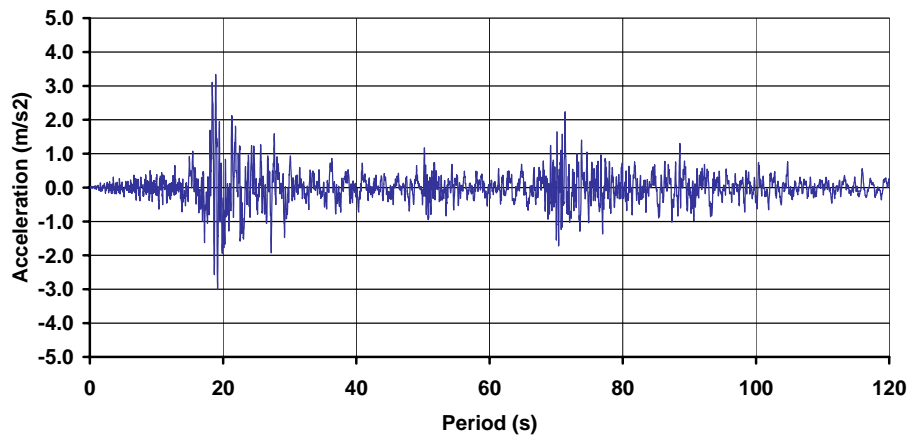


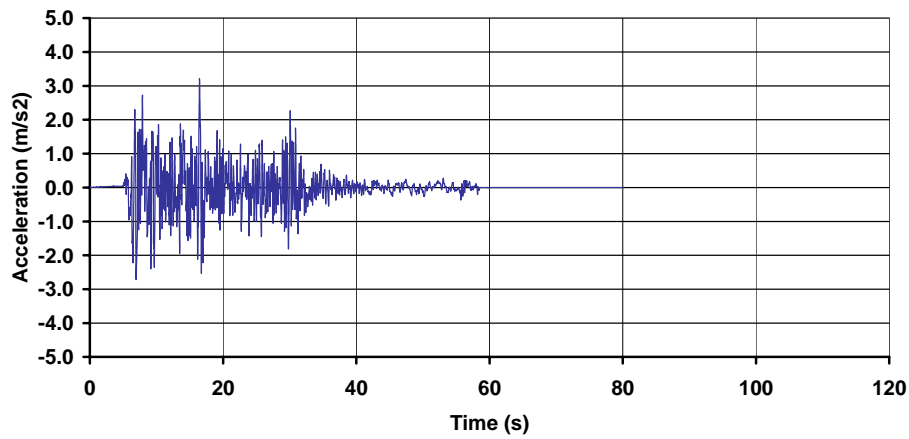
Figure 93. Ica, El Centro and 1170 spectra compared

A comparison of the ICA2 time-history records with the records of other earthquake events illustrates that indicates that the Pisco event had a lower number of peak cycles, and lower excitation ‘density’; while the Pisco event had a high level of energy it was spread out over a longer time period,

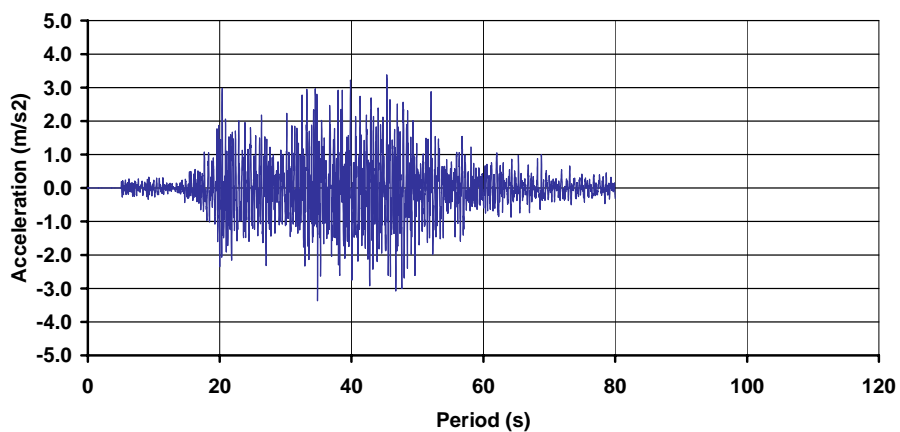
hence for the majority of the duration the excitation was less intense than similar magnitude events. This can provide some lower level of damage in confined masonry and reinforced concrete structures.



*Figure 94. ICA2:NS:1.0*



*Figure 95. El Centro:N:1.5*



*Figure 96. Lolloo:N:1.0*

A further investigation of the likely response levels and damage levels for the selected earthquake events was made by carrying out comparative out time-history analyses of an elasto-plastic single degree of freedom oscillator; with an elastic period of 0.45 seconds and a nominal ductility (demand) of 5. System response was plotted in the form of

cumulative system energy; both total energy (kinetic, elastic, viscous damping & hysteretic damping) and hysteretic damping (damage) energy only (note: energy scale varies). These plots illustrate lower cumulative total energy and hysteretic energy for the ICA2 analysis.

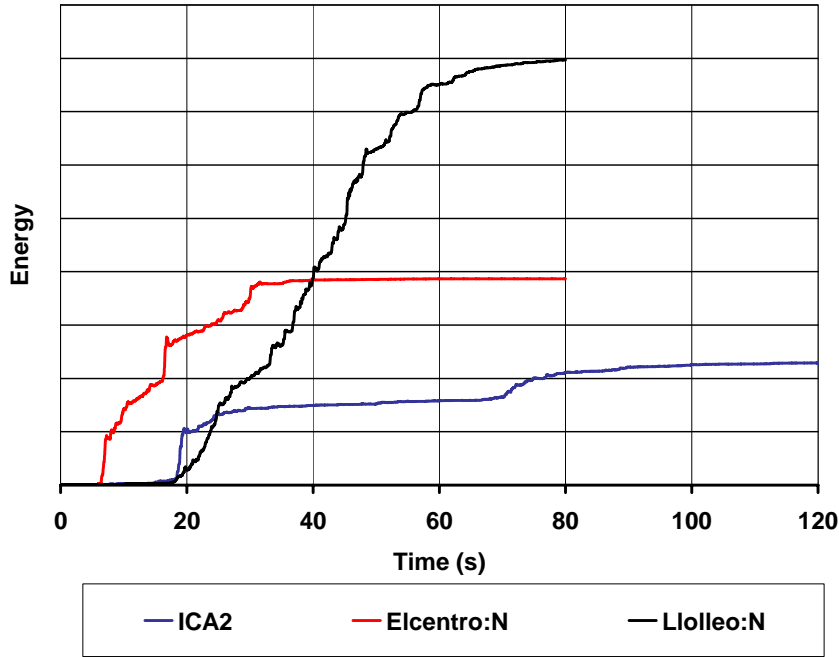


Figure 97. System Cumulative Total Energy

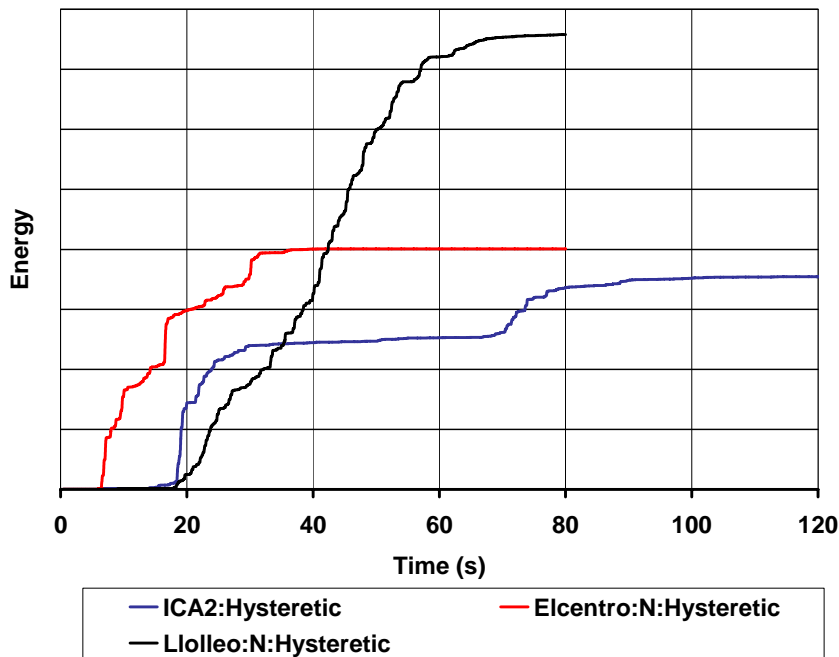


Figure 98. Cumulative Hysteretic Damping Energy

## 6.9 Industrial Structures

Inspections were made of a number of industrial structures in the epicentral region, principally on the road between Pisco and the Port of San Martin. In general both structural and non-structural damage was limited, despite these industrial sites being located close to Pisco in areas susceptible to ground subsidence. The performance of these plants may in part be a result of industrial structures being more likely to be engineered than typical building structures. Some, such as the steel mill and gas liquefaction plant would have been to international standards. Disruption to industry and services as a result of staff unavailability was significant. In Pisco particularly many staff had priorities to protect their own property and care for family..

A summary of industrial site inspections/observations is presented below:

### Port of San Martin

Steel portal frame warehouses adjacent wharf were supported by steel encased concrete piles with perimeter tie beam. Though the floor settlement was in the order of 1 m there was no visible damage to the superstructure. There was the loss of some cladding.

A water storage tank was located close to the access road near the port. The tank was anchored to a concrete base. There was no discernable damage or movement



**Figure 99. Steel Portal Warehouse, Port of San Martin**

***Steel production plant of Acero Arequipa, a major steel plant near Pisco.***

This plant makes billet and structural reinforcing steel from 20% scrap and 80% pellets. Billets are processed at this plant and at Arequipa. A transformer insulator failed, causing an oil leak, requiring replacement of the whole transformer. Power was shut down and the plant was checked according to emergency drills.

The plant normally runs three shifts totalling 1200 staff and workers, mostly from Pisco. 178 of these had houses destroyed, and 90% of staff did not show up until three days after the earthquake. There were no injuries as a result of the earthquake, but the plant was affected for 4 days. By the fourth day, production was back to 50% and by the sixth day, 100%.

Emergency lighting worked, but there was not enough capacity to keep the plant going. Office equipment fell down

but there was very little non-structural damage in the plant – one effect not expected was the shaking loose of accumulated dust.

The buildings had been designed by Eng. Antonio Blanco of Catholic University, based on a site specific study. Recently, some columns and foundations had been upgraded and jacketed to account for higher working loads. No special measures had been taken to tie cranes down from vertical movement. Transformers were on rails without tie-downs.

There was very little damage to the buildings and plant, typically minor cracking of infill panels. Two ladles of product needed to be discarded.



**a). Overview of loading areas**

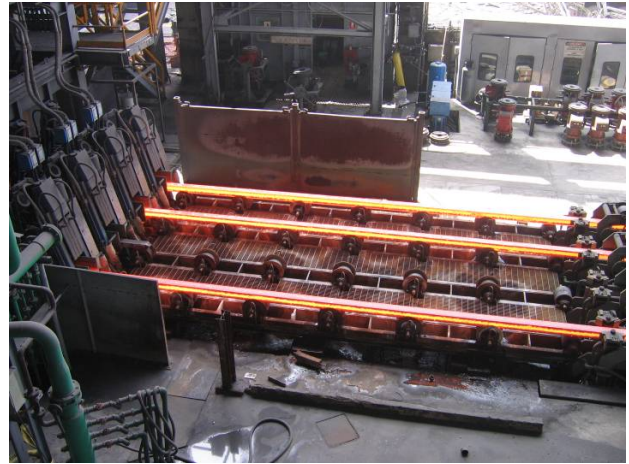


**b). Detail of process plant**

**Figure 100. Continued over the page.**



c). Structure detail and furnace building



d). Rolling mills



e). Replaced transformer



f). Exhaust fume stacks

**Figure 100. Acero Arequipa Steel Plant**

### **Blue Pacific Oil**

This is a large fish oil processing and storage facility on the coast. There are 10 large steel tanks about 12 m diameter and 10 m high, connected by pipework. They were built in 1967. Six of the tanks were reported to be on a 1.5 metre deep reinforced concrete raft. Three tanks classic elephant type buckling around a large extent of their perimeter. One tank

showed buckling and the showed buckling at the first strake level (1.5 m above ground)

No product was lost due to pipe or tank failure, but some had sloshed out at the top through inspection holes.

There was no sign of lateral movement or any restraints to prevent it, but there is was a possibility that there was some settlement.



**Figure 101. Tank Damage - Blue Pacific Oil**

***Austral Fish Oil Plant***

This plant was one of a number on the coast between Paracas and Pisco. It contained a building, some tanks and pipework. We were told that there had been no damage due to the earthquake. The plant was closed due to a break in the fishing season, but was due to start up about two weeks after the earthquake.

***Epesca Peru***

Another fish oil plant next door to Austral, with similar facilities. We were told there was no damage. Plant was due to start up about two weeks after the earthquake.

***Pluspetrol Peru***

This gas liquefaction plant consisted of several tanks and process equipment, further inland than the fish processing plants. We were not allowed access but were told that there had been no interruption to operations.

***Storage depot near Pisco***

This facility takes oil and gas pipelines from offshore platforms and stores it. A water tank had buckled and split at the bottom, but this was a rusted skirt only and no product was lost. There were no signs of sideways movement. All other tanks were undamaged.

A tsunami had demolished most of the perimeter fence and had reached halfway across the site. It was a gentle upwelling of water, not a wave, and had not gone above the bund.



**Figure 102. Oil Terminal – Pisco**

### 6.10 A New Zealand Perspective

The Pisco Earthquake provided ground motion and response data for a high magnitude event. Such data is vital to the investigation and development in the fields of earthquake engineering. The ground motion characteristics for the Pisco Earthquake differ from other high magnitude events, being characterised by a long duration (over 2 minutes), two distinct strong motion phases, low frequency components, and low energy density. A review of the strong motion records and the performance of buildings during the events highlighted the large variations in seismic demand on building structures within and between individual earthquake events. Building performance was greatly influenced by a wide range of parameters, including frequency components, energy, duration and acceleration levels of the earthquake event, site conditions, building form and materials, and building frequency characteristics.

The reconnaissance of the effected regions of the Pisco Earthquake revealed that damage was principally attributable to structural form (Adobe) or the presence of major critical structural weaknesses. Engineered buildings and other buildings, which did not have major critical structural weaknesses appeared to perform well; better than would be expected. Due to the nature of the ground motion, detailed study would be required to make an accurate assessment of relative building performance.

A notable development in earthquake engineering in Peru is the utilisation of shear walls in buildings. Revised building standards for educational and medical facilities public are based on the use of shear walls (or wide columns) distributed through out buildings. This structural form appears to provide robust structures that perform well (both at service and ultimate level) and have a high level of redundancy. This differs somewhat from current New Zealand practice which

appears to focus on providing the minimum seismic structure that complies with drift limits. This can result in buildings that are relatively flexible and feature either moment frames or minimum localised braced frames or shear walls.

## 7 LIFELINES

### 7.1 Telecommunications

Indications are that soon after the event telecommunication systems were disrupted to varying degrees. Landlines as well as mobile phone systems were damaged and for up to four hours very limited access was available to either landlines or mobile systems. System overloading was a common factor which made communications during the first 24 hours difficult.

### 7.2 Transport networks and facilities

#### 7.2.1 Roads and bridges

In the area of the epicentre, two major roads intersect at the town of San Clemente. These are the Pan American Highway, which runs north-south along the Pacific Coast, and the Carretera los Libertadores (route 24a), which runs in a general east-west direction. From San Clemente, the Carretera follows the Pisco River in an easterly direction towards the mountainous areas of the Andes. Along this road there are a number of small bridges crossing irrigation canals and small streams. Refer to Figure 103. The structures on this route are modern, well-constructed reinforced concrete bridges with single spans in the order of 20 m. A limited reconnaissance of bridges on a portion of the Carretera highway revealed no damage to bridges on this route. Bridges on the Pan American Highway are older.



**Figure 103. Typical bridge on Carretera los Libertadores (Route 24a)**

Generally, the bridges in the epicentre region performed well and the only bridge with notable damage was the Huamani Bridge on the Pan American Highway at San Clemente. Refer to Figure 104. The Huamani Bridge is approximately 60 years old and consists of a superstructure of 5 spans of reinforced concrete beam-and-slab construction. The total length of the bridge is approximately 100 m with average span lengths of

25 m. The superstructure is made up of a combination of continuous spans with cantilevered sections, which support two simply supported drop-in spans. The abutments and piers are of solid wall-type construction and indications are that the piers may be supported on short concrete piles. Movement joints (steel roller bearings) are provided at the abutments as well as one of the piers.



**Figure 104. Huamani Bridge on the Pan American Highway at San Clemente**

Damage to the bridge superstructure was limited to permanent transverse displacement of the drop-in spans, as well as damage to the bridge barriers. Refer to Figure 105.



**Figure 105. Superstructure damage**

Shear cracks were observed in the diaphragm beams. Damage to the substructure was localized at the restraining walls extending from the pier on the side of the bridge decks. These

walls were designed to prevent lateral movement of the bridge superstructure at the pier support, a design detail that performed well during the earthquake.



**Figure 106. Damage to restraining walls**

Liquefaction was observed at a number of the piers in the riverbed, but no settlement of the pier caps was observed. The biggest settlement and lateral movements were found at the southern abutment with the road embankment settling approximately 1.5 to 2 m. Extensive damage to the bridge approach resulted in the closure of the bridge. Refer to Figure 23. Given that the bridge has an important lifeline function,

the closure had a serious impact on the relief and reconstruction efforts in the Pisco area. The bridge accommodates a number of utilities and services, i.e. water main and telecommunications. The lack of detailing for movement in the water main resulted in the pipe rupturing during the earthquake.

A by-pass was constructed in the riverbed on either side of the bridge, as, fortunately, the earthquake took place in the dry season. The bridge was re-opened to traffic just in time for the wet season, which would make the riverbed impassable.

Discussions with the Ministry of Transport and Communications confirmed that the Pan American Highway

from Lima to Pisco (and Ica) was closed due to a major slip just north of Chincha. Along the Pan American Highway a number of sections of road were also damaged due to liquefaction. Along the inland route (24a), rock falls were the major cause of road closures and disruption for approximately 3 days after the earthquake. Refer to Figure 18 .



**Figure 107. Rock falls on Route 24a**

The Ministry responded by sending thousands of workers out into the affected areas to start clearing roads. The highway network is managed through long-term maintenance concessions to private contractors. These contractors played a major role in response and reconstruction as emergency response forms part of their maintenance responsibilities.

### 7.2.2 Marine (ports, shipping, fishing)

Reconnaissance of the coastal areas around Paracas and Pisco identified a number of wharves and small piers, which were damaged during the earthquake. In some areas damage was compounded by the effects of the resulting tsunami. Refer to Figure 108 and Figure 109.



**Figure 108. Tsunami damage to pier on Paracas coast**  
Photo courtesy Alfonso Rey

While the smaller piers do not have large commercial value, there is a significant level of disruption to local coastal communities, e.g. impact on fishing.



**Figure 109. Structural damage to pier**  
Photo courtesy Alfonso Rey

From a commercial, shipping and lifelines perspective the most significant damage was caused at the Port of San Martin. The port is situated approximately 20 km south-west of Pisco

along a coastal road. Because the port serves both Pisco and Ica, it has significant commercial value.



**Figure 110. Wharf damage - Port San Martin**

The port comprises a wharf area of approximately 1000 m x 20 m constructed by means of reinforced concrete beams and slabs supported by steel-encased concrete piles. A settlement

slab and cut-off wall provides support for the compacted backfill behind the wharf structure.



**Figure 111. Settlement behind wharf**

Damage to the port was caused mainly by liquefaction of the compacted fill behind the wharf. This resulted in damage to the settlement slabs and back walls on the wharf but, essentially, the wharf remained operational. The value of the port and wharf facility as a lifeline is obvious and at the time of our reconnaissance it was evident that the port performed a

critical function in getting supplies into the devastated areas of Pisco and Ica. Normal commercial operations could also continue.

Damage to the wharf shed is shown in Figure 29.



**Figure 112. Settlement of backfilled areas behind wharf**



**Figure 113. Wharf operation delivering emergency supplies to Pisco area**

### 7.2.3 Rail

There are no rail networks between Lima, Pisco and Ica.

### 7.2.4 Air

The Pisco airport remained operational after the earthquake and played a very important role in transporting the injured from Pisco to Lima. The loss of hospitals and medical facilities in Pisco, combined with the delays caused by the closure of the Huamani Bridge, meant that the only viable way to get the seriously injured to Lima was by air.

Fortunately the airbase south of Pisco was available and also used as base for the Civil Defence activities. The value of helicopters was obvious, not only for transportation of supplies and personnel, but also for reconnaissance and accessing remote areas.

### 7.2.5 Transport networks and facilities - implications

The importance of critical lifelines facilities is one of the main areas for any country to focus on in preparing for a major event, such as an earthquake. Identifying critical facilities such as hospitals, water supply, wharves, airports, road links and associated bridges is one part of the process. Investing in strengthening/retrofitting and protection of these elements is the next important step. Given that upgrading work will compete against other state-funded projects, there needs to be a strategic funding mechanism to ensure that lifelines are given high priority..

Evidently, Peru has a history of large earthquakes, an “advantage” from which they can, and do learn by constantly upgrading their design standards to accommodate the latest information. The results of this can be seen in the performance of the modern school buildings, as well as more recent bridge designs. New Zealand, while at the forefront of seismic design research and development, has not had many large earthquakes to “test” design and construction standards. The Peru experience confirms that it is important that our critical infrastructure has the capacity to withstand a major earthquake event.

## 7.3 Water and Wastewater

### 7.3.1 Pisco

Major damage occurred to waste water supplies. Details of the systems were not obtained, but a waste water pumping station was damaged due to liquefaction settlement. Instances of liquefaction settlement around the town suggested that damage to the distribution networks would have been extensive. Some residents indicated that their situation was normal, which was puzzling.

Water distribution networks were extensively affected within the town, requiring distribution throughout the town by tankers. The almost zero rainfall on these coastal areas means that water supply must come from reservoirs well inland, and the main supply pipes were functioning. A major elevated (1,200 cubic metre) reservoir structure survived well with damage to linking beams but not to the tank or supporting columns. As a precaution, the reservoir was being run at about one quarter of its normal level which was sufficient to supply the tankers.

Every few seasons these communities have significant rain storms for brief periods. Otherwise there is no rain. Basic stormwater drainage is provided but any damage would be of little consequence in the response and early parts of the recovery phases. (Rain water damage to buildings with damaged roofs is likewise not an issue in these areas.)

### 7.3.2 Ica

The team met with several engineers and managers at the headquarters of the water authority and obtained maps of the water supply network and waste water reticulation for Ica. Technical services are provided by a consultant company, similar to a New Zealand Local Authority Trading Enterprise (LATE).

There was very little damage to the water supply network and limited damage to the waste water collection system.

Figure 114 shows the layout of Ica and the sewage collection system, showing the two main collectors converging into a single collector to the south.



**Figure 114. Ica waste water network**

A section of 2 m diameter concrete sewer main collapsed in the earthquake, and was been repaired with PVC pipe. Some damage to pipes was caused by the heavy earthworking machinery used to clear up the debris from damaged buildings. Interestingly, the flows into the treatment station are now higher than before the earthquake. This may indicate that the replacement pipes have less leaks. The treatment ponds comprise 4 ponds, each 3.2 ha and 2.5 m deep, totalling 190,000 cubic metres. Damage to some sewers occurs on a

regular basis due to trucks on the Pan-Pacific highway and replacement is needed every two years.

Figure 115 shows the water supply zones of Ica, each served by a separate, elevated reservoir. Damage to the distribution network was negligible, but some reservoirs suffered minor damage which resulted in them being emptied pending engineering evaluation. A reservoir similar to the one at Pisco suffered less damage.



**Figure 115. Ica water supply zonation**

Water authority representatives took us to another large (1,200 m<sup>3</sup>) elevated reservoir which had been taken out of service. The reservoir (Figure 116) was supported on 200 mm thick doubly reinforced walls. Cracks were evident at about 3 m and 6 m up, matching the construction joints. Some minor spalling had occurred, with reinforcement exposed in one or two places. It was said that the structure had developed a lean during the earthquake, but this was difficult to detect. We were told that the tank was leaking quite badly and observed

what appeared to be cracks at construction joints in the tank structure itself. Peruvian engineers had recommended demolition of this structure, but it seemed capable of repair. We were told that the neighbours had long regarded the structure as a major visual intrusion and possibly a danger to them. It seemed that the earthquake was an opportunity to get the tank removed – a reminder that post-earthquake recovery is not driven solely by technical considerations.



**Figure 116.** 1,200 cubic metre reservoir in Ica

A near-identical reservoir adjacent to the main sports stadium had less damage and had not been taken out of service. This reservoir showed clear evidence of non-technical considerations in its planning – a viewing platform had been added high up on the stadium side.

## 7.4 Energy supply and distribution

### 7.4.1 Electricity

Eighty percent of Peru's generation is from hydro sources in the Andes. There were no reports of damage to major distribution networks. The EERI reconnaissance team reported damage to two transformers in a substation near Paracas and

many broken power poles due to liquefaction and building collapses. The steel mill at Paracas lost power due to a damaged insulator on one transformer. The transformer was replaced and power restored within four days.

### 7.4.2 Oil and Gas

A gas liquefaction plant just north of Pisco (Figure 117) reported no damage due to the earthquake, but was not accessible for inspection. This facility processes natural gas for distribution within Peru and for export through a pipeline to an offshore loading platform. No damage was reported to the pipeline or platform.



**Figure 117.** Gas liquefaction plant near Pisco

A storage facility for oil and other liquids suffered little damage. A tsunami had demolished most of the perimeter fence and had reached halfway across the site without significant effect on operations.

In Peru, domestic and industrial gas is distributed in bottles and there are no piped networks. There were no reports of fire following the earthquake.

## 8 SOCIAL AND ECONOMIC IMPACTS

### 8.1 Social impacts

To fully appreciate and understand the impacts of this earthquake on Peruvian society, a separate in-depth study is required. However, discussions with the various agencies involved in the response provided an insight into the range of issues and decisions that were needed, or were being made to address recovery of the social environment.

The Peruvian Ministry of Education had already taken steps to understand the impact of this event on the school system. Reinstatement of school facilities and organisations is recognised as a key component in the recovery of social structures and thus critical for social recovery.

By 18 September 2007, 786 classrooms had been assessed as in good condition, allowing 85% of schools in the affected areas to restart classes. In those areas where schools were inhabitable, temporary shelters were made to accommodate children. Whilst much of the built environment may well have been intact or alternative arrangements put in place, some social and/or cultural barriers were preventing attendance at school.

The Ministry of Education recognised that providing psycho-social assistance to teachers and students and redesigning the entire education program in order to recover the missed time during the remaining academic year were key objectives in their recovery programme.

Within the health community, one of the significant issues being discussed was the 'mental health' of people and how this would place a strain or lead to a change or breakdown in social structures. Peruvian officials recognised that this was not simply restricted to those directly affected i.e. those who have lost a house, but that it extended into all areas of the community such as those at the welfare camps, organised response workers and spontaneous volunteers.

In some areas, community leaders formed committees to address specific community needs, whilst in other areas some people at welfare camps were disgruntled at not seeing any community leaders offering this support. It was recognised that this disgruntlement could lead to a lack in public confidence leading to a social behavioural change and creating further issues for response agencies. Careful consideration and planning across a number of different agencies was being undertaken to ensure that the response and management of these social issues is effective.

### 8.2 Economic impacts

The damage cost and economic impact of the Pisco earthquake has not been estimated. However, with over 58,000 houses destroyed, destruction of 14 hospitals and damage to schools and public buildings and infrastructure, the economic impact is expected to be significant.

The overall impact on the Peruvian economy is likely to be slight, but for organizations and individuals in Pisco the earthquake will have ongoing and significant economic consequences. For those in Ica, the impact was considerably less in proportion to the population.

The lack of damage to the steel mill and liquefaction plant, for example, will make the impact less than it would otherwise have been. At least those employed will have ongoing income to pay for repairs to their properties and help the local economy. The Economist newspaper quoted that the fish oil plants sustained a total of \$30 m damage.

Availability of money from government was reported to be dependent on the earthquake being of at least magnitude 8.0. Those with their houses destroyed would get 6,000 soles (US\$2,200), but partially damaged houses did not qualify for relief.

Damage to hotels affected the tourist industry and until these are repaired or replaced, tourists are unlikely to return, even if essential infrastructure is restored.

The fact that Lima was 150 km from the epicentre meant that impact on it was slight and thus the large pool of resources from the capital city was available to assist in response and recovery. A similar sized earthquake located near Lima would cause much greater physical and economic impact.

## 9 Key lessons and implications

### 9.1 General

In the worst-affected areas ground shaking was comparable to that expected in a major event in the lowest seismic regions of New Zealand, such as Auckland. This provides some indication of likely performance of buildings and infrastructure in New Zealand.

Key points noted by the team included the:

- good performance of buildings that were well designed and constructed, including houses, recent schools, water towers, bridges and grandstands
- importance of applying higher design standards to protect infrastructure built on critical lifelines routes, for example bridges on highways and water resources (water towers etc.)
- use of shear walls for major structures in Lima, an important factor in limiting damage
- importance of communications immediately following an event.
- importance of the four R's: Reduction, Readiness, Response and Recovery. In particular, it is important that response plans recognize and allow for the anxiety and concerns of all personnel. Every one desperately needs to know what has happened to their personal property and loved ones.
- value of an effective building controls regime
- wisdom of special protection for hospitals, such as the base isolation.
- value in having a comprehensive network of instruments to measure ground and building response
- need to plan the co-ordination of international response and aid.
- survival with minimal disruption of industrial facilities, including a steel mill. This did much to mitigate economic and social effects by allowing people to get some 'normality' back.
- need to better understand the mechanics of earthquake shocks and their propagation outwards from the source as well as of the site effects on ground motion.
- The highly variable performance of unreinforced masonry (brick) buildings. Variation of the effects on similar buildings in the same area was extreme.

Some buildings showed no signs of having been through two minutes of strong shaking while others collapsed.

Perhaps the most important point overall was the good performance of well designed and constructed buildings and civil engineering structures as bridges. This supports the best of current design approaches and the value of quality construction. It is clear that the best Peruvian earthquake engineers are of international standard. The challenge for Peru is to put in place the measures that would see application of the best earthquake engineering practice to a wider range of buildings. This would require strengthening of research activities, education of designers and builders, and improved building controls.

## 10 IMPLICATIONS FOR THE 4 R'S OF EMERGENCY MANAGEMENT

In terms of the four R's for earthquake risk mitigation, these lessons may be summarized as follows:

- Reduction
    - Mitigation is an investment, not simply a cost
    - Design well.
    - Build well.
    - Research well.
    - Develop standards well.
    - Legislate well.
    - Implement well.
    - Take advice. (Seek it and follow it.)
  - Readiness
    - Be prepared for co-ordinated response - quick and effective
    - Address vulnerabilities, especially communications
    - Estimate nature and extent of damage (seismic risk analyses)
    - Estimate resources required to respond and recover
    - Understand the roles, responsibilities and interdependencies of other responding agencies.
    - Build and nurture relationships
  - Response
    - Resources needed fast
      - Urban Search and Rescue
      - Health supplies
      - Damage information to help plan response
      - Emergency communications
    - Co-ordination and control vital
    - Human response is important
  - Recovery
    - Resilient industries are important
- Examine resource requirements and scenarios
  - Consider human factors
  - Special legislation may be necessary.

Finally, there is a strong reminder that:

**Readiness + Reduction + Response + Recovery = Resilient communities.**

## ACKNOWLEDGEMENTS

The technical reconnaissance mission was conducted under the control of the NZSEE, supported from its own funds and generous support from the New Zealand Earthquake Commission and New Zealand Department of Building and Housing.

The team was grateful for the co-operation of the many people and agencies visited and their willingness to share information to assist New Zealand earthquake professionals to learn from this devastating earthquake.

In particular the team would like to thank:

- His Excellency the Ambassador of Peru, Mr Carlos Zapata for his support, facilitation of contacts and insights.
- His Excellency, the New Zealand Ambassador to Chile, Mr Nigel Fyfe, and First Secretary, Guy Lewis, for interest and support.
- The New Zealand Honorary Consul in Peru, Mr Alfonso Rey, whose early information and guidance was invaluable.
- Mr Cesar Arestegui, Third Secretary, and New Zealand desk officer, Ministry of Foreign Affairs, Lima, who assisted in making arrangements for meetings.
- Dr Hernando Tavera, Dr Hernan Montes and Dr Ronald Woodman of the Geophysical Institute of Peru for their time in sharing information, and particularly for information on the geophysical characteristics of the event. Dr Woodman's personal insights and information on the tsunami in and around Paracas were most interesting.
- Ing Luis Huaylinos and Arq Miguel Nuivez at the Ministry of Education (ENFES), together with Dr Ing Javier Pique for detailed and relevant information on school buildings, particularly their design and performance in this and other earthquakes.
- Those we met at the Ministry of Housing, including:
  - Julia Velasquez – Director of Construction
  - Ing. Jose Luis Ibanez – Coordinator of Valuations
  - Julio Morales Palomin – Assessor Department
  - Roberto Prieto – Standards Engineer
  - Ing Enrique Carrivee – Financial supervisor
  - Carlos Carbatal – Standards Engineer
- Arq. Leonardo Munante Caprio, Section Chief, Lima Municipality.
- Those we met at the CISMID (Peruvian-Japanese Centre for earthquake research and disaster mitigation), for presentations and information, especially for providing acceleration time series and feedback on early field visits they had undertaken, including:
  - Dr Ing Jorge Alva Hurtado, Dean of Engineering Faculty, National University of Engineering,
  - Dr Fernando Lazares, faculty member
  - Dr Ing Javier Pique
- Dr Ing Carlos Zavala
- Prof. Marcial Blondet, of the Catholic University of Peru, for his willingness to meet us and share information.
- Ing Miguel Angel Ochoa, Director General of Ministry of Transport and Communications, and 7 staff who briefed us on the early effects and response to the earthquake.
- Ministry of Health, especially the following for their interest, information and support:
  - Dra. Fatima Villavicencio Puntriano, Executive Director, International Cooperation Office and General Planning and Budget Office
  - Elena Mercedes Tanaka Torres, Director General, General Planning and Budget Office
  - Dr Edward Cruz Sanchez, Assessor, Direction General of Health
- International aid representatives at Pisco Air Force Base Emergency Operations Centre, especially Gabriel Diaz, UNDAC; Guido Cornale, UNICEF; Raul Salazar, UNDP; and Luis Ronaldo Duran Vargas, Red Cross Federation.
- The controller of the emergency operations in Pisco, Mr Percy Alvarado (INDECI).
- Manuel Arcos, INDECI for the province of ICA
- Eng. Carlos Esponzoza, Luis Pisconte and Efrain Mancco who were assisting the Mayor of Ica with the aftermath of the earthquake, for their time in providing details and arranging follow-up visits to the water authorities.
- Director and staff at the Ica Municipality water supply authority and representatives of their consultants, Emapica, for information and for accompanying the team to sites of damaged water tanks. These included, Juan Cucho Gauilan, Humberto Ramos Vazquez, Nemesio Efrain Mancco Leon, Fernando Legus Nieto, Victor Baltazar Ramos and Gustavo Jaurequi Romero.
- Maximo Enrique Ecos Lima, Director of the Regional Hospital in Ica, for sharing his experiences of the earthquake and its effect on the hospital and staff.
- Ing Mendoza Almanoz, of Acero Arequipa, and colleagues, for a detailed description of the earthquake effects and tour of the steel making plant near Pisco.
- All those who assisted on an impromptu basis in response to our requests, notably those from Pacific Blue Oil and the people in the welfare camps and on the street who shared their personal experiences.

## APPENDIX A

### Recommendations for future reconnaissance visits

The experience of the Peru reconnaissance provided some pointers for future reconnaissance missions. These following recommendations are intended to assist NZSEE in planning future visits to major earthquakes overseas.

#### 1. Availability of members and in-country contacts

As soon as a major earthquake occurs that could result in a reconnaissance mission, email all members of NZSEE and other relevant contacts. Advise them of the prospect of a reconnaissance mission and possible dates. Ask two questions:

- Are you interested and prepared to go on such a mission on the terms of the NZSEE Reconnaissance Scheme?
- Do you know of any earthquake professionals or other contacts in or from the affected country who may be able to assist with initial information gathering to help NZSEE decide or with logistics if the mission proceeds?

*Members who are interested in going on reconnaissance missions should continue to register with the scheme, but the emails should not be restricted to them.*

*Emailing in this way will ensure that all interested parties are informed and given the chance to express interest. More importantly, vital in-country contacts may be identified, not only to assist in deciding whether or not to send a team, but may be able to assist or join the mission if it proceeds.*

#### 2. Political and trade contacts

Make early contact with the affected country's representative in New Zealand, and with New Zealand foreign affairs and trade contacts in New Zealand and, through them, in the affected country.

*Apart from following desirable protocols, this can lead to much better information about the event, and to an improved range of contacts.*

#### 3. Contact with EERI

Contact the Earthquake Engineering Research Institute (EERI) immediately.

*The EERI in California have many members from different countries. They have considerable resources and are usually quick to respond and identify in-country contacts.*

#### 4. Local professionals on NZ team

Seek to put local engineers on the New Zealand team.

*These should have a good knowledge of the local geography and location of key and vulnerable assets.*

*One or two such people have been invaluable in the past, in many cases doubling as interpreters. If this can be arranged or set up prior to arrival of the NZ team, that is preferable, but can be left to the team leader on arrival.*

#### 5. Non-travelling team members

Appoint non-travelling team members to help with mission preparation and logistics, keep track of internet and other information, and to assist with report compilation.

*A huge amount of information is available on the internet and through email contacts. Members of the NZ team, when appointed will do what they can to glean information about the earthquake before they depart and while on the mission. However, the logistics involved in preparation to go, travelling, meeting people and viewing / recording relevant points make it impossible to keep up.*

*They should pass relevant information on to the team and then be invited to be part of the team to write up the reconnaissance mission.*

#### 6. Internet protocols

Define internet protocols for dealing with information and reporting from the field.

Some thought needs to be given on how to use the internet for reporting on the mission as it happens. The daily diary kept for the Peru mission was a good way of recording details day by day. Email and internet allowed this to be shared via the NZSEE website and was apparently of some interest and value to members and others wishing to follow the progress of the mission.

It is recommended that NZSEE look to define some basic expectations and protocols for compiling and disseminating such information. For example, careful editing may be needed before the information is made available on the website. Other agencies such as DPMC, EQC, MFAT, NZAID, NZTE and EERI could be actively updated.

#### 7. Report production

The collation, editing and production of the reconnaissance report can be a major exercise. Secretarial support would make the task easier. Early appointment of someone to assist is recommended, even as a non-travelling member of the team.

## APPENDIX B – TEAM MEMBERS AND MISSION OBJECTIVES

The following briefing note was prepared before departure and sent to the Ambassador of Peru in Wellington to inform him and others of the team composition, travel arrangements and mission objectives

### 1. Team

The team members are as follows with their main responsibility shown:

**Table B1: Reconnaissance team members and responsibilities**

<b>Name/Organisation</b>	<b>Principal Responsibilities</b>
<b>Dr David Hopkins</b> David Hopkins Consulting, Wellington (David is Director of the International Association for Earthquake Engineering and of the World Seismic Safety Initiative)	Leader. Overall responsibility – all aspects Structures, Building Codes Lifelines Economic impacts
<b>Dr James Burr</b> Tonkin & Taylor, Consulting Engineers, Auckland	Geotechnical, Foundations
<b>Dr Rafael Benites</b> GNS Science, Wellington	Site Response, Geology/Tectonic/Seismology
<b>Mr Rudolph Kotze</b> Bridges and Structures Manager Transit NZ, Wellington	Bridges, lifelines and industrial facilities
<b>Mr Craig Hamilton</b> Civil Defence and Emergency Management Specialist Greater Wellington Regional Council, Wellington	Emergency management, social impact, lifelines
<b>Dr Darren Bell</b> Connell Wagner, Consulting Engineers Wellington	Buildings, civil engineering structures. damage assessments, non-structural elements.



*Figure B1. Reconnaissance team members*

**Team members (from left):**

Craig Hamilton, Rafael Benites, Darrin Bell, Rudolph Kotze, James Burr, David Hopkins

## 2. Proposed Itinerary

- Arrive Lima on Flight LA530 from Santiago at 10.45pm on Saturday 25 August. (We are being met by Mr Roberto Chavez, who is the brother-in-law of one of our Wellington colleagues, Mr Wayne MacArthur. Roberto will accompany us during our visit.)
- Staying in a hotel in Lima (name to be advised) on Saturday, Sunday and Monday nights.
- Arrangements for the rest of the week will depend on access to areas of interest and availability of people we would like to meet.
- We plan to make contact with some key organizations on Monday 27 and Tuesday 28 to obtain information and establish contacts that could help with access to affected areas. See below for organizations we are hoping to meet.
- Depart Lima on Flight LA573 for Santiago at 2.30pm on Sunday 2 September

## 3. Objectives

- To gather technical information on the effects of the earthquake – physical, organizational and social – that is relevant to New Zealand and internationally in the efforts to reduce earthquake risk and respond better to earthquake events.
- To share our interpretations with colleagues in New Zealand and elsewhere.
- To identify any technical issues on which NZ may be able to assist Peru, or work jointly with them.

The team will write a report for the Bulletin of the New Zealand Society for Earthquake Engineering, copies of which will be provided to you and to those contacts made during our visit who indicate an interest.

## 4. Organisations we would like to contact

We are very mindful of the demands that the earthquake will have placed on these organizations, but we do hope that we can meet with key people in some of them in order to target our observations and gain insights into the effects and the concerns of those having to deal with the response and recovery. We know that New Zealand will one day face a similar situation. Having the chance to talk to some of those responsible for design and construction standards, response to the earthquake and recovery from it will be invaluable and much appreciated.

From our discussion this morning, the following organizations are of interest: (There may be others)

- INDECI – the civil defence and emergency management organization
- Ministry of Transport, Communications and Housing – responsible for roads and bridges.
- Ministry of Housing – buildings, houses, water supply
- Ministry of Health – we are interested in the effects of the earthquake on hospitals and health facilities
- Ministry of Education and its subsidiary organization, ENFES – we are interested in schools and educational facilities
- The counterpart organization to GNS Science, who have knowledge of the seismicity of Lima and surrounds.

- The Municipality of Lima, particularly those responsible for building standards and for assessing the buildings after the earthquake.
- Other municipalities such as in Pisco, Chichan Alta, and Ica.

We have contacts in the Catholic University of Peru.

We are also interested in:

- The effects on lifelines such as electricity supply, waste water treatment, oil and petroleum supplies and storage.
- Transportation facilities such as ports and railways
- The social impacts

### APPENDIX C – ACKNOWLEDGEMENT AND CONTACT LIST

The team and the NZSEE would like to thank:

- His Excellency the Ambassador of Peru, Mr Carlos Zapata for his support, facilitation of contacts and insights.
- His Excellency, the New Zealand Ambassador to Chile, Mr Nigel Fyfe, and First Secretary, Guy Lewis, for interest and support.
- The New Zealand Honorary Consul in Peru, Mr Alfonso Rey, whose early information and guidance was invaluable.
- Mr Cesar Arestegui, Third Secretary, and New Zealand desk officer, Ministry of Foreign Affairs, Lima, who assisted in making arrangements for meetings.
- Dr Hernando Tavera, Dr Hernan Montes and Dr Ronald Woodman of the Geophysical Institute of Peru for their time in sharing information, and particularly for information on the geophysical characteristics of the event. Dr Woodman's personal insights and information on the tsunami in and around Paracas were most interesting.
- Ing Luis Huaylinos and Arq Miguel Nuivez at the Ministry of Education (ENFES), together with Dr Ing Javier Pique for detailed and relevant information on school buildings, particularly their design and performance in this and other earthquakes.
- Those we met at the Ministry of Housing, including:
  - Julia Velasquez – Director of Construction
  - Ing. Jose Luis Ibanez – Coordinator of Valuations
  - Julio Morales Palomin – Assessor Department
  - Roberto Prieto – Standards Engineer
  - Ing Enrique Carrivee – Financial supervisor
  - Carlos Carbatal – Standards Engineer
- Arq. Leonardo Munante Caprio, Section Chief, Lima Municipality.
- Those we met at the CISMID (Peruvian-Japanese Centre for earthquake research and disaster mitigation), for presentations and information, especially for providing acceleration time series and feedback on early field visits they had undertaken, including:
  - Dr Ing Jorge Alva Hurtado, Dean of Engineering Faculty, National University of Engineering,
  - Dr Fernando Lazares, faculty member
  - Dr Ing Javier Pique
  - Dr Ing Carlos Zavala
- Prof. Marcial Blondet, of the Catholic University of Peru, for his willingness to meet us and share information.
- Ing Miguel Angel Ochoa, Director General of Ministry of Transport and Communications, and 7 staff who briefed us on the early effects and response to the earthquake.
- Ministry of Health, especially the following for their interest, information and support:
  - Dra. Fatima Villavicencio Puntriano, Executive Director, International Cooperation Office and General Planning and Budget Office
  - Elena Mercedes Tanaka Torres, Director General, General Planning and Budget Office
  - Dr Edward Cruz Sanchez, Assessor, Direction General of Health
- International aid representatives at Pisco Air Force Base Emergency Operations Centre, especially Gabriel Diaz, UNDAC; Guido Cornale, UNICEF; Raul Salazar, UNDP; and Luis Ronaldo Duran Vargas, Red Cross Federation.
- The controller of the emergency operations in Pisco, Mr Percy Alvarado (INDECI).
- Manuel Arcos, INDECI for the province of ICA
- Eng. Carlos Esponzoza, Luis Pisconte and Efrain Mancco who were assisting the Mayor of Ica with the aftermath of the earthquake, for their time in providing details and arranging follow-up visits to the water authorities.
- Director and staff at the Ica Municipality water supply authority and representatives of their consultants, Emapica, for information and for accompanying the team to sites of damaged water tanks. These included, Juan Cucho Gauilan, Humberto Ramos Vazquez, Nemesio Efrain Mancco Leon, Fernando Legus Nieto, Victor Baltazar Ramos and Gustavo Jaurequi Romero.
- Maximo Enrique Ecos Lima, Director of the Regional Hospital in Ica, for sharing his experiences of the earthquake and its effect on the hospital and staff.
- Ing Mendoza Almanoz, of Acero Arequipa, and colleagues, for a detailed description of the earthquake effects and tour of the steel making plant near Pisco.
- All those who assisted on an impromptu basis in response to our requests, notably those from Pacific Blue Oil and the people in the welfare camps and on the street who shared their personal experiences.

- Roberto Chavez, the team's guide, agent, interpreter, organizer and adviser on local matters. His support was invaluable.
- Professor Michael Pender, NZSEE President, Andrew King, Reconnaissance Team Organiser, Wayne MacArthur for assistance in preparing the mission.
- Ian Brewer, NZSEE member, for vital assistance with final editing of the report.