THE 15 AUGUST 2007 PISCO, PERU, EARTHQUAKE - POST-EARTHQUAKE FIELD SURVEY

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ABSTRACT :

On 15 August 2007 a moment magnitude M_w 7.9 earthquake hit the central coast of Peru, causing severe damage to houses, buildings and infrastructure in areas within the Ica and Lima regions. The earthquake is reported to have caused 519 deaths and 1,366 injuries and the collapse of more than 58,000 houses. The Earthquake Engineering Field Investigation Team (EEFIT), part of the Institute of Structural Engineers of the United Kingdom, undertook a post-earthquake field survey mission to Peru. The mission focused on the behaviour of non-engineered structures, in particular those of adobe construction, but engineered structures and geotechnical effects were also surveyed. This paper presents the earthquake characteristics and summarises the main findings from the post-earthquake field survey carried out by the EEFIT team.

KEYWORDS: Peru Earthquake, Field survey, Adobe houses, Subduction ground-motions.

1. EVENT DESCRIPTION

1.1 Earthquake Characteristics

On 15 August 2007, at 23h 40min 59sec (UMT) – 18h 40min 59sec (local time), a 7.9 Mw magnitude earthquake occurred off the coast of Central Peru. The epicenter of the event was located about 60 km west of the city of Pisco, and about 140 km south-east to the capital city of Peru, Lima. The event had a focal depth of 40km. The seismic activity in Peru is related to the subduction of the Nazca plate under the South American plate at a mean rate of about 70-80 mm/year (Norabuena et al., 1999). Shallow interface events with small magnitudes along the coast of Peru occur frequently at depths of less than 60km (Tavera et al., 2006). The Pisco event occurred in a seismic gap of large earthquakes ($M_w \geq 7.5$) recorded from 1946 to 1996 (see Figure 1). Based on the tectonics of the region and employing the tensor solutions presented by the USGS, the Pisco earthquake is defined as a reverse fault earthquake with strike 324° and dip angle of 27°.

A total of 355 aftershocks with local magnitudes M_L equal to or larger than 3.0 were recorded by the Peruvian Geophysics Institute (IGP) between the 15th and the 20th of August 2007 (IGP, 2007) (see Figure 2a). The main earthquake rupture plane and the correspondent aftershocks ruptured an area parallel to the coast of Peru of about 170 km long and 130 km wide (Tavera et al., 2008) (see Figure 2a and the shaded area associated to the Pisco earthquake in Figure 1). These aftershocks have focal depths of less than 50 km, and are grouped into three clusters (G1, G2 and G3). According to the location and distribution of aftershocks, IGP suggests a rupture process occurring south-eastward. This process of rupture may be confirmed by the mainshock source process estimated by Ji & Cheng (2007) from teleseismic inversion (Figure 2b), in which the location of large aftershocks coincide with the location of high slip rates. Other source models by different authors also identify this trend of rupture (Tavera et al., 2008).

The direction of rupture propagation and the identification of two zones of high slip rates (i.e. the epicentral zone and the area SSE of it) are the likely explanatory reasons for the particular characteristics of the strong ground-motion recordings described below.

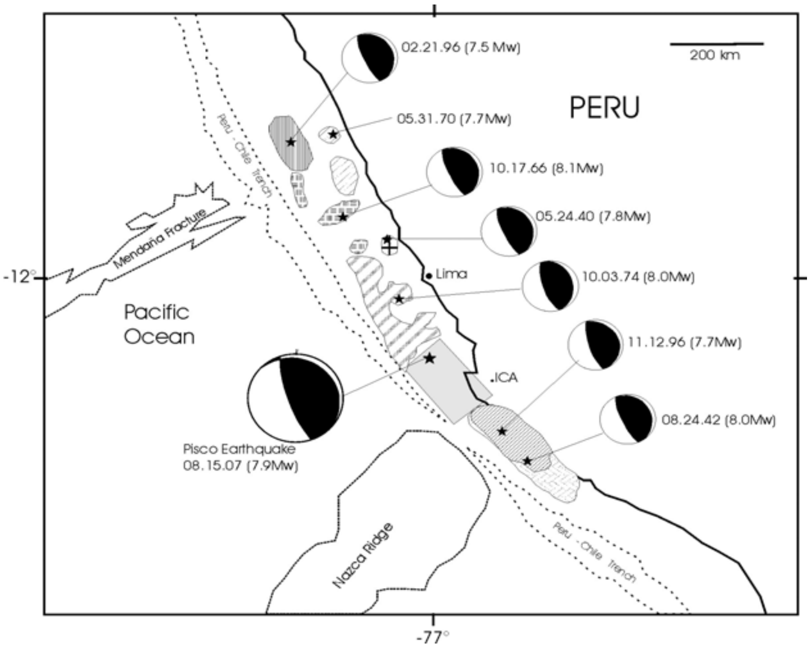

Figure 1. Epicentral location of the Pisco earthquake. Data of large magnitude earthquakes recorded between 1940 and 1996 is also presented (after Tavera et al., 2008).

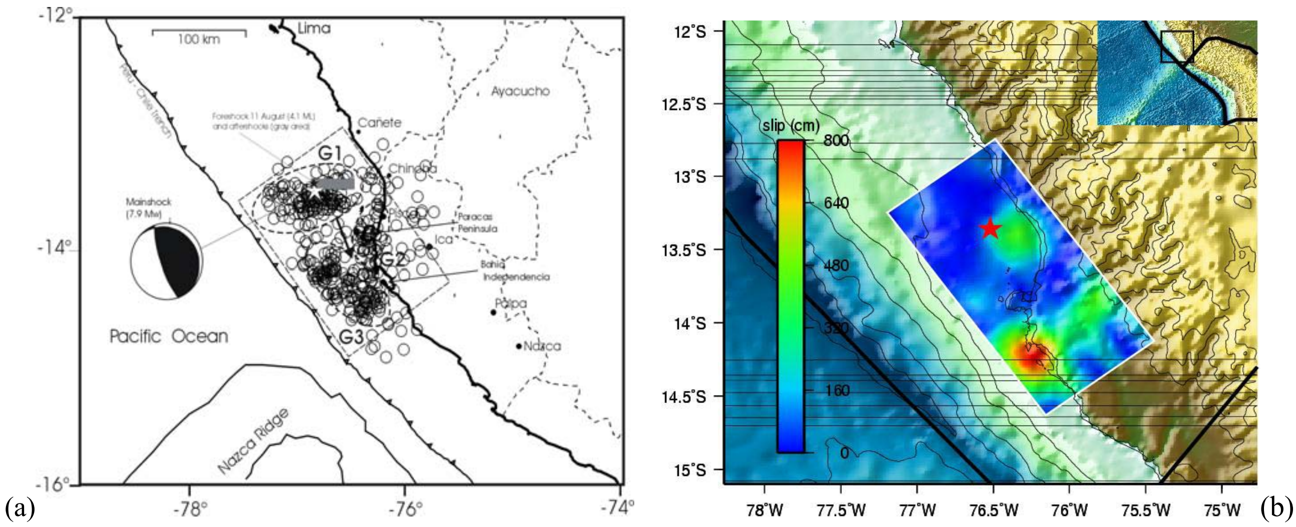

Figure 2. *(a)*: Epicentral location of the $M_L \geq 3.0$ earthquake aftershocks (www.igp.gob.pe). *(b)*: Earthquake slip distribution assessed from the teleseismic invertion carried out by Ji & Cheng (2007) (www.usgs.gov).

1.2 Strong Ground-Motion Recordings

A total of 18 accelerometer stations recorded the 15 August 2007 mainshock, with most of the instruments being located in the city of Lima and two of them installed in the city of Ica. The Lima and Ica instruments are located at epicentral distances of approximately 160km and 140km respectively, but at Joyner-Boore distances (see Abrahamson and Shedlock, 1997) R_{jb} of 105km and 0km respectively. Surface rupture distance metrics R_{rup} are about 110km and 37km for Lima and Ica stations.

These strong ground-motion time histories were filtered and processed at Imperial College London and thereafter thoroughly analysed. The detailed analysis carried out on these recordings is presented in full in Tavera et al. (2008) and therefore only a general description of the ground motions is included herein for illustrative purposes.

Figure 3 presents the East-West components of the strong ground-motions recorded at Callao and La Molina stations (in Lima city) and at Ica2 station (in the city of Ica). Two relevant features of the recorded time-histories are the length and the amplitude distribution of the ground motions. All recordings show total durations of approximately 160 seconds (about 2.6 minutes) with three sequences of motions: the first part lasts around 30-50 seconds (this duration varies from Lima to Ica recordings, with the latter ground motions having shorter duration); the second part has smaller amplitudes that last 20 to 30 seconds, with finally a sequence of larger motions. This form of the ground motions being distributed in two strong sections helped most of the population to evacuate their houses during the intermediate sequence of the shaking. The peak ground acceleration at Ica city (which corresponds to the largest PGA values recorded during the main shock) is about 60% of the design acceleration given in the Peruvian code for the site.

The principal explanations for the duration and distribution of these ground motions are the rupture model having two zones of large displacements (which generated the two sections of motions) and a low fault rupture velocity, calculated at about 1.4 km/s, which is about half of the mean expected velocity of similar earthquakes of about 2.5 to 3.5 km/s (e.g. Pelayo and Wiens, 1992).

The event was felt within a radius of 600 km to the northwest, 400 km to the southeast, and 300 km to the east, and caused general panic and disrupted power and communication lifelines in the towns located closest to the epicentral region. The highest maximum intensities corresponded to VIII on the Modified Mercalli scale (MMI) and were reported for Pisco city (see Figure 4 for location). In the cities of Ica, Chincha and San Vicente de Cañete the maximum MMI intensities were of VII. The higher-intensity isoseismals (VI, VII and VIII) are elongated to the South East with respect to the epicenter (Tavera et al., 2008), reflecting the fault rupture direction previously discussed and the seismic energy being attenuated more strongly in an easterly direction due to the presence of the Coastal Cordillera.

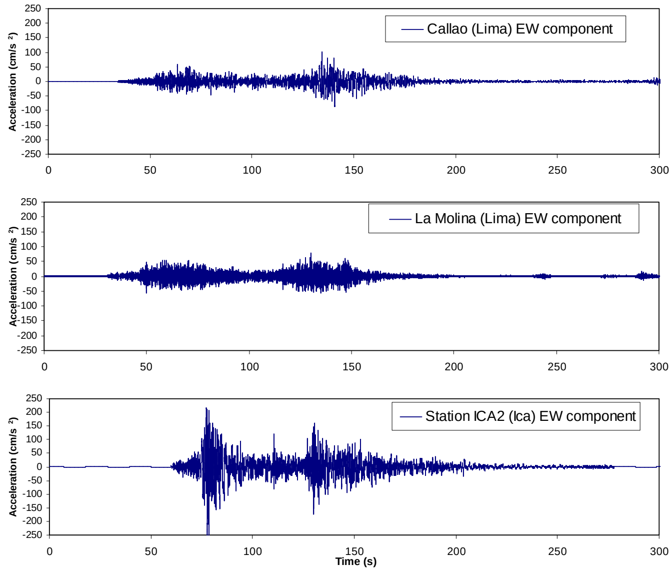

Figure 3. East-West component of the ground-motion recordings at Callao, La Molina and ICA2 stations

2. FIELD SURVEY OBSERVATIONS

The areas mostly affected by the earthquake are within the Ica and Lima regions (see Figure 2), with an official death toll of 519 with 1,366 injured, a total of 58,581 houses destroyed or demolished as a result of the severe damage induced, and 13,585 houses affected to some degree (www.onu.org.pe). The Peruvian Government estimated losses from the earthquake in US$450 million, and expected a reduction in the economic growth of 0.3% for 2007 as a direct result of the event. This section summarises some of the damage observed during the EEFIT team field survey. For the complete description of the findings and field observations the reader is referred to the EEFIT report (Taucer et al., 2008). A preliminary version of this report can be found at www.eefit.org.uk.

The areas visited during this EEFIT mission are shown in Figure 4. Even though the capital city Lima was not surveyed it is plotted in the figure for reference.

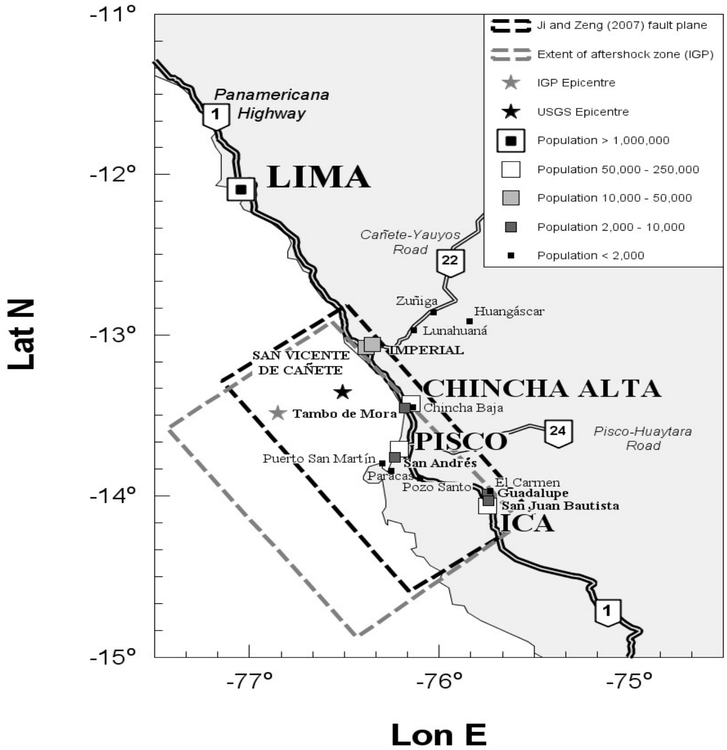

Figure 4. Sites visited during the EEFIT (2007) field survey. The capital city of Lima, which was not surveyed, is shown for reference. The epicentral locations given by the USGS (black star) and IGP (grey star) are plotted in the figure (after Tavera et al., 2008).

2.1. Performance of building structures

The performance of building structures is presented by distinguishing two cases: non-engineered and engineered structures. Most of the damage observed was caused to non-engineered structures whilst engineered structures performed satisfactorily, with the exception of buildings of low quality construction or having poor seismic resistance designs.

Non-engineered structures in the earthquake affected region can be classified as traditional earth structures, masonry structures and infilled reinforced concrete (RC) frames. Most of the non-engineered houses in the region are made of adobe, from which about 80% of the existing houses collapsed during the event (see Figure 5) or were demolished after it for being severely damaged during the shaking (INDECI personal communication). The collapse of adobe structures is due mainly to heavy mass that induce large inertial forces from the earthquake in combination to the very low strength with respect to the density of the material. These factors usually lead to failure of the material in a brittle manner, thus not allowing for energy dissipation and giving no warning to occupants before collapse. However, during the Pisco earthquake, the characteristics of the ground motions induced (i.e. very long duration distributed in three phases) allowed people to evacuate their houses in the middle phase of the ground shaking, before the collapse of the houses.

(a)  (b)

Figure 5. *(a)*: Collapsed adobe house in Ica. *(b)*: Debris of adobe houses in Guadalupe

Masonry structures have been included in the list of non-engineered structures as the majority were built prior to the existence of modern construction codes. These structures correspond to those of cultural heritage or government buildings, and are mostly found near the central squares of cities and towns. The masonry structures in the areas visited are built from clay bricks, usually with elaborate facades and arches at the front. Apart from a few collapses, these structures showed medium to light damage. Finally, very few infilled RC frames were found and hence no collapses were observed. The low number of RC infilled frames in the region is due to the fact that building owners with limited economic means can only afford adobe construction, whereas families with higher economical resources very often choose to build with RC confined brick masonry.

Engineered constructions in the region correspond to RC confined masonry, RC moment frames and strengthen adobe houses. Engineered buildings represent a small fraction of the total number of buildings and are concentrated in the major cities of Ica and Pisco. This type of structures performed satisfactorily. Most of the engineered houses in the region correspond to reinforced concrete confined brick masonry. A feature commonly observed along the region was the collapse of adobe houses neighbouring RC confined masonry which suffer no or very light damage (Figure 6a). Reinforced concrete infilled frames are most commonly found in the largest city centres of Pisco and Ica as multi-storey residential, commercial or office buildings. With the exception of cases where poor quality materials were employed in the construction or by constructive weaknesses such as short columns mechanisms, soft storey configurations, or poor steel reinforcement, these structures performed satisfactorily.

A few examples of adobe houses designed or retrofitted for earthquake resistance prior to the disaster event were found in the towns of Guadalupe, Zúñiga and Huangáscar. They all performed satisfactorily during the earthquake. In the town of Guadalupe, an adobe house was upgraded by the Universidad Pontificia Católica del Perú (PUCP) by means of strips of steel net tied and plastered to the exterior and interior surfaces of the adobe walls (Figure 6b). All other adobe houses near this retrofitted house suffered medium to severe damage or collapsed. In the town of Zúñiga a new two-storey house built by the Japan International Cooperation Agency (JICA) resisted the earthquake with minor damage (for more details the reader is referred to Taucer et al., 2008).

Most churches in the region are dated to colonial times (about 1700's -1800's).The large majority of churches surveyed during the EEFIT mission suffered considerable damage after failure of the roof, longitudinal walls and bell towers. The church of San Clemente in the main square in the city of Pisco collapsed during a funeral service at the time of the earthquake event, causing the single largest death toll during the earthquake (about half the total casualties during the event).

(a)  (b)

Figure 6. *(a)*: Collapsed adobe house besides a RC confined masonry in Ica. *(b)*: Strengthened adobe house

2.2. Performance of ports and bridges

Two key Peruvian ports are located along the affected region: the ports of El Callao and San Martín. The activities of the first port were not affected by the event but damage associated to poor soil conditions was reported in the areas adjacent to it. On the other hand, severe damage was observed to the access to the dock of San Martín port due to settlements and lateral displacements of the underlying soil (Figure 7a). The soil on site is composed of a conglomerate of angular stones of up to 150 mm in size, mixed with sand. These settlements reach values of up to 1.2m with respect to the dock structure (an 18 m wide reinforced concrete 0.55 m thick slab supported on 0.6 m diameter circular steel piles spaced at 4 m) which did not suffer damage. According to information from local authorities, some damage to the dock access was caused during the main shock, but it increased severely with the occurrence of aftershocks during the following weeks.

With respect to bridges, and in spite of the low number of these structures present in the visited areas, the EEFIT team observed about 10 road bridges of various sizes, which, with the exception of the Huamaní Bridge (a five span reinforced concrete motorway bridge located along the Pan American Highway linking the towns of San Clemente and Pisco), performed satisfactorily. Damage on the Huamani bridge corresponded to the relative displacement of 10cm at the south pinned connection, resulting in local damage to the deck and to the west parapet of the south abutment as a result of the pounding action, (Figure 7b). The main reinforcement of the parapets showed insufficient shear reinforcement and lack of confinement. The EERI team that visited the area 3 days after the earthquake reported evidence of liquefaction at three piers of the bridge and in the surrounding area (EERI, 2007).

2.3. Tsunami

After the main shock, a tsunami warning was issued for Chile, Colombia, Ecuador and Peru by the Hawaii Institute of Geophysics. The tsunami waves travelled as far as Japan, where heights of 0.5 m were recorded. Fishermen unions from San Andrés creek in Pisco estimated that about 107 boats were damaged, 50 destroyed and 2,000 fishermen affected as a consequence of the tsunami triggered by the earthquake. Locals in the town of Paracas recall a wave height reaching up to 1.6 m at the coast and informed the EEFIT team that the runup of the tsunami went as far as 200 m inland. In Tambo de Mora, locals observed a tsunami wave height of approximately 2.5 m. The EERI tsunami reconnaissance team determined a maximum run-up of 10 m south of the Paracas peninsula occurring along inhabited areas (EERI, 2007).

(a)  (b)

Figure 7. *(a)*: Severe damage to the dock access in San Martín port. *(b)*: Detail of parapet damage

2.4. Geotechnical features

2.4.1 Liquefaction

Liquefaction effects were observed at Tambo de Mora over an area of approximately 3.0km by1.0km along the coast. Damage to residential areas occurred on an area of about 300×150 metres, where settlements due to liquefaction reached up to about 1.0 metre, electricity poles tilted about 30 degrees and sand boils were observed. This same area had been affected by liquefaction during earthquakes occurring in 1970 and 1974, but no re-location of houses or ground improvements were carried out at the time. People were able to leave their houses during the intermediate phase of the strong ground-motions, being this the reason why the collapse of these houses caused only five casualties. Local inhabitants mentioned that the large settlements and failure of structures occurred during the second phase of the strong motion.

2.4.2 Landslides

A variety of landslides were observed during the field visit. Some rotational landslides in soil were observed in the coastal area along the Pan Americana motorway (these kinds of landslides block the road making an ordinary 3 hour travel from Lima to Pisco a 8-9 hours travel). At the time of the EEFIT team visit, 22 days after the main event, the Pan-American Highway had been cleared from debris and entirely repaired. According to information received at the Pontificia Universidad Católica del Perú (PUCP), the area mostly affected was the stretch of the Pan Americana motorway between Chincha Alta and San Clemente. Debris and boulder flows were observed in the Zuñiga area on the Andean mountains, and rock falls in the step slopes near Huangascar in the high mountains.

2.4.3 Foundation behaviour

Evaluation of foundations is rather complex since access to them is rarely possible; foundation failure is only observable in extreme cases when its failure is evident, which was not the case in any of the areas visited in Peru. Considering the structural typology of most of the structures observed during the visit, foundations can be assumed to be shallow with isolated poorly connected footings. In general terms, such foundations did not suffer serious problems during the earthquake, with the exception of the liquefaction induced failures.

3. CONCLUSIONS

In spite of the large number of destroyed houses (58,581) and affected population (200,000), the number of casualties was relatively low (519 deaths). This is due to three main factors: the long duration of the earthquake event with an intermediate portion of low level ground motions that allowed dwellers to escape, the fact that most adobe houses were single storey with light roofs – typical of arid climates –, and the time of the day (18:40, local time), when most people are awake and out of their homes.

About 80% of all traditional adobe structures within the affected area (about 3,000km^2) collapsed or were severely damaged. Earth structures designed for earthquake resistance performed satisfactorily. Structures built for earthquake resistant design, such as 1 to 6 storeys RC confined masonry buildings had minimum levels of damage.

Most of the attention in emergency relief was focused in the largest cities (Ica, Pisco and Chincha Alta), while rural, remote areas, especially along the valleys running up the Andes, were facing delays in receiving emergency relief. As the reconstruction process led by governmental institutions had not commenced at the time of the field mission, part of the affected population had already started reconstruction, in general without qualified assistance. In rural areas with higher levels of poverty, the adobe bricks from the fallen houses were being reused for reconstruction following traditional techniques, thus reestablishing the same level of high risk that existed prior to the earthquake event.

ACKNOWLEDGMENTS

The authors wish to acknowledge their gratitude towards Arup (UK), the European Commission, and the Engineering and Physical Sciences Research Council (UK), for providing the necessary funding for the field mission. Special thanks are given to Zygmunt Lubkowski for reviewing this manuscript.

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