Observed behaviour of earthen structures during the Pisco earthquake (Peru)

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ABSTRACT :

On August 15, 2007, at 18:40 local time (23:40 UTC) an earthquake of magnitude M_w 8.0, shook the southern area of central Peru. Ica, Lima and Huancavelica were the most affected regions. According to the latest statistics 593 people died, 48 208 dwellings completely collapsed and 45 500 were left uninhabitable (INDECI 2008). Adobe dwellings –both old and new– along with historical monuments (such as churches that were built using soil or bricks) were the most affected structures. Constructions built with fired clay brick or with reinforced concrete didn't suffer from strong damage, except when the buildings were poorly constructed or they did not have a secure structural configuration. The intention of this report is to describe the damage that the earthquake caused in Pisco's dwellings and earthen structures. The report will also present a brief analysis of the various construction failures and errors that were encountered, along with recommendations on how to improve the seismic-resistance of the ground buildings.

KEYWORDS: Pisco Earthquake, earthen dwellings, earthen monuments.

1. INTRODUCTION

The majority of seismic events that occur on the Peruvian coast are produced by the subduction process, where the Nazca plate moves under the South American plate at a rate of 80 mm per year. The epicentre of the earthquake, with 13.35°S and 76.60°W coordinates, took place 60 km west of Pisco and 150 km southwest of Lima and lasted for about 3 minutes and 30 seconds (IGP 2007). The hypocenter was located at a depth of approximately 40 km. The intensity of the earthquake in Pisco and Chincha was of VIII in the Modified Mercalli Intensity scale. In Lima the intensity was of VI while in Arequipa (730 km south of Pisco) and Chiclayo (1100 km north of Pisco) the intensity calculated for these cities was that of III and II, respectively. Between August 15 (date of the earthquake) and August 27, more than 3000 replicas were registered in the area (Tavera et al. 2007). The strongest one took place on Sunday, August 19, at 15:11 (local time) and had a 5,7 M_L magnitude.

The earthquake that took place on August 15 is related to previous seismic activity recorded in the area, such as the one that occurred on October 20, 2006. The 2006 earthquake had a M_w 6,4 magnitude and its hypocenter was located 90 km west of Pisco, at a depth of 43 km. The rupture area of both earthquakes took place on a seismic gap previously registered between the rupture areas of the 1974 Lima earthquake (M_w 7,6) and the 1996 Nazca earthquake (M_w 7,7) as shown on Figure 1.

2. VISITED CITES

Within two to six days after the disaster had occurred, a group of researchers from the PUCP visited six cities. The cities seen were San Clemente, San Miguel, Pisco, Guadalupe, Pachacutec and Ica (Figure 2). According to 2005 Statistics and Informatics National Institute census (INEI 2005) adobe is one of the primary construction materials used in dwellings in that area. In Chincha (north of Pisco), 67% of the buildings were made using adobe, while in Pisco and Ica it was 42 and 39% respectively. Most adobe dwellings are located in the districts surrounding the capital of each province. The National Institute of Civil Defense (INDECI 2008) reported on February 07, 2008, 593 casualties, 48 208 dwellings completely collapsed and 45 500 were left uninhabitable by the earthquake. The majority of the affected buildings were located in the areas surrounding Ica, Lima and Huancavelica respectively.

Figure 1 Distribution of the epicentres and rupture areas from 1994 to 2007 (Tavera et al. 2007).

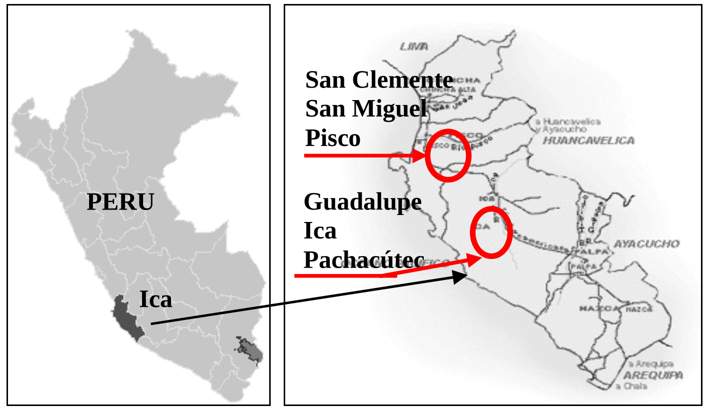


Figure 2 Visited sites.
(http://upload.wikimedia.org and http://www.info-hoteles.com)

3. DAMAGE IN EARTHEN BUILDINGS

As observed in all the visited cities, the collapse in earthen constructions was triggered by the progressive formation of cracks in the walls. The most common types were vertical cracks at the wall's corners and the x-shaped cracks in the façade walls. The cracking of the walls triggered the collapse of the structure and the partial or complete overturning of the walls caused the roof's collapse. The effect that the earthquake had on adobe constructions was catastrophic. In the Pisco area, for example, nearly 80% of the adobe buildings were completely damaged and destroyed by the earthquake. The high collapse percentage on the adobe buildings can be attributed mainly to the lack of seismic reinforcement on the dwellings. The reinforcement would have contributed to the displacement control between the walls, avoiding their collapse and allowing them to withstand further seismic movements. Other factors that influenced the buildings' collapse and that were responsible for much of the structural damage were the soft soils, the low quality of the building materials and the labour, the thinness of the walls, the inadequate configuration and location of openings (doors and windows), and the weak bond in the intersection between the walls and the roof.

3.1. Characteristics of earthen structures

The oldest earthen houses in the area were built more than 50 years ago, and are located in downtown Pisco and Ica. The usual thickness on these buildings' walls tends to range between 0,7 m and 0,8 m thick and about 4 m high. This means that their slenderness ratio (height/width) is below 6. Some of these buildings have used *quincha* panels to create interior independent environments. *Quincha* is a construction method that is widely used in South America, consisting on a wood and cane framework that is then covered with mud or gypsum. In some of the older 2-storey high buildings, adobe was used for the construction of the first floor, while the second floor was built using *quincha*. The more modern adobe buildings, on the other hand, have thinner and shorter walls (0.25 m and 3 m respectively) and their slenderness ratio is 8 or higher. These buildings don't have *quincha* walls and although most of them are only 1-storey high, a lot of them have interior rooms without a roof.

The older adobe dwellings surrounding Ica's main square have a 0,8 m high plinth wall made with fired clay bricks (Figure3a) to protect the walls from the humidity in the area, as Ica has already suffered several floods in the past. The completed wall is usually 4 m. high and 0,8 m thick. Eucalyptus trunks are sometimes placed within walls to partially bear the roof's weight (Figure 3b). The roofs of these constructions are built using a of wooden joists framework covered with a first layer of crushed cane, a second layer of straw mats (*esteras*) and finally plastered with mud. The wooden joists can either be parallel or perpendicular to the façade walls.

a) Plinth wall made using clay bricks b) Eucalyptus trunks used as columns

Figure 3 Old adobe dwellings in Ica.

3.2. Soil settlement

Due to the fact that Pisco's soil is composed of saturated sand layers, it is prone to suffer soil settlement or even to be affected by soil liquefaction, especially in the areas closer to the coast. In some coastal areas, like those near Pisco's waterfront, the soil has suffered from soil saturation due to the effect of the ocean and from dynamic compaction during the earthquake.

3.4. Overturning of the walls and roof's collapse

The most common failure observed in earthen buildings, especially in those with thin walls, was the overturning of the façade walls and their collapse onto the street. This was caused because the wall strength in the intersection between the façade wall and the other house walls was too low to withstand the earthquake's movement. The walls usually collapsed as follows: first vertical cracks appeared on the wall's corners causing the adobe blocks in that area start to break and fall (Figure 4). This triggered the walls to disconnect until finally the façade wall turned over (Figure 5). The situation was worsened by the fact that separation joints between the buildings seems to be an uncommon practice in the area. Consequently, the direct contact between the walls during seismic activity leads to their collapse.

The observations made after the earthquake have shown that the magnitude of the damage that the buildings suffered when their walls collapsed, was directly related to whether the roof's wooden joists where supported on the façade wall or not. If they were supported by the façade, the wall's collapse caused them come off balance, causing the roof to collapse as well. If, on the other hand, the joists were supported by the walls that were perpendicular to the façade wall, the roof didn't fall apart (Figure 5).

Figure 4 Vertical cracks in the wall's corner.

Figure 5 Collapse of the façade walls in adobe buildings.

Many adobe buildings located on street corners suffered from heavy structural damage due to the collapse of their two façade walls and roof. The cracks produced on the corner between these two walls are both vertical and diagonal. The diagonal cracks extend from the highest part of each wall's corner down to the house base, forming a 'v' like crack pattern (Figure 6).

Figure 6 Diagonal and vertical cracks shown on corner buildings.

3.5. Shear failure on the walls

The walls that didn't overturn where able to withstand the earthquake's in plane actions. In some of these cases, however, the appearance of diagonal cracks was observed.

3.3. Quality of the constructions materials

The adhesion between the adobes and mortar in most collapsed or heavily damaged walls (especially in the ones belonging to the more recent buildings in Pisco) is quite poor and weak. When the adobe walls collapsed, most of the adobe blocks that were used for these constructions didn't hold together with the mortar and crumbled (Figure 7). It is presumed that, as it is obtained from a coastal area, the soil used for the making of the bricks and mortar contains too much sand and too little clay, producing as a result a weak bond between the mortar and the adobe blocks. Unfortunately clay is the only soil component that, as a reaction to water contact, causes the soil particles to chemically bond. In some of the houses in the area, it was observed that the adobe used for the constructions would easily crumble when scratched with the nail.

Figure 7 These images show the weak bond between the mortar and the adobe blocks.

4. Construction on developing areas

Some of the more recent buildings located on the developing areas around Guadalupe and Ica have been constructed without taking seismic security guidelines into consideration and are, therefore, more susceptible to suffer damage due to seismic activity than the older constructions in the area. The walls on the modern buildings are more susceptible to collapse due to out of plane loads as they are narrower (with a 0,25 m thickness) and more slender than the older walls. Many of the houses in the area only have 1 or 2 enclosed rooms, and many of them have enclosure walls constructed using adobe. The roofs were built using wood that was covered with crushed cane, straw mats, cardboards or sandbags, used as insulation to keep the house inhabitants warm. The floor of the houses is usually moistened soil that has been compacted. Most of the dwellings constructed following this model collapsed during the earthquake (Figure 8).

Figure 8 Collapse of buildings located on developing urban areas.

5. Reinforced buildings

The PUCP's Engineering Faculty has been working since the 70's to study and develop new ways to improve earthen constructions by increasing their stability in seismic areas (Vargas et al. 2005). The following seismic reinforcement systems for adobe constructions were tested and developed since then (Vargas et al. 2005):

- 1975: Interior reinforcement made of natural cane mesh combined with a perimeter crown beam.
- From 1994 to 1999: External electro-welded steel mesh plastered with cement and sand mortar, placed vertically in the corners and horizontally at the top part of the walls.
- From 2004 to 2007: External polymer mesh applied to both the outer and inner faces of each wall, covered using mud stucco and combined with a perimeter crown beam made using wood and cane lintels.

Between September 1998 and January 1999, a pilot plan was introduced by the CERESIS (South American Regional Center for Seismology) - GTZ (German Cooperation Agency) - PUCP project to reinforce adobe dwellings (San Bartolomé et al. 1999). 19 adobe constructions located in different areas all throughout Peru were reinforced to withstand seismic activity. The reinforcement system consisted on electro-welded steel mesh strips nailed to the walls and covered with cement and sand mortar. Vertical reinforcing strips were added to the walls' intersections and horizontal strips placed on the highest part of the walls. Two of these reinforced houses are located in the villages of Pachacutec and Guadalupe in Ica. None of these buildings suffered from any damage related to the earthquake. The reinforcement applied to these dwellings prevented the formation of vertical cracks. After the reinforcement was applied to the house in Guadalupe (Figure 9a), an enclosure wall was built by its owner without taking any seismic reinforcement considerations into account. This wall collapsed as observed in Figure 9b.

Between November 2005 and April 2006, the National Service for the Construction Industry (SENCICO) carried out a training program in which participants were instructed on the construction of three adobe buildings with seismic reinforcement (the first two houses were 1-story high while the second one was 2-storys high) in Lunahuana and Pacaran, in the province of Cañete (north of Chincha, Figure 2). The reinforcement used into these houses consisted of internal cane mesh and a perimeter wooden crown beam. The foundation of the house was built using cyclopean concrete and the plinth wall with simple concrete. The second floor of the third house was built using prefabricated *quincha* panels. The post-earthquake evaluation of the houses shows that the buildings that were 1-story high didn't suffer from any damage while the only consequence of the earthquake in the 2-storey high dwelling was the detachment of some of the mud plaster from the *quincha* panels (SENCICO 2008).


a) Reinforced building


b) Collapsed enclosure wall

Figure 9 Adobe construction in Guadalupe, Ica.

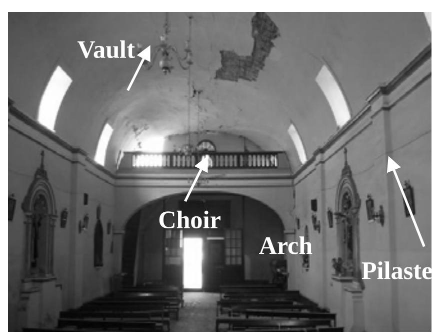
A different group of adobe houses were built by the Japanese Agency for International Cooperation Agency (JICA) taking seismic precautions into account, applying an internal cane mesh with a wooden perimeter crown beam as reinforcement. Only minor damage was reported on these constructions after the earthquake, such as the appearance of fissures around the doors and windows of the second floor.

6. DAMAGE IN EARTHEN AND BRICK-MADE HISTORICAL LANDMARKS

Almost all of the churches and historical landmarks that had been built with soil and bricks suffered heavy damage or even collapsed as a consequence of the earthquake. According to the National Institute of Culture (INC), 32% of the historical and cultural monuments in Ica have completely collapsed, 23% are under strong risk of collapsing, 26% are under moderate risk and 19% show minor damage to their structure (24 Horas Libres, 2007). Most of the earthen churches in Ica have one or two towers that are about 3 to 4 story high as part of their façade, lateral adobe walls (1,20 m thick and 5 to 6 m high approximately), and a roof consisting of a cylindrical vault constructed using wooden arches, crushed cane, straw mats and a mud coat on the outside and stucco on the inside (Figure 10).

The plan view of the church is cross-shaped. The choir area (which is 2-story high) is located right behind the church's main door and the altar is on the back of the church. The church's lateral walls have pilasters built approximately every 4 m that simulate columns (Figure 10b).


a) Front view



b) Internal view

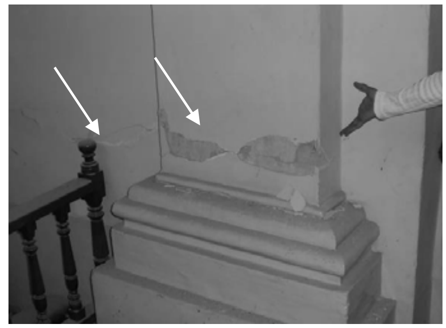
Figure 10 Typical earthen churches.

The most common failures observed in the local churches are:

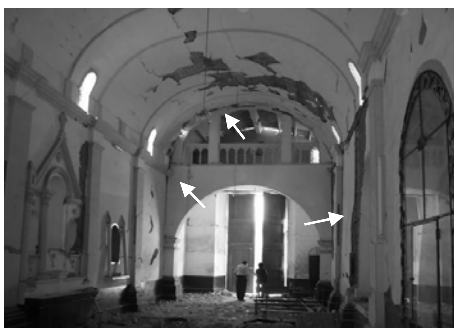
- Horizontal cracks on the lateral walls at about 1/3 of their total height (Figure 11a). These cracks can even break through the earthen pilasters (Figure 11b), causing the walls to collapse.
- Diagonal cracks on some of the lateral walls.
- Detachment of the choir (Figure 11c) and the altar's wall (parallel to the façade) from the church's lateral

walls and cylindrical vault ceiling (Figure 11a).
- Detachment of the towers from the rest of the church (Figure 11d).
- Appearance of vertical cracks and fissures on the church towers (11d).
- Humidity related damage.

a) Detachment of the main



b) Horizontal crack in pilaster



c) Detachment of the choir from the vault

d) Vertical cracks on the intersection between the tower and walls

Figure 11 Most common post-earthquake damages on churches.

The following is a report on the damage observed on the main churches in Pisco.

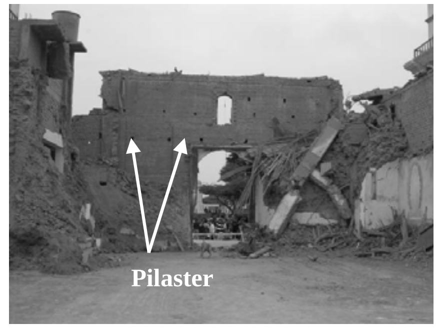
6.1. Church "San Clemente"

This church dates back to the XVIII century. Its façade was constructed using fired clay bricks masonry (Figure 12a) and its most outstanding feature were the two 4-storey high towers and 4 pilasters (that simulated columns) located equidistantly from the main entrance to the church (Figure 12b). The church's lateral walls were built using adobe. The church had a cylindrical vaulted ceiling that was constructed using wooden arches and crushed cane covered by a mud and gypsum stucco. The roof rested on the lateral walls and the main altar's wall had been reinforced using concrete frames. This reinforcement was probably a latter addition to the structure, most likely done during a more recent restoration of the church. There were 300 people attending a mass when the earthquake happened. About half of them died when the roof and walls collapsed. It is possible that the church's collapse initiated with the cracking and overturning of the lateral walls, to which the roof followed.

6.2. Church "Compañía de Jesús"

This church built in Baroque style in the XVII century (Figure 13a) had brick and adobe walls and, like previous churches, had a cylindrical vaulted ceiling. This church, however, presented opening in the intersections between the walls and the inner arches. As shown in Figure 13b, the church suffered from a complete collapse during the earthquake.


a) Frontal view of the church



b) Façade wall viewed from the inside of the church

Figure 12 Church “San Clemente”.


a) View of the church before the earthquake


b) Lateral view of the church

Figure 13 Church “Compañía de Jesús”.

7. RECOMMENDATIONS AND CONCLUSIONS

As observed during this study the adobe dwellings that without receiving any seismic-reinforcement during their construction either collapsed or suffered heavy structural damage. One of the main factors contributing to the stability of adobe constructions is the quality of the materials used and labour. This proves that unreinforced and poorly constructed buildings are highly vulnerable to seismic activity. Buildings that were poorly constructed with materials other than adobe (such as concrete or fired clay brick masonry), or that had inadequate or no reinforcements, also suffered from heavy damage or collapse.

One of the most common failures in the churches occurred in the intersection between the towers and the main nave. The separation (vertical crack) between the façade and the lateral walls (which support the vaulted ceiling) was also a common damage experienced in churches. The amount of failures observed in the walls and ceilings of the churches was notorious, revealing the weak bond between them, as well as the lack of maintenance and restoration in the parts of the church made with wood or cane.

The cane mesh reinforcements with mud (plastered on the walls), and the electro welded reinforcements (plastered with cement and sand mortars) have proved to improve the capacity of adobe dwellings to withstand seismic activity. It is imperative to educate both the construction workers and the general public on the latest reinforcement techniques that can be used in earthen structures. The use of polymer geomesh plastered with mud has proven to be an efficient seismic-reinforcement method in adobe constructions. Moreover, this kind of reinforcement can be quite economic (Blondet et al. 2006).

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