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. The result was that over 139 500 families were affected by the earthquake (INDECI 2008).

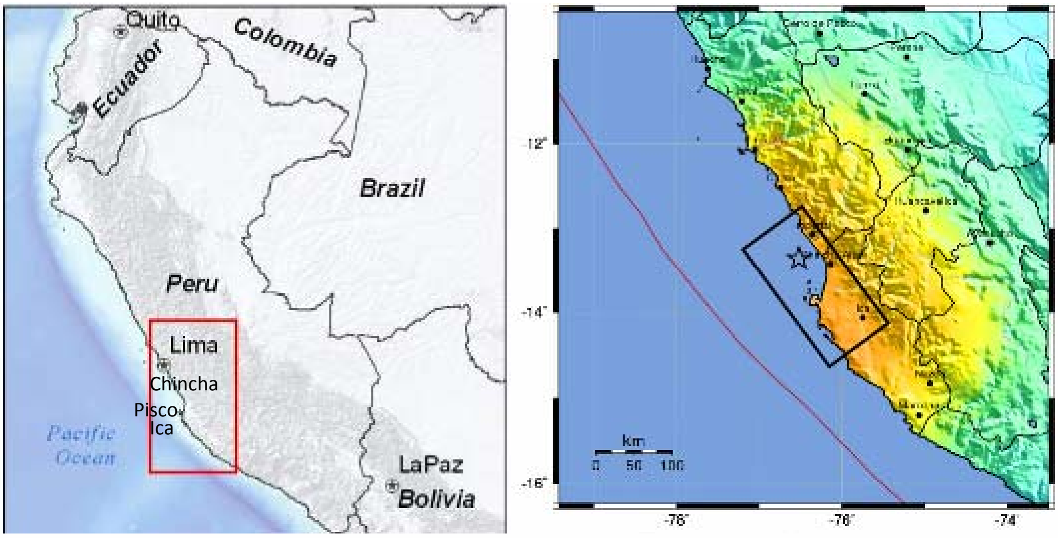
Adobe dwellings –both old and new– along with historical monuments (such as churches that were built using soil or bricks) were the most affected structures. Constructions built with fired clay brick or with reinforced concrete didn't suffer from strong damage, except when the buildings were poorly constructed 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, as observed and recorded by a research group sent by the Engineering Department of the Catholic University of Peru (PUCP). The report will also present a brief analysis of the various construction flaws and errors that were encountered, along with recommendations on how to improve the seismic-resistance of the ground buildings.

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 continental 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, 40 km west of Chincha and 150 km southwest of Lima and lasted for about 3 minutes and 30 seconds (IGP 2007). Figure 1 shows the different MMI intensities estimated in the affected areas by the USGS (USGS 2007). 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.

The hypocenter was located at a depth of approximately 40 km, so the event is considered as shallow earthquake. Fault rupture propagated about 100 km north, parallel to the coast, from Pisco to Cañete. Between August 15 (date of the earthquake) and August 27, more than 3000 aftershocks 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.



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

Figure. 1. Registered seismic intensity for Pisco earthquake (USGS 2007)

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 2.

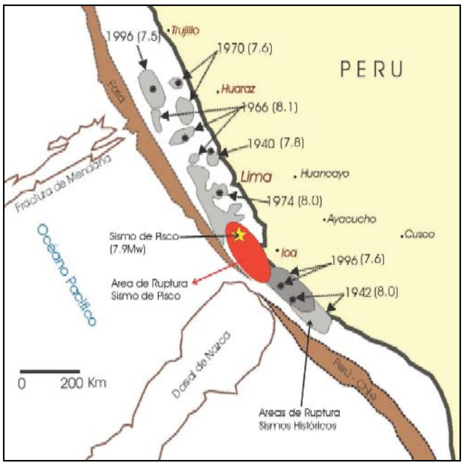


Figure. 2. Distribution of the epicenters and rupture areas of the large earthquakes that occurred in the central region of Peru from 1994 to 2007 (Tavera et al. 2007).

2. VISITED SITES

Within two to six days after the disaster had occurred, the group of researchers visited six cities. The cities seen were San Clemente, San Miguel, Pisco, Guadalupe, Pachacútec and Ica. Figure 3 shows their location of the visited sites.

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.

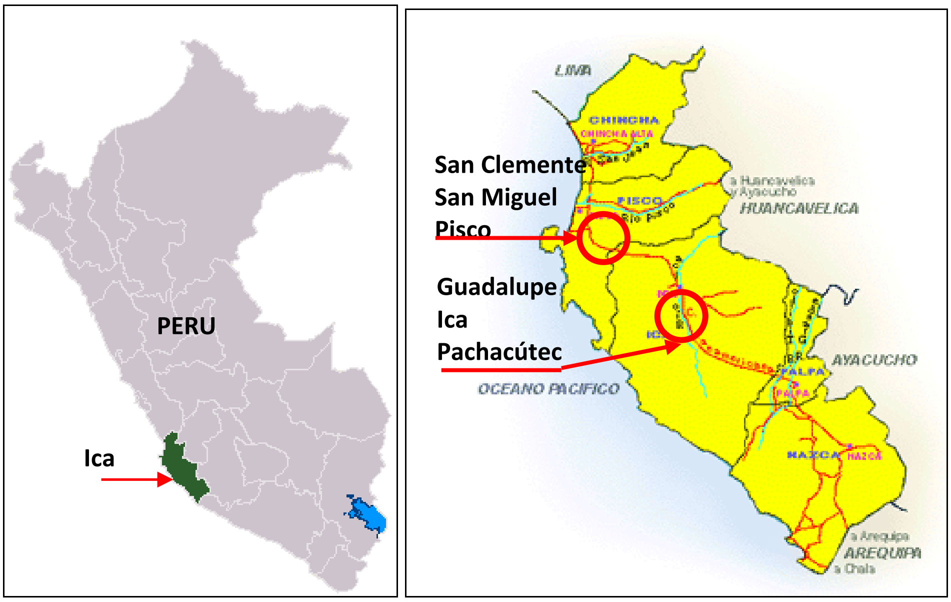


Figure 3. Visited sites
(http://upload.wikimedia.org and http://www.info-hoteles.com)

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.

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 plaster. 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* (Figure 4a). The more modern adobe buildings, on the other hand (Figure 4b), 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.

a) Old building **b) Modern building**

Figure 4. Adobe dwellings

The older adobe dwellings surrounding Ica's main square have a 0,8 m high plinth wall made with fired clay bricks (Figure 5a.). The plinth walls on these houses were built 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 5b).

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

Figure 5. Old adobe dwellings in Ica

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 (Figure 6). The wooden joists can either be parallel or perpendicular to the façade walls.

Figure 6 - Materials used for the roofs

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. Figure 7a shows the sedimentation that's taken place in one of Pisco's central areas (shown in the cracks on the sidewalk), and the damage this process has caused on one of the local buildings (Figure 7b.). 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.

a) Cracks on the pavement **b) Building that has suffered sedimentation problems**

Figure 7.- Soil sedimentation

3.3.Quality of the construction 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 8).

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 8.- These images show the weak bond between the mortar and the adobe blocks

3.4.Overturning of the walls and roofs' collapse

The most common failures observed in earthen buildings, especially in those with thin walls, were 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 9). This triggered the walls to disconnect until finally the façade wall turned over (Figure 10). 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.

Figure 9. Vertical cracks in the wall's corners

Figure 10. Collapse of the façade walls in adobe buildings

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 (Figure 11a). 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 11b). In some cases; however, roofs that weren't supported by the façade wall collapsed as well because the lateral walls collapsed.

a) Roof supported by the façade wall **b) Roof that wasn't supported by the façade**

Figure 11. Roofs in adobe dwellings

Many adobe buildings located on street corners suffered from heavy structural damage due to the collapse of their two façade walls and roof (Figure 12). 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 13).

Figure 12. Collapsed dwellings located on street corners

Figure 13. Diagonal and vertical cracks shown on corner buildings

The collapse mechanisms for unreinforced masonry subjected to out of plane loads has been determined by d'Ayala and Esperanza (2003, Figure 14). On adobe constructions, mechanisms A, C and D are the most appropriate to describe the overturning capacity of the walls when withstanding seismic activity.

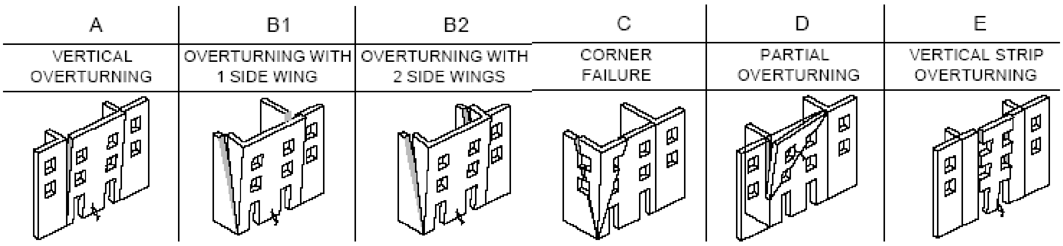


Figure 14. Collapse mechanisms for unreinforced brick masonry (D'Ayala y Esperanza 2003)

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 (Figure 15).

Figure 15.- Flaw due to x-shaped cut on the wall.

4. CONSTRUCTIONS 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. Because this method causes humidity to affect the walls by capillary action, the construction loses strength and stability. Most of the dwellings constructed following this model collapsed during the earthquake (Figure 16).

Figure 16. 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). Different construction models have been tested throughout the years, first testing full-scale adobe walls and house models on a tilt platform (before 1984) and then using the PUCP's Structures Laboratory's shaking table (after 1984).
The following seismic reinforcement systems for adobe constructions were tested and developed during this time period (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 to 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 (Figure 17).

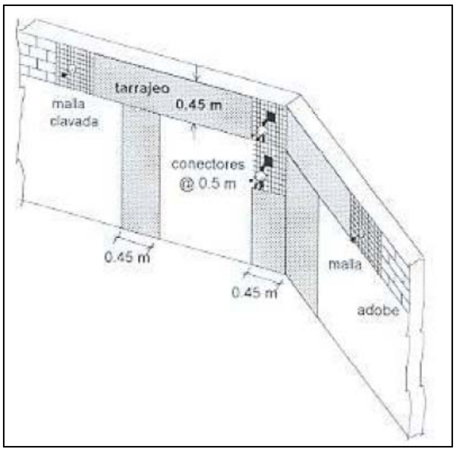


Figure 17. Detail of the seismic reinforcement (San Bartolomé et al. 1999)

Two of these reinforced houses are located in the villages of Pachacútec 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, an enclosure wall was built buy its owner without taking any seismic reinforcement considerations into account (Figure 18a). This wall collapsed as observed in Figure 18b.

a) Reinforced building **b) Collapsed enclosure wall**

Figure 18. Adobe construction in Guadalupe, Ica

Figure 19a shows the house in Pachacútec that was reinforced as part of the pilot plan. The neighbouring building is a non-reinforced adobe house on which the earthquake caused little damage (Figure 19b). The reinforced construction apparently acted as a support for the non-reinforced dwelling, preventing its walls from collapsing. Figure 20 shows the after-shake state of a third building located at approximately 10 m from the pilot construction that has visibly suffered stronger damage.

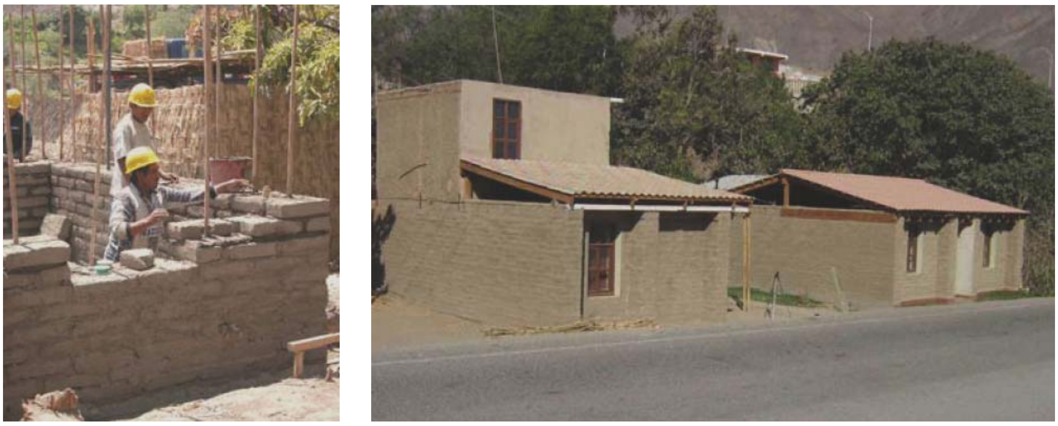
a) Reinforced dwelling b) Unreinforced dwelling

Figure 19. Dwellings located in Pachacútec, Ica

a) Neighboring house b) Nearby collapsed house

Figure 20b. Adobe dwellings near the reinforced house

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 3). The reinforcement used into these houses consisted of internal cane mesh and a perimeter wooden crown beam (Figure 21a). 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 (Figure 21b, SENCICO 2008).



a) Internal cane reinforcement **b) Reinforced houses (1-storey high and 2-storey high)**

Figure 21. Reinforced adobe houses in Lunahuana and Pacaran (SENCICO 2008)

Figure 22 shows a different group of adobe houses that were built taking seismic precautions into account, applying an internal cane mesh with a wooden perimeter crown beam as reinforcement. These houses were built by the Japanese Agency for International Cooperation Agency (JICA). 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.

a) Second floor made using quincha **b) Use of short distance recesses**

Figure 22.- Reinforced dwellings located in Zuñiga (a) and Huangascar (b) (Taucer et al. 2007)

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. The churches shown on Figure 23a, 23b and 23c are from the XIX century (according to the parish from the church "San Juan de Dios").

a) Church “Virgen de las Nieves” b) Church “Parcona”

c) Church “San Juan de Dios” d) Church “Catedral de Guadalupe”

Figure 23. Earthen churches located in Ica

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 24).

Figure 24. Internal view, from Church “San Juan de Dios”

The rooms and environments located next to the church, present post-earthquake cracks and failure as well, mainly on the wall’s intersections.

The most common failures observed in the local churches are:

a) Horizontal cracks on the lateral walls at about 1/3 of their total height (Figure 25a). These cracks can even break through the earthen pilasters (Figure 25b), causing the walls to collapse.
b) Diagonal cracks on some of the lateral walls.
c) Detachment of the choir (Figure 25c) from the altar's wall (parallel to the façade) and the church's lateral walls and cylindrical vault ceiling (Figure 25a).
d) Detachment of the towers from the rest of the church (Figure 25d).
e) Appearance of vertical cracks and fissures on the church towers (Figure 23a, 23d and 25d).
f) Humidity related damage (Figure 25e).

a) Detachment of the main altar

b) Horizontal crack in pilaster

c) Detachment of the choir from the vault

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

e) Humidity related damage

Figure 25. Most common post-earthquake damages on churches

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

6.1. Church "San Clemente" (Pisco)

This church dates back to the XVIII century. Its façade was constructed using fired clay bricks masonry (Figure 26a) 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 26b, 26c).

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 (Figure 26d).

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.

a) Frontal view of the church **b) Façade wall viewed from the inside of the church**

c) Detail of the facade wall **d)Main altar (Photo credits: E. Fierro)**

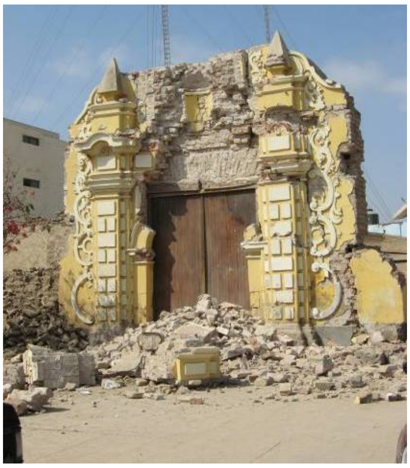
Figure 26.- Church "San Clemente" (Pisco)

6.2. Church "Compañía de Jesús" (Pisco)

This church built in Baroque style in the XVII century (Figure 27a and 27b) 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 (Figure 27b). As shown in Figure 27c and Figure 27d, the church suffered from a complete collapse during the earthquake. As part of the emergency works that took place in the city, this church had to be completely demolished.

a) View of the church before the earthquake
http://www.camisea.com.pe/cdia_detalle.asp?c_not=62

b) Interior view of the church
http://www.youtube.com/watch?v=F7e071lJFD4



c) Lateral entrance to the church

d) Lateral view of the church

Figure 27. Church "Compañía de Jesús", Pisco

6.3. Ica's Cathedral

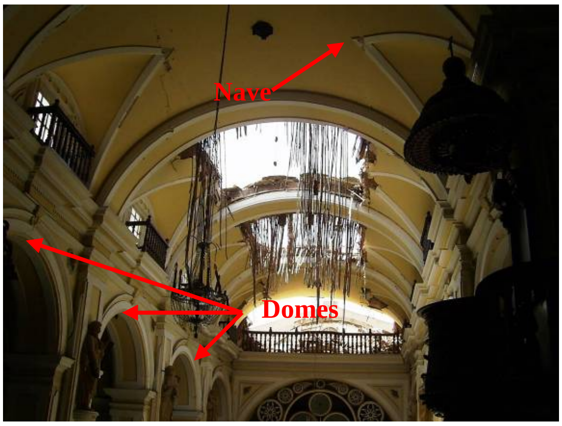
Ica's Cathedral (Figure 28a) was built in the XVIII century and has two 3-storey high towers, a triangular pediment over its main entrance, a vaulted nave with 8 smaller domes on its sides (Figure 28b) and a central dome, which is a part of the main altar. The church was built following a Baroque and Neoclassical style. Its columns are internally made of vertical and diagonal *huarango* (local tree) frameworks that have been plastered with crushed straw and mud. The walls have been plastered with soil and mouldings have been reinforced using chopped straw (Figure 28c). The vault's ceiling was built using wooden arches with crushed straw and plastered with mud. The older walls are made of mud, while the more recent ones were built using adobe blocks.

The earthquake caused damage on both towers, as well as the partial collapse of the triangular pediment. It also caused fissures on the ceiling, in addition to its partial collapse.

Damage was also suffered by the domes (Figure 28d) and the choir. Vertical and diagonal cracks appeared on the inner earthen walls, the plaster on the columns came off and vertical cracks appeared on the intersection of the right tower and the lateral wall.

Most of the crushed cane in the columns and the vertical canes that were a part of the choir's *quincha* structure are rotten. The restorations that had been made using cement on the mouldings have completely fallen off. Nevertheless, the majority of the plaster mouldings have stayed in place due to their internal cane framework.

a) Frontal view of the Cathedral



b) Interior view of the Cathedral

c) Columns

d) Damage in the main dome

Figure 28.- Ica's Cathedral

6.4. Church "Señor de Luren" (Ica)

This church (Figure 29a) was built at the beginning of the XX century, and restored in 1943. One of its lateral towers collapsed during the Nazca earthquake that took place on November 12, 1996, but it was rebuilt in 2004. This church is built mostly with clay bricks and reinforced with concrete frames.

The church's ground floor is cross-shaped (Figure 29c) and there are still remains of a main tower and two smaller towers on its entrance area. Behind these towers, a 12 m. high (approx.) nave is located, joint by a dome to two other vaults. The two lateral towers had hollow columns, made of clay bricks (Figure 29b).

The earthquake caused the collapse of all the three towers (Figure 29b). The main tower collapsed inside the church, causing main vault's partial collapse (Figure 29d). The vault was supported by two lateral walls that haven’t completely collapsed, but that present diagonal fissures.

a) Pre-earthquake façade

b) Post-earthquake façade

c) Aerial view of the church
http://uterodemarita.com

d) Interior view of the church

Figure 29. Church “Señor de Luren”, Ica

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.

Due to the soft soil in Pisco, the dynamic amplification of the seismic waves played a fundamental role in the destruction the constructions suffered. Seismic microzonation studies based on geotechnical and geophysical analysis can show areas under risk of liquefaction. It is imperative for both state and private entities to respect the results and recommendations produced by these studies and to avoid constructing in hazardous areas. 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.

One of the most common failures in the churches occurred in the intersection between the towers and the main nave. Due to the difference between their fundamental vibration periods, the towers experience a dynamic behaviour different to the main body of the church. 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.

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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