4. BUILDING DAMAGE

4.1. Background

4.1.1. Structural types in the earthquake affected area

In the earthquake affected areas, there are different types of construction systems including: adobe, rammed earth (or *tapial*), *quincha*, reinforced concrete (RC) confined masonry, RC buildings with masonry infill. Hybrid systems, i.e. combination of any of these, are also found.

Adobe is a traditional construction system which consists of sun dried bricks laid with mud mortar. It has been used not only for houses but also for churches. In the case of houses, walls are 400mm thick whereas in churches, walls are taller and thicker, 850mm or more. If unreinforced, adobe structures are weak against earthquakes because they are heavy, inducing large inertial forces, and have almost no tensile strength. The stability of adobe walls depends strongly on their slenderness ratio. Recently, slender walls made of adobe bricks with size similar to those of baked bricks, the so called *adobitos*, have become increasingly popular. However, their largest slenderness ratio makes them even more vulnerable.

Rammed earth or *tapial* was found in the earthquake affected areas but mostly as fences marking limits of agriculture land. In other parts of the country it is also commonly used for dwellings. Similarly to adobe, it is made of mud. However, in this case the mud is compacted in situ, i.e. a wooden formwork is set and the mud is compacted in it. When the mud is dried enough, the formwork is moved sideward or upwards depending on where the wall shall continue.

Fig. 4.1 Two story adobe house mostly common in the high lands

Fig. 4.2 Rammed earth or tapial. Note the vertical and horizontal cold joints showing different construction stages

Quincha is a construction system consisting of panels with bamboo skeletons plastered with mud. It is also known as *bahareque* in other Latin American countries. The bamboo skeleton makes the system ductile and thus it has a good seismic behavior. However, bamboo deteriorates with time and this affects the structural performance.

Confined masonry is currently the most popular construction system for new houses. As long as people can afford it, it is the material of choice. It is used as an economic solution in Peru for buildings up to six stories high. If it is well designed and constructed it performs well. In this system, walls are constructed with *solid* bricks at first and then reinforced concrete confinements (columns and beams) are cast against them. According to the building code, a solid brick is defined as a brick with an area equal or more than 70% of its gross area. Column reinforcement is anchored in the foundation. Because brick wall and confinements work as a unit, the size of the columns is smaller than that of a RC building where brick walls are only supposed to work as partitions.

Reinforced concrete is also used in the affected areas but mostly for public buildings.

Fig. 4.3 Quincha

Fig. 4.4 Confined masonry

Fig. 4.5 Confined masonry in process of construction

Fig. 4.6 Reinforced concrete (RC) school

Hybrid systems are a combination of some of the previous construction systems. Some of them are the result of engineering design some others the consequence of improvisation. For example, it is common to combine confined masonry walls with

RC shear walls and columns in buildings. If these elements are well proportioned and distributed, both systems contribute to each other.

However, there are bad examples of hybrid systems. In Peru, it is a common practice to construct dwellings in stages as soon as financial resources are available and also as the resident needs increase. It is not uncommon to start a house with one story and when the family grows, a second or third story is built. If the family economic situation changes with time, the first story may be made of adobe, while the upper stories are made of confined masonry. This system was observed at several places in the earthquake affected areas.

Another type of traditional hybrid system is the one in which the first floor is made of adobe and the second is made of *quincha*. This system is very common in old 2-story houses and has had a relatively good seismic performance. However, due to poor maintenance and aging, these structures have become very vulnerable. Although this system has not been used lately, some experts are trying to revalue it.

Fig. 4.7 Old traditional structure with 1st story made of adobe and 2nd story made of quincha

Fig. 4.8 House with 1st story made of adobe and 2nd story made of confined masonry. In this case, RC columns were cast in the existing adobe walls to support the 2nd story.

There are four main types of roof systems in the affected areas. Straw mat with bamboo joists, light gage steel plate on bamboo joists, reinforced concrete joists with hollow bricks and wooden roofs. The first two are very light and are used in combination with adobe and confined masonry walls. RC joists are used with confined masonry walls and RC buildings. Wooden roofs were found mostly in old buildings and are not used in new constructions anymore.

The connection between light roofs and walls is weak but nevertheless restrains the movement of the walls on which it is supported. RC joists are cast on top of brick walls together with the confining beams and therefore is well connected to the walls.

Fig. 4.9 Roof made of straw mat and bamboo joist

Fig. 4.10 Light gage steel plate roof

Fig. 4.11 RC concrete joist with clay hollow bricks

Fig. 4.12 Wooden roof common in old constructions

4.1.2. Housing statistics

Censuses are regularly carried out in Peru by the National Institute of Statistics and Informatics (INEI), the latest one in October 2007. Table 4.1 summarizes the figures of houses distribution for the earthquake affected areas as of 2005 (data for the 2007 Census will not be available until 2008). Predominant construction material of the walls is adobe (50% of total) followed by masonry (39%) whereas in term of roofs, the predominant roof type is light mostly made of straw mats and bamboo joists (59%).

Table 4.1 Distribution of houses according to the predominant material of walls and roofs in the earthquake affected areas in thousand of units as of 2005 [1]

	Masonry	Adobe	*Quincha*	Others	Total
RC	52.950	0.718	0.000	0.030	53.698
Light gage steel	1.742	16.568	0.118	1.141	19.569
Straw mat / bamboo	19.778	79.004	5.581	9.187	113.550
Others	0.740	3.811	0.331	2.350	7.232
Total	75.210	100.101	6.030	12.708	194.049

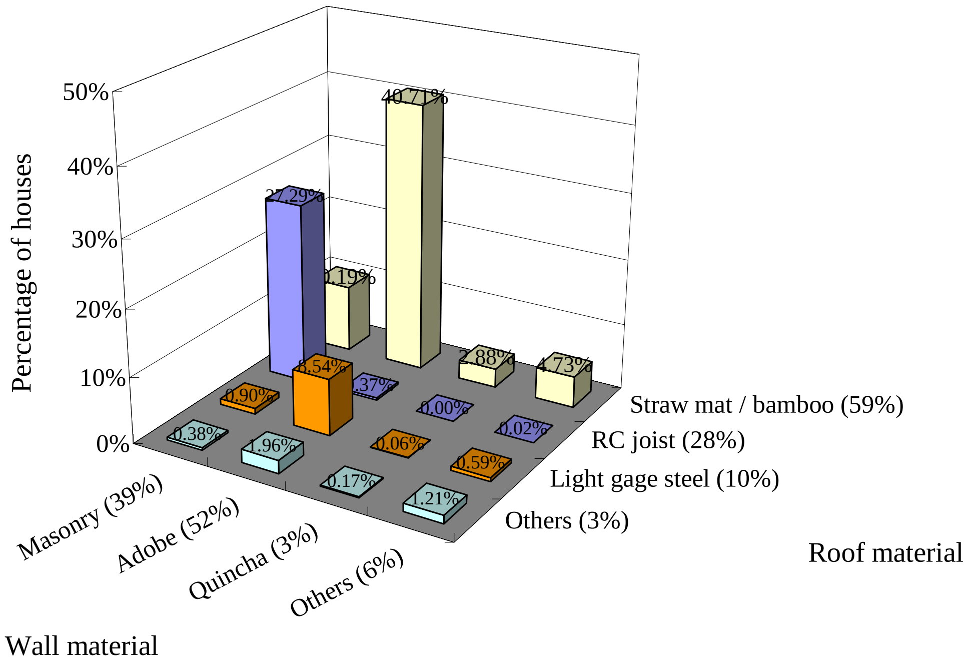
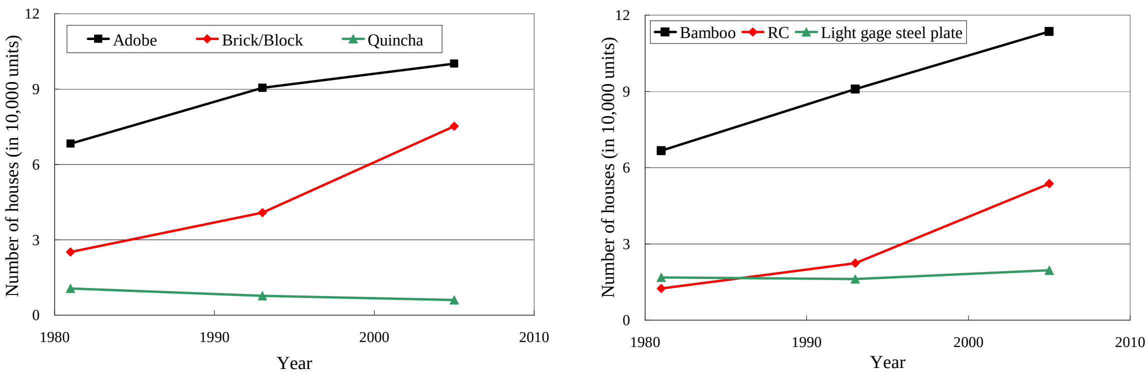


Fig. 4.13 Distribution of houses in the earthquake affected areas as of 2005 [1]

Fig. 4.14 shows the evolution of wall and roof material in the earthquake affected areas. Adobe use decline and masonry use growth are observed. If the trend continues like this, it may be expected that by 2020, masonry will become the predominant wall material as it has already happened in other regions in the country. As for the roofs, it may be expected that straw mat and bamboo will still be preferred in the coming years.

It is worth noting that more than 70% of the adobe houses are older than 25 years. It is not a common practice in Peru to invest in house maintenance. Therefore, it may be expected that the vulnerability inherent to unreinforced adobe construction is worsened by aging.



(a) Predominant material of walls (b) Predominant material of roof

Fig. 4.14 Evolution of material use in the earthquake affected regions [1, 2, 3]

4.1.3. Building code

The National Service for Training for the Construction Industry (SENCICO) has among its functions to develop regulations for building design and construction technologies that aim at improving quality and reducing costs. It is also in charge of training and certifying construction workers of different levels. Following its functions it has enacted the following building codes:

- NTE E.010 Wooden structures (latest revision 2003)
- NTE.E.020 Loads (latest revision 1985)
- NTE E.030 Seismic design code (latest revision 2003)
- NTE.E.040 Glass
- NTE E.050 Soils and foundations (latest revision 1997)
- NTE.E.060 Reinforced concrete (latest revision 1989)
- NTE.E.070 Masonry (latest revision 2006)
- NTE E.080 Adobe (latest revision 1999)
- NTE E.080 Metallic Structures

According to the seismic design code, Peru is divided in three regions as shown in Fig. 4.15. The ground accelerations for design are 0.40g, 0.30g, and 0.15g for Zone 3, 2, and 1, respectively. These are supposed to be the accelerations with a 10% probability of exceedance in 50 years [4].

Fig. 4.15 Seismic zonation of Peru

Although the above mentioned codes keep up to date the developments of design and construction technologies providing a huge amount of information, in the practice most of buildings do not comply with them, i.e. codes are enacted but not enforced. There is no statistic showing how many buildings not complying with the codes exist. However, experts suggest that between 50% and 80% of the buildings fall in this category in Lima [5, 6].

One of the main reasons why building codes are not enforced is that obtaining the license for construction, the first step of code enforcement until very recently is lengthy and costly process. It requires submitting a set of drawings (architecture, structure, utilities) with the signatures of an architect or civil engineer, a sanitation engineer, and an electric engineer, the land property certificate, and a fee payment. In addition, many people do not have a land property certificate and therefore cannot complete the required documentation. Getting the land property certificate is another lengthy procedure.

Another reason why building code is not enforced is that municipalities, which are in charge of giving the licenses and supervising that the construction is carried out following the project, are understaffed. Based on the field survey it was found that in Pisco, a city of almost 55,000 inhabitants, only four civil engineers were working at the municipality on a regularly basis.

In September 2007, a law to ease the process of obtaining construction licenses was enacted. For some constructions, the project reviewing process has been simplified and for some small projects, even eliminated. Although this may result in many more construction licenses, many fear that this will worsen the problem of code enforcement.

Self construction, an extended practice in Peru, also hinders code enforcement. Self construction is considered here as the construction by the dweller himself or otherwise a mason, without proper training. This system is much enrooted in the Peruvian society as a result of the large housing deficit and insufficient governmental policies to address the issue.

4.2. Building damage

4.2.1. Statistics

The INEI carried out a census to estimate the number of affected people and houses due to the Pisco Earthquake. According to this census, 77% of the housing units were affected in some way and 23% did not suffer any damage. The hardest hit provinces were Chincha, Ica, and Pisco, where 33.7%, 24.4%, and 22.4% of the houses, respectively, collapsed. 9.5% of the houses were slightly affected, suffering just minor damage or cracking, and therefore are suitable for living.

Table 4.2 Housing damage statistics in the earthquake affected areas

Province	Destroyed	Very affected	Affected	Slightly affected	Not affected	TOTAL
Ica	19 937	7 075	23 005	8 513	22 637	81 167
Chincha	17 763	6 911	16 619	3 414	4 231	48 938
Pisco	8 756	4 521	14 526	3 272	5 223	36 298
Cañete	4 545	3 434	18 349	4 804	18 180	49 312
Yauyos	359	675	8 028	1 289	2 427	12 778
Huancavelica	6	24	538	214	52	834
Castrovirreyna	371	520	5 931	910	465	8 197
Huaytará	434	560	6 370	1 030	726	9 120
TOTAL	52 171	23 720	93 366	23 446	53 941	246 644

Notes: **Destroyed**: houses with fallen/destroyed walls and roofs; **very affected**: house with serious damage in most of its walls (collapsed or destroyed) and is not suitable for living; **affected**: houses whose structure (walls or roof) is partially affected and require more detailed evaluation; **slightly affected**: house exhibits small cracks and minor damage and is suitable for living: **not affected**: no damage whatsoever.

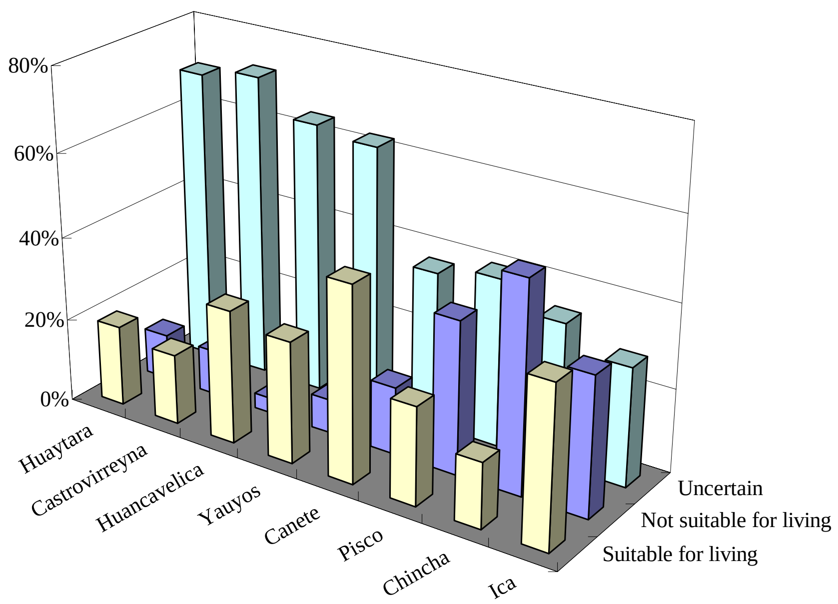


Fig. 4.16 Housing damage in the earthquake affected regions [7]

It is worth noting that the provinces located in the mountainous regions where adobe is predominant (Huaytara, Castrovirreyna, Huancavelica, and Yauyos) show the highest percentages of uncertainty regarding the conditions of their houses. Also, most of the houses in Chincha and Pisco are not suitable for living.

Regarding schools, the National Civil Defense Institute (IINDECI) carried out the initial damage evaluation shown in Table 4.3. This evaluation aims at determining whether the facilities are suitable for immediate use. A more detailed evaluation to determine the extent of the damage and the amount of investment required to recover them is responsibility of the Ministry of Education.

Table 4.3 School damage, in terms of classrooms, due to the 2007 Pisco Earthquake

Region	Schools	
	Destroyed	Affected
Ica	187	214
Lima	396	329
Huancavelica	22	71
Ayacucho	38	21
Total	643	635

The Direction of Infrastructure, Equipment and Maintenance of the Health Ministry (DIGEM) performed the evaluation of the health facilities in the earthquake affected area. Table 4.4 shows the summary of the most affected structures, i.e. with more than 15% of its infrastructure affected. Although not included in it, DIGEM concluded that all health related facilities of the provinces of Castrovirreyna, Huaytara and Huancavelica need to be replaced.

Table 4.4 Damage to health related facilities [8]

Name	District	% of infrastructure affected
Ica Departament Hospital	Ica	60%
Santa Maria del Socorro Hospital	Ica	40%
San Juan de Dios Hospital	Pisco	70%
San Jose de Chincha Hospital	Chincha Alta	90%
Tupac Amaru Health Center	Tupac Amaru	15%
San Clemente Health Center	San Clemente	30%
Casalla Health Post	Tupac Amaru	15%
Los Alamos Health Post	Pueblo Nuevo	80%
Hoja Redonda Health Post	El Carmen	60%

Note: Hospital, Health Center and Health Post are health related facilities presented in order of their size.

4.2.2. Housing damage

Damage to adobe houses may be categorized, in order of severity as: plaster spalling, wall separation, corner collapse, partial collapse of walls and total collapse of walls. Important factors increasing the vulnerability of adobe structures were: wall slenderness, construction age, and roof layout. Walls supporting light roofs, which are predominant in the region, were less likely to collapse than those not supporting it due to the restrain at the top that the roof joists provided them.

Adobe plastered walls seem stronger than those without plastering. Front walls of houses did not exhibit damage whereas the inner walls, apparently without plaster, suffered damage. A few walls which survived out-of-plane collapse developed in-plane shear cracks.

It was observed that in many locations, these houses did not have any foundation. This contributed to the moistening of the walls, where the ground water table was high, with the consequent strength reduction.

Fig. 4.17 Adobe house with plaster spalling (San Luis, Canete)

Fig. 4.18 Adobe house with cracks at wall intersections (Huaytara, Huancavelica)

Fig. 4.19 Corner collapse in adobe house (San Luis, Canete)

Fig. 4.20 Wall partial collapse. Walls supporting the roof are standing. This was observed at several locations (Ica).

Fig. 4.21 Collapsed adobe house (Nuevo Monterrico, Canete)

Fig. 4.22 Totally collapsed adobe houses (Hualcara, Canete) – The hanging electric lines show the location where houses used to be.

Fig. 4.23 RC confined adobe wall (in the back), survived the quake, and unconfined adobe wall (front) failed out-of-plane (San Luis, Canete)

Fig. 4.24 The house shown "borrowed" the wall of the neighboring adobe house, which collapsed. Only the RC columns built to support the 2nd floor survived. (Pisco, Ica)

Confined masonry houses designed and built according to the building code did not suffer major damage. All the damaged structures had some type of deficiency. The most common were the use of bricks with horizontal alveolus for load bearing walls (locally called *pandereta* and prohibited by the code in this region), lack of confinement of parapets and façade walls, insufficient wall density, badly distributed stiffness (in plan and elevation), and a poor understanding of the confined masonry construction procedure. Another deficiency found was the lack of steel reinforcement in the confining beam or the lack of confining beam altogether.

As mentioned earlier, the assumption that brick wall and RC confinement work together, which is accurate if constructed in the right way, does not hold if the RC elements are built first and then the brick wall is laid. The size and steel reinforcement of RC confinements is not enough if the RC skeleton is the main structural system.

Fig. 4.25 Load bearing wall made of pandereta bricks and poor steel reinforcement in the confinement (Pisco, Ica)

Fig. 4.26 Collapsed façade wall due to lack of confinement (Sunampe, Chincha)

Fig. 4.27 Lack of confining beam (Tambo de Mora, Chincha)

Fig. 4.28 Corroded column reinforcement (Tambo de Mora, Chincha)

Fig. 4.29 5-story confined masonry building apparently built in several stages (Pisco, Ica)

Fig. 4.30 Detail of the 5th story of the building to the left. Note the small amount of reinforcement in the columns. The failure pattern suggests that the columns were built first and then the brick wall.

Fig. 4.31 Shear failure of masonry wall due to excessive interstory drift

A few apartment buildings made of RC were found in the affected areas and in some of the cases, the structure was a mixture of confined masonry and RC. Fig. 4.32 shows an apartment building with a car parking in the first floor. The RC columns used to leave space for the cars to access had smaller stiffness than the back wall, a solid confined masonry element. This generated a torsion effect imposing the columns a demand larger than their capacity.

Fig. 4.32 Apartment building with inadequate stiffness distribution (Pisco, Ica)

Fig. 4.33 Back view of the building shown in previous picture

Fig. 4.34 Beam-column joint detail of building in Fig. 4.32.

Fig. 4.35 Soft-story failure due to insufficient stiffness in one direction (Pisco, Ica)

Fig. 4.36 Shear failure of beam-column joint (Parcona, Ica)

Fig. 4.37 Weak cold joint between column and beam/slab (Parcona, Ica)

4.2.3. Damage to public facilities

Public facilities, both governmental and private, performed badly in the 2007 Pisco Earthquake. In this section, damages to hospitals, schools, churches, and hotels observed during the field survey are reported.

Hospitals

Table 4.5 summarizes the characteristics of the two health related facilities that were visited in this field survey.

Table 4.5 Health related facilities visited

Characteristics	San Juan de Dios Hospital	Huaytara Health Center
Location	Pisco, Ica	Huaytara, Huancavelica
Number of beds	100	8
Occupancy rate	50-60%	Handles approximately 100 births per year
Medical services	Surgery, Internal Medicine, Pediatrics, Gynecology, Obstetrics, Ophthalmology, Trauma	2 doctors, 1 midwife
Ambulatory services	80-100 patients /day (before the quake), 50 patients / day (as of September 13)	Prenatal checkups
Comments	Responsible of the health requirements of approximately 125,000 people	Handles births of the region
Infrastructure	Most of buildings constructed in the 30’s with reinforced concrete and concrete blocks and another few 12 years ago. Two new buildings made of RC were completed this year. The New Emergency Building was unequipped before the earthquake.	Confined masonry structure approximately 18 years old

Fig. 4.38 to 4.41 show the conditions of the San Juan de Dios Hospital after the earthquake. At the time of the survey, most of the heavily affected buildings were being or had been already demolished. The only permanent operational facility was the Emergency Building which suffered no damage. It was constructed with funding of UN Health Organization and started operations the night of August 15. According to the interview survey, 200 badly injured people were evacuated to Lima for treatment. The hospital hyperbaric chamber, the only one in this region, is not functioning because the building where it operated collapsed.

Fig. 4.38 Newly constructed Emergency Building

Fig. 4.39 Heavily damaged building. Note the hyperbaric chamber on the back

Fig. 4.40 Concrete block wall collapsed out-of-plane

Fig. 4.41 A hospital building made of non-reinforced adobe was heavily damaged

The Huaytara Health Center, although smaller than the San Juan de Dios Hospital, handles most of the births in the region. As mentioned in Chapter 3, ground failure was the main reason for the structural damage.

Education related facilities

Several schools and one university were visited in the affected areas. Table 4.6 shows information of the schools where interview survey was carried out. Other schools were visited but no interview was done.

Table 4.6 Schools where interview survey was carried out

	San Juan Bautista	Beatita de Humay 22451	San Luis Gonzaga de Ica
Location	Huaytara	Humay	Ica
Education level offered	High school	Elementary and high school (2 shifts)	High school (2 shifts)
No. of students	210	460	2992
Infrastucture	Mostly RC buildings with concrete blocks (1992), one building of confined masonry (2006) and one adobe building	Elementary school classrooms made of adobe and a few new construction of RC	RC buildings constructed in the 50’s
Re-started classes on	August 22nd, 2007	Not restarted as of Sept. 11, 2007	Not restarted as of Sept. 18, 2007
Comments	Part of the school was used by the army who was assisting the disaster response activities	No debris removal had been carried out by Sept. 11, 2007.	12 wood prefabricated and 20 straw mat temporary classrooms were been set on Sept. 18, 2007

At San Juan Bautista School no major structural damage was observed. However, the masonry partition walls, which were correctly separated from the main RC structure to prevent short column effects, did not have confinements and therefore were not anchored to the beams underneath. As a result, the connection between walls and beams, most likely provided just by cement mortar, failed. Although the walls did not collapsed, they were very unstable posing risk to the people nearby. The classrooms that had this situation were not operational. In this school, the hall was made of adobe and did not present considerable damage. Classes were been held in this building.

Fig. 4.42 Masonry panels in the second floor were damaged, (San Juan Bautista school, Huaytara)

Fig. 4.43 Detail of the joint connection, (San Juan Bautista school, Huaytara)

Fig. 4.44 Non-reinforced adobe building normally used as a hall, (San Juan Bautista school, Huaytara)

Fig. 4.45 Confined masonry building did not suffer any damage, (San Juan Bautista school, Huaytara)

All of the adobe classrooms at Beatita de Humay School were left useless. Adobe walls and straw mat roofs collapsed. Fortunately, at the time of the earthquake there were no students in the facility and therefore nobody was injured there. The columns of a RC building with masonry panels exhibited mild shear failure.

The infrastructure of the San Luis Gonzaga de Ica School exhibited typical damages of RC structures such as pounding between buildings, lack of column shear reinforcement, insufficient separation between partitions and structure, and insufficient expansion joints between structural units. Also, some unreinforced brick parapets collapsed.

Fig. 4.46 Elementary school classrooms made of adobe were heavily damaged (Beatita de Humay School, Humay)

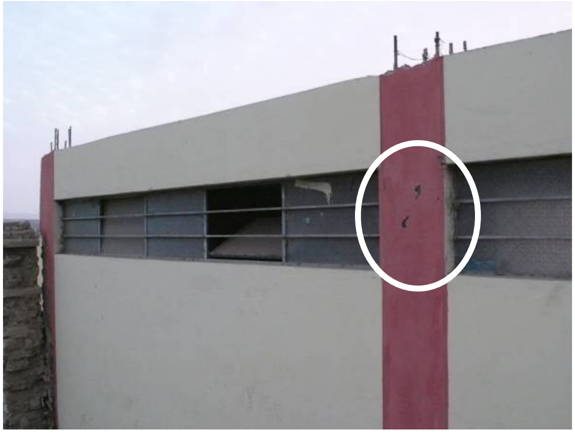


Fig. 4.47 RC-buildings with masonry panels suffered slight shear damage (Beatita de Humay School, Humay)

Fig. 4.48 Pounding between buildings (San Luis Gonzaga School, Ica)

Fig. 4.49 Parapet overturning (San Luis Gonzaga School, Ica)

Fig. 4.50 Lack of shear reinforcement in columns (San Luis Gonzaga School, Ica)

Fig. 4.51 Insufficient clearence between masonry panels and RC structure (San Luis Gonzaga School, Ica)

In general, the design/construction quality of the schools visited during the survey was very varied. For example, at Los Molinos in Ica, a very new and well constructed school (shown in Fig. 4.6) was found next to another which obviously did not followed any design or construction standard. Fig. 4.52 shows one of the building walls in which it is seen that columns in the 1st floor are not aligned with the columns in the 2nd floor. Furthermore, one of the columns is interrupted

Many classrooms made of non reinforced adobe were also found as well as schools built in places unsuitable for construction due to poor soil conditions, such as Tambo de Mora marine deposits. Although it is difficult to control informal housing construction there, public buildings, especially schools should never be built in these places.

It is worth mentioning that at many schools, non-structural measures to mitigate earthquakes, such as pasting adhesive tape to the glasses, were observed

Fig. 4.52 Bad construction example in Los Molinos, Ica

Fig. 4.53 Classroom at Tambo de Mora marine deposits, Ica.

As mentioned in Chapter 2, two strong ground motion records were obtained close to the epicenter. One of the recording instruments, belonging to CISMID, was located in the first floor of the Soil Mechanics Laboratory Building of the San Luis Gonzaga National University. In order to assess a possible effect of the structural response on the record, microtremor measurements to evaluate its dynamic properties were measured. Additionally, concrete strength was estimated with a Schmidt hammer.

The RC frame structure was built in two stages: the first floor in 1998 and the second floor in 2002. Although it did not suffer major structural damage, some of the brick partitions cracked and needed repairing. In the 1st story, where partitions suffered more damage, the joint left between structure and wall was not wide enough in some cases and in others filled with mortar. This limited the freedom of the structure to deform. The joints in the second floor were wider and thus partition damage here was less.

Fig. 4.54 Soil Mechanics Laboratory Building

Fig. 4.55 Joint between brick partition and RC structure filled with mortar

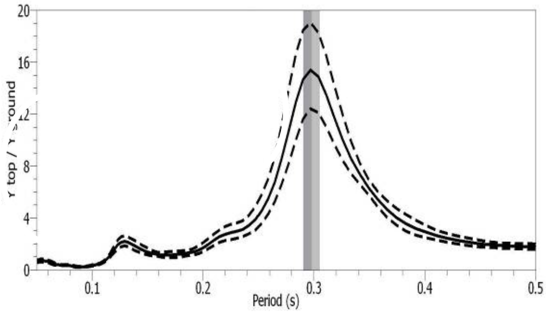


Fig. 4.56 Microtremor measurement analysis results (Transverse direction)

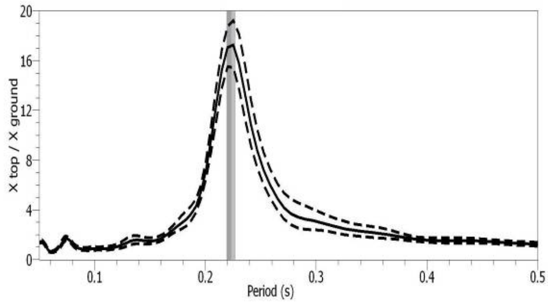


Fig. 4.57 Microtremor measurement analysis results (Longitudinal direction)

Microtremors were measured in free field, 1st story floor slab, 1st story roof, and 2nd story roof. To determine the fundamental period the ratio of the Fourier spectra of the records at the 2nd story roof and free field were calculated. The analysis suggests that the fundamental period in transverse and longitudinal direction are 0.30s and 0.22s, respectively. This frequency content do not coincide with the predominant frequencies observed in the acceleration record suggesting that the structure did not affect the measurements. However, further analysis is necessary to confirm this idea.

The Schmidt Hammer tests suggested that the quality of the concrete was good with compression strengths approximately 36MPa and 31MPa, in the 1st and 2nd floor, respectively.

One of the most damaged buildings in the campus was that of the Chemistry Faculty. These were among the first buildings in the university constructed more than forty years ago. In here, short column effect and poor shear reinforcement detailing were observed. Also, parapets with no anchorage to the structure were damaged although they did not collapse.

Fig. 4.58 Chemistry Faculty Building with short column failure and parapet damage

Fig. 4.59 Insufficient shear reinforcement

Churches

This survey did not focus in surveying churches in detail. However, it was obvious from our field work that these structures performed very badly. Reportedly, more than 30% of the fatalities due to this earthquake were caused by the collapse of the San Clemente Church in Pisco. In this church, only the portion which had been rebuilt recently did not collapse. A block away from it, only a couple of the 850mm-thick adobe walls of the Compania de Jesus Church were left standing.

Many of the churches in Peru were built before any seismic design code was enacted. There is no regulation that requires upgrading of these structures as to comply with the latest codes. These facilities belong to the Catholic Church and therefore it is under their responsibility to improve their quality. Many of these buildings are cultural patrimony and thus the National Cultural Center (INC) is also a stakeholder. There is always controversy about which is the best way to intervene this monuments without altering their original essence.

Fig. 4.60 San Clement Church (Pisco)

Fig. 4.61 Compania de Jesus Church (Pisco)

Hotels

Hotels suffered extensive damage in the affected areas putting in evidence the lack of control that the authorities have over the security of these facilities. A remarkable case was that of the Embassy Hotel one of the most exclusive in Pisco City. The first and second stories of this hotel completely collapsed. This structure had construction license for the first three stories. However, later the management decided to build two more stories without permission.

The Paracas National Reserve, which is located south of Pisco, is a tourist destination for locals as well as foreigners. Many hotels, among which the Libertador Hotel Paracas is probably the most famous, were damaged. This hotel is located in front of the coastline and was badly damaged by the shake and the subsequent tsunami.

Fig. 4.62 and 4.63 show one small hotel that was observed during the field survey. Insufficient shear reinforcement in the columns among other deficiencies was observed.

Fig. 4.62 Heavily damaged hotel (San Clemente, Ica)

Fig. 4.63 Insufficient column shear reinforcement.

4.3. Mitigation initiatives

Taking into account the vulnerability of traditional adobe houses, construction technologies to improve their seismic performance have been developed. In the affected areas, two reinforcing techniques were implemented during the last decade as part of two international assistant projects and are described below.

4.3.1. Retrofitting of existing adobe houses

The project "Retrofitting of existing adobe houses" carried out by GTZ, CERESIS, and the Pontifical Catholic University of Peru (PUCP) was developed to improve the seismic strength of existing adobe houses in 1996. The main purpose was to provide some ductility to the houses so as to allow safe evacuation. The project retrofitted 12 prototype houses located in the Ancash, Cusco, Tacna, Moquegua, Ica and La Libertad Regions, all of them seismically active.

The retrofitting system, devised at the PUCP [9], consists of placing welded wire steel meshes at the wall intersections, "columns", and also on top of the walls, "collar beams" as shown in Fig. 4.64. The meshes (1 mm wires spaced at ¾ inches) are attached to both sides of the adobe walls using nails and connected with wire connectors passing through the wall. A cement mortar cover is laid on the steel mesh.

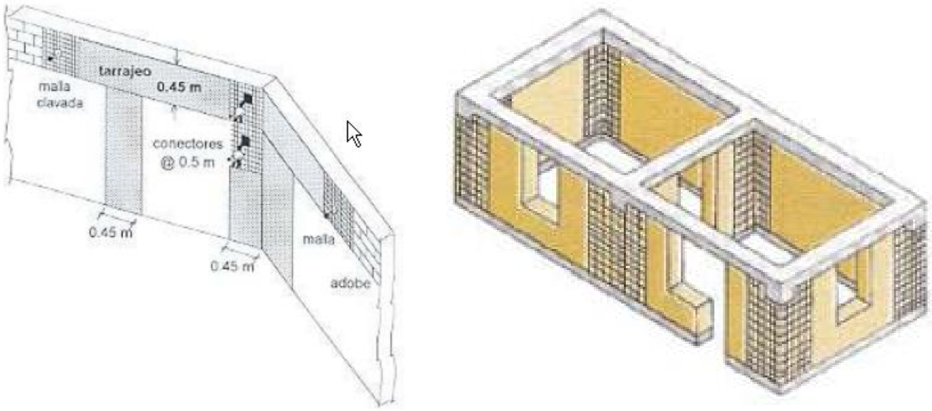


Fig. 4.64. Wire mesh reinforcement. After Blondet [9]

The construction procedure followed for the prototype adobe wire steel meshes retrofitted house is shown in Fig. 4.65.

Step 1. Remove the existing gypsum or mud plastering.

Step 2. Open 5-cm (2-inch) square holes every 50 cm (20 inches) at the intersection of vertical mesh strips. Insert small steel connectors into each hole, moisten the interior and fill them with 1:4 cement:sand mortar.

Step 3. Fasten the vertical mesh strips to the adobe wall with nails, and then the horizontal strips. The usual width of mesh strip was 45 cm (18 inches). Bend the ends of the connectors 90° and nail them to the adobe wall.

Step 4. Moisten the area and plaster it with cement sand mortar applied in two layers.

Fig. 4.65 Construction procedure for adobe wire steel meshes' retrofitted houses. Adapted from Quiun [10]

Evaluation of seismic performance of retrofitted houses

One of the houses retrofitted in the above mentioned project was located in Guadalupe, Callao Street #304, Panamerican Highway, Km. 193 (S 13º 59.179’ W 75º46.458’). The house is located in a flat area in the vicinity of a small canal and surrounded by several adobe houses and two unpaved streets as shown in Fig. 4.66.

The fairly symmetric house is a one story building with a shared wall, two façade walls aligned with Callao Street and Rimac Street, respectively, and three internal walls. The roof is made of straw mat with bamboo joists. There was no evidence of foundation, however, based on an interview survey, it was found that, in this region, it is common to dig a 60cm-deep trench, place thick adobes inside, and then build walls on top of them. It may be possible that this “foundation” was used when the house was originally constructed.

Fig. 4.66. Front and side of Guadalupe retrofitted adobe house.

The house was retrofitted based on the guide shown in Fig. 4.65, and the details of the construction for the wire steel mesh are shown in Fig. 4.67. The mesh was set in all house’s corners and in the intersection of internal and external walls. In the internal walls additional mesh was installed beside the doors, the backyard wall was not retrofitted at all due to budget constraint. No mesh was installed on the main entrance wall.

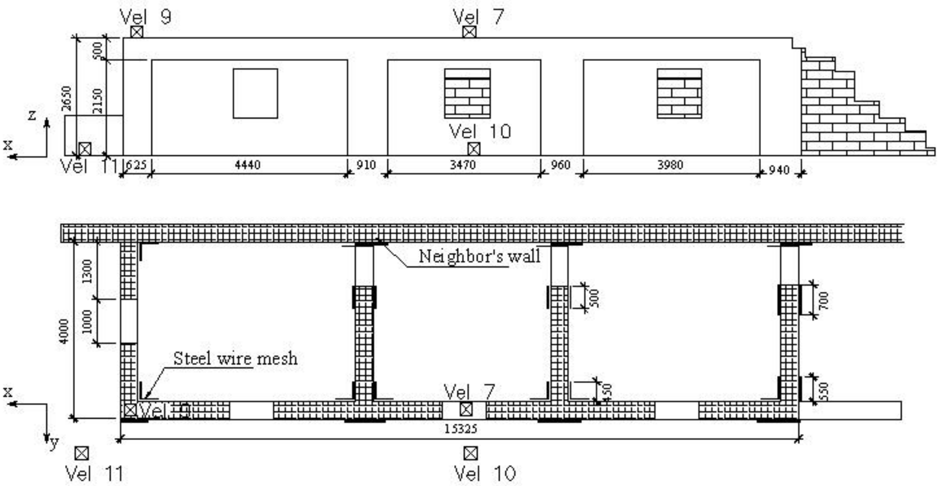
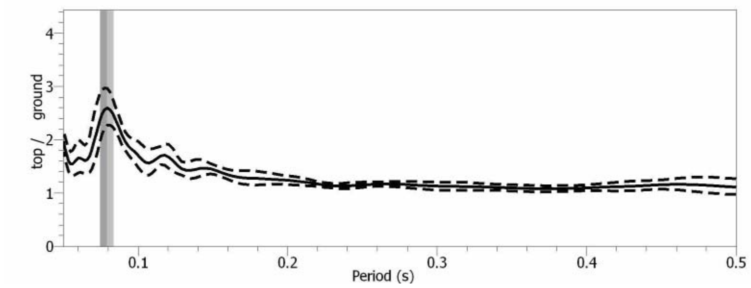


Fig. 4.67. Layout of Guadalupe adobe retrofitted house.

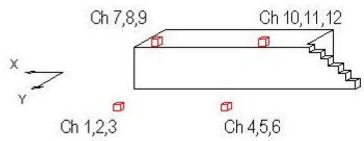
The inspection of the house showed that it suffered almost no damage due to the earthquake although the damage rate of adobe houses in Guadalupe was over 80%. A few vertical cracks were observed in the mortar cover of the “collar beams” inside the house. It is believed that they just affected the cover and did not pass through the walls. It is important to mention that the backyard wall, which was not retrofitted, collapsed due the shaking. A small portion of the steel wire mesh, without any corrosion signs, was exposed as shown in Fig. 4.68.

Fig. 4.68. Retrofitted house after the Pisco Earthquake

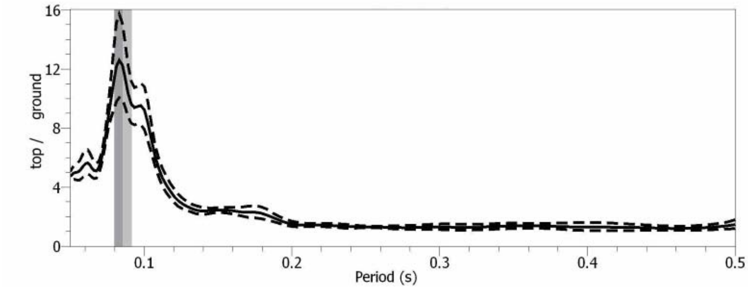
In order to identify the dynamic properties of the structure, microtremors were measured on the house roof and at the ground as shown in Fig. 4.69. Two 300sec-long measurements, sampled at 100Hz, were taken. The spectral ratios were calculated and they are shown in Fig. 4.69. A clear peak at 0.08sec is observed. This predominant period is similar to those measured in non reinforced adobe structures with similar characteristics suggesting that, as expected, the retrofitting procedure, did not affect the natural period of the structure.



(a) X-Axis



(c) Measurement arrangement



(b) Y-Axis

Fig. 4.69. Ratio of Fourier spectra of microtremor measurement in retrofitted adobe house.

4.3.2. Construction of new earthquake resistant adobe houses

The Japanese International Cooperation Agency (JICA), the Peruvian NGO Alternativa and the National Service for Training for the Construction Industry (SENCICO), worked together between 2004 and 2006 in the pilot project “Training and Diffusion of Improved Adobe Technology for the Construction of Healthy and Secure Houses”. The main purposes were to train and motivate local people to construct adobe houses using an improved technology. During the development of the project seven model houses, located in the rural areas of Lunahuana, Pacaran and Vinac in Lima Region, were constructed. All these locations are seismically active.

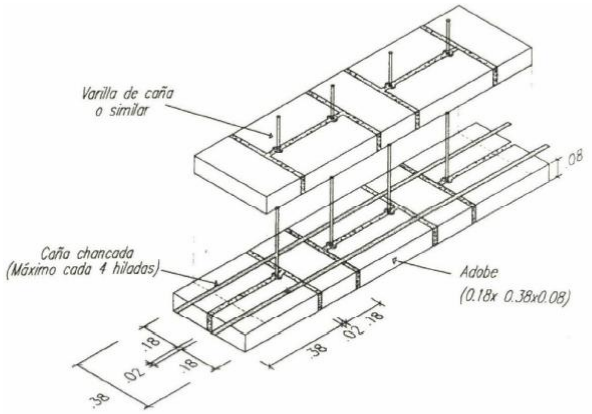


Fig. 4.70 Vertical and horizontal adobe reinforcement. After E.80 [11]

The construction technique for the model houses followed the adobe standard NTE E.80 for cane reinforcement. It incorporates techniques regarding improvements in adobe fabrication and reinforced construction processes. The cane reinforcement consisted of a grid of vertical and horizontal canes (see Fig. 4.70), tied-up in the crossing points of the walls, foundation and ring beams. This type of reinforcement improved the response of adobe walls against seismic loads. Vertical reinforcement restrains out-of-plane bending and in-plane shear, while horizontal reinforcement transmit the out-of-plane forces in transverse walls to the supporting shear walls and restrain the shear stresses between adjoining walls. An additional reinforcement used in the model houses was the timber ring beam that ties the walls in a box-like structure and supports the roof. A systematical procedure for the construction of this kind of reinforced adobe house is shown in Fig. 4.71.

Step 1. Foundation. No reinforce beam W= 55cm H=80cm. Vertical reinforcement is fixed to the beam.

Step 2 Vertical Reinforcement. Canes are placed on center of wall every 80cm, buried 10cm.

Step 3. Horizontal reinforcement. Crushed canes are placed every four layers and connected to vertical canes with nylon strings.

Step 4. Ring beam. Timber beams are fixed the top of adobe wall. (7.5x7.5cm)

Step 5. Roof. Timber beams are placed every 60 cm (5x20cm)

Step 7. Finishing.

Fig. 4.71. Construction procedure for adobe cane reinforced house. After Narafu [12]

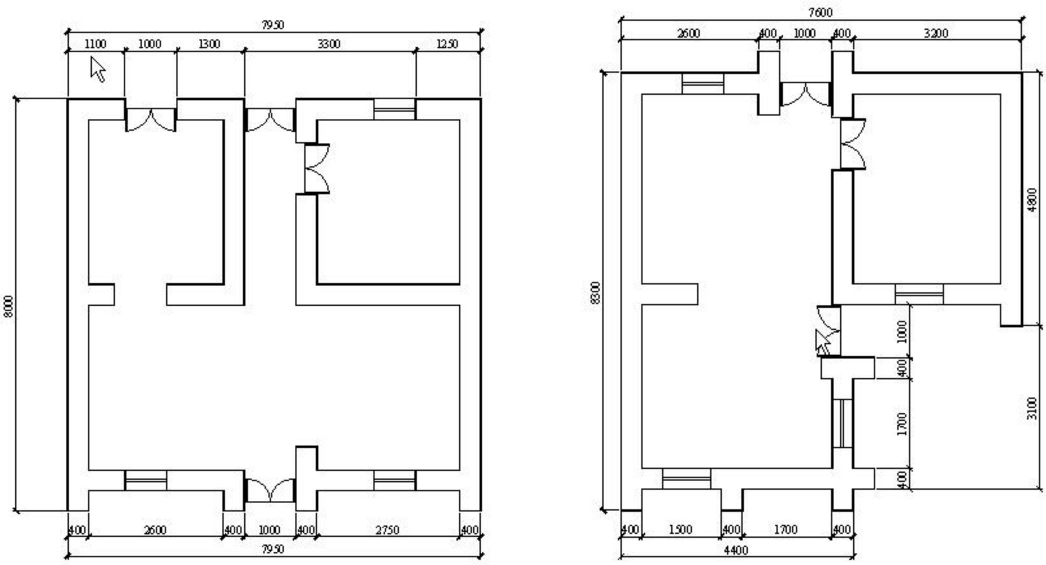
4.3.3. Evaluation of the seismic performance of reinforced houses

Three reinforced adobe houses, 1- and 2-story, inside of the affected area were visited and two of them were evaluated in detail. These are located near Pacaran city, in a flat area with a small hill at the backside (S 12º 51.719’ W 76º 03.271’).

(a) 1-story house (b) 2-story house

Fig. 4.72. Pacaran reinforced adobe houses.

The plan view of both houses is shown in Fig. 4.73. Both of the reinforced houses were constructed following the procedure shown in Fig. 4.71. The roofs are light and well connected and the foundations were made of unreinforced concrete. The 2nd floor of the 2-story house was made of light prefabricated quincha panels.

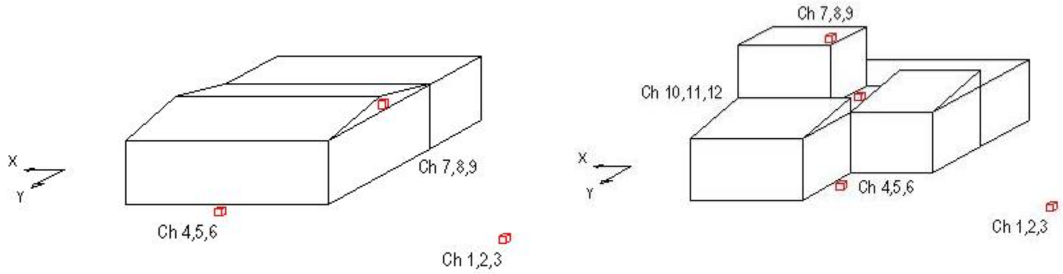


(a) 1-story house (b) Two story houses.

Fig. 4.73. Pacaran reinforced adobe houses layout.

After the Pisco Earthquake, the houses seemed to be in good condition, although some cracks in the plastering of the *quincha* panels on the second floor were observed. It is important to mention that the number of damaged houses in Pacaran was not as large as other cities inside of the affected area. However, some nearby public buildings made of adobe collapsed due to the shake.

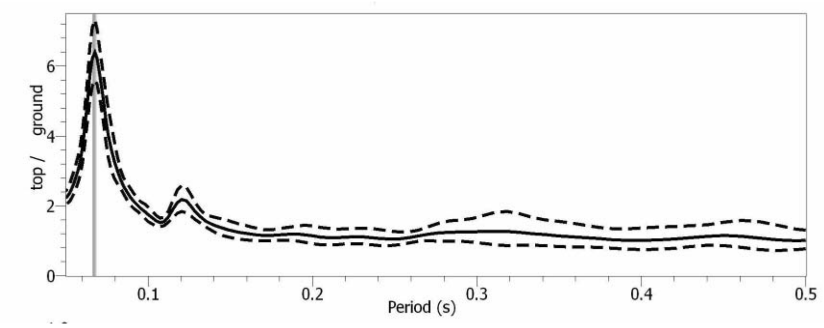
The dynamic properties of the structure were evaluated using microtremor measurements. The arrangement used for reinforced houses is shown in Fig. 4.74. In this case one sensor was located in open field, another close to house's foundation, and the other ones on the roof of each floor.



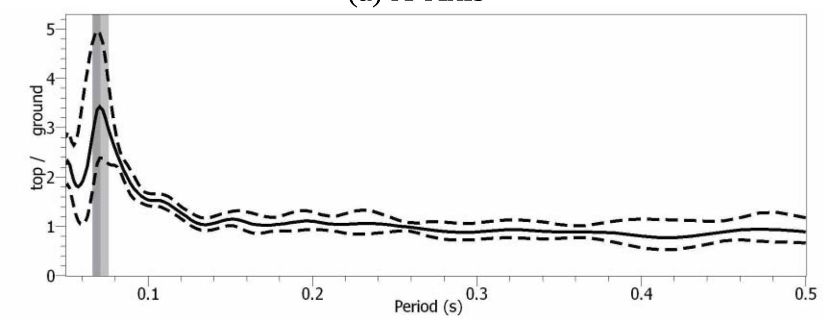
(a) 1-story house (b) 2-story house

Fig. 4.74. Pacaran reinforced adobe houses microtremor arrangement.

Three measurements were taken at 100Hz during 300 sec. The spectral ratio was calculated and it is shown in Fig. 4.75 for the 1-story house. A clear peak at approximately 0.07 sec is observed in both X- and Y-directions. Compared to the house measured at Guadalupe, Ica, this structure is stiffer. This may be due to the buttresses which are used in this structure and the stiffer roof.



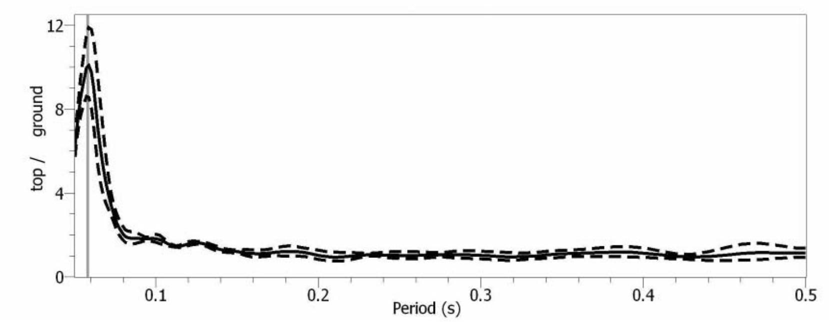
(a) X-Axis



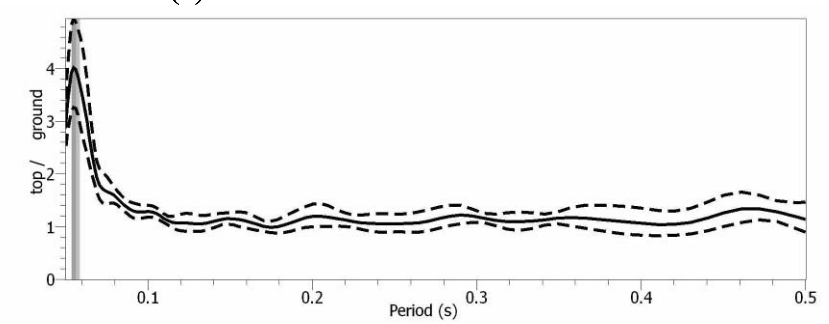
(b) Y-Axis.

Fig. 4.75. Ratio of Fourier spectra of microtremor measurement in reinforced 1-story adobe house.

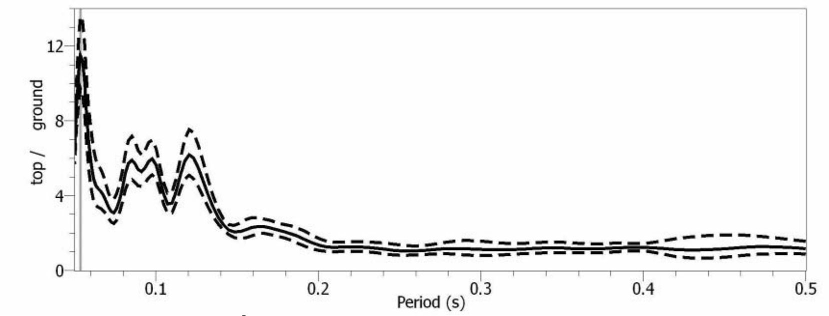
For the 2-story house, spectral ratios 1st Floor Roof / Free field and 2nd Floor Roof / Free field were calculated and are shown in Fig. 4.76. Although the response at the 1st floor roof shows one clear peak at 0.06s in X- and Y- directions, the response at the 2nd Floor roof is more complex and shows multi peaks. The lowest period corresponding to one of these peaks is 0.06s, in both X- and Y-directions, which coincides with the natural period of the 1st floor roof response. This may suggest that it is the effect of the 1st floor on the 2nd. The remaining peaks may indicate additional vibration modes active for the 2nd floor, which are not transmitted to the 1st floor because the mass of the second floor is very small compared to that of the 1st floor. Further analysis is necessary to confirm these interpretations.



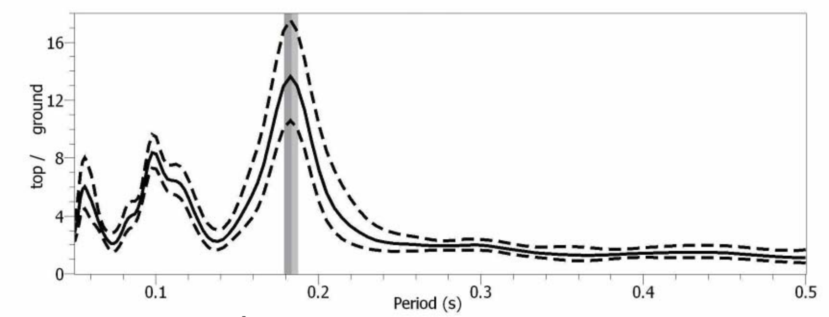
(a) 1st Floor Roof / Free field - X-Axis



(b) 1st Floor Roof / Free field - Y-Axis



(c) 2nd Floor Roof / Free field - X-Axis



(c) 2nd Floor Roof / Free field - Y-Axis

Fig. 4.76. Ratio of Fourier spectra of microtremor measurement in reinforced 2-story adobe house

4.4. Final Remarks

Predominant construction systems in the areas affected by the 2007 Pisco Earthquake are adobe and confined masonry combined with light roofs made of either straw mat or light gage steel plates. Although the relatively small death toll during this earthquake was mostly due to the time occurrence, 18:41, the predominant light roofs may have also contributed to keep this number low.

The structures that were designed and built according to the construction codes performed well. Design and construction deficiencies caused most of the observed structural damage.

Many public facilities, including schools, hospitals, churches, and hotels, performed badly. More than 30% of the casualties in this earthquake were caused by the collapse of San Clemente Church in Pisco. The main hospital of Pisco City was also heavily damaged as well as large part of the school infrastructure.

A few reinforced adobe houses were located in the affected area and performed well during the event. They demonstrate that adobe can have a good seismic performance if adequately treated. The reinforcement with bamboo is adequate for new constructions as long as there is enough bamboo. The reconstruction experience after the 2001 El Salvador Earthquake showed that in some cases, when the number of houses to be reconstructed is too large, there may not be enough material available and using industrial materials is needed.

For retrofitting existing structures, the steel wire mesh has showed good performance. However, there is controversy among experts who argue that instead of increasing strength, as with this method, it is more important to increase ductility. In addition, this system is still expensive for the majority of the Peruvian population. Other cheaper solutions which address the ductility issue are presently available such as external coatings with polymer meshes and PP-band meshes [18, 19, 20].

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