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Structural condition of Peruvian heritage architecture to resist earthquake actions

*Carlos Cuadra[1)]

[1)] *Department of Architecture and Environment Systems, Akita Prefectural University, Yurihonjo, Akita 015-0055, Japan*
[1)] *carlos@akita-pu.ac.jp*

ABSTRACT

This paper attempts to describe the general structural conditions of historical buildings located in Peru that is a zone of high seismic activity. The seismicity of the zone is discussed through an earthquake hazard analysis and the importance of action towards the protection of heritage architecture in Peru is emphasized. It is noted that the state of general disrepair and the intrinsic weakness of the old historical constructions add to the seismic vulnerability of this kind of heritage architecture. Besides, the repair after actual damage or destruction from earthquakes, even when timely undertaken, may lead to alteration of valuable originality of heritage structures, owing to the unavailability of materials or skill from the time of the original constructions. The need for initiatives towards preventive actions for protection from damages and prevention of collapse due to earthquake disasters appears quite evident.

1. INTRODUCTION

Peruvian territory is affected by frequent earthquakes that are originated by the tectonic interaction between the Nasca plate and the South American plate. Protection of life and property from earthquakes disasters has been a subject of major emphasis in engineering research and practice in this region. However, this seems to be little effort made to evaluation of the vulnerability of heritage architecture to earthquake disasters and in general to natural disasters.
In the coast of Peru that presents high seismic hazard level, many historical sites are located, and the constructions are mainly made of adobe (sun-dry bricks), stone masonry and other traditional material. In the case of Lima, the capital of Peru, the historical center has been declared as UNESCO world heritage site, and many adobe buildings exist together with another earthen system called quincha which consists of wooden frames with mesh of cane that receives a mud plaster. This wall system is always used in combination with adobe walls and it is common to observe two stories or three stories buildings where the first story is made of adobe walls and the upper

[1)] Associated Professor

stories are made of quincha. It is well known that earthen constructions are in general weak structures to resist earthquake actions. Recent earthquakes like Pisco earthquake of the year 2007 occurred in Peru illustrate this situation. Moreover, the local economy makes it impossible to pay attention to cultural heritage in the aftermath. Therefore, the constant disrepair of the heritage architecture and the luck of research on hazard, resistance and strength of historical building make critical the vulnerability of these constructions.
Earthquake disaster is not the only hazard that affects the vulnerability of historical buildings; there are also other kind of natural disasters like rarely rains, floods, sand storm, etc. On the other hand, in the urban areas, these historical buildings are affected by the invasion of people that constructs houses in reserved zones or people that uses part of the structure or materials to construct their houses.
This paper attempts to describe the structural conditions of historical buildings, in special earthen constructions which are located in the coast of Peru that is a zone of high seismic activity. The seismicity of the zone is discussed through an earthquake hazard analysis and the importance of action towards the protection of heritage architecture in emphasized. It is noted that the state of general disrepair and the intrinsic weakness of the earthen constructions add to the seismic vulnerability of this kind of heritage architecture. Besides, the repair after actual damage or destruction from earthquakes, even when timely undertaken, may lead to alteration of valuable originality of heritage structures, owing to the unavailability of materials or skill from the time of the original constructions. The need for initiatives towards preventive actions for protection from damages and prevention of collapse due to earthquake disasters appears quite evident.

2. SEISMIC HAZARD OF PERU

The west coast of South America is affected by frequent earthquakes originating mainly from tectonic interaction between Nasca plate and South American plate. The Peruvian Institute of Geophysics (IGP) has published the catalogue of historical earthquakes in this region, consisting of information from year 1471. Old records of this earthquake catalogue have information of probable magnitude and estimated location inferred from historical reports on damages in affected zones. Moreover, earlier records prior to instrumental measurement are not representative of the actual distribution of hazard since at earlier times only earthquakes occurring around populated areas seem to have been reported. If only records with complete information of location, magnitude, and depth are selected, the distribution of these instrumental recorded earthquakes appears as can be observed in Fig. 1. It can be noted that there is a concentration of epicenters along the coast line. Also it can be observed that the Southern part of Peru presents more activity that the North and Central part. To analyze the nature of the earthquake of the Northern zone, the Central zone and the Sothern zone, sections that show the earthquake distribution in elevation were constructed. The location of this sections are indicated in the Fig. 1 as section A-A for the North part, section B-B for the Central part and section C-C for the South part of Peru. In all cases earthquakes located inside a band of 200 km with center at the correspondent section line were considered.

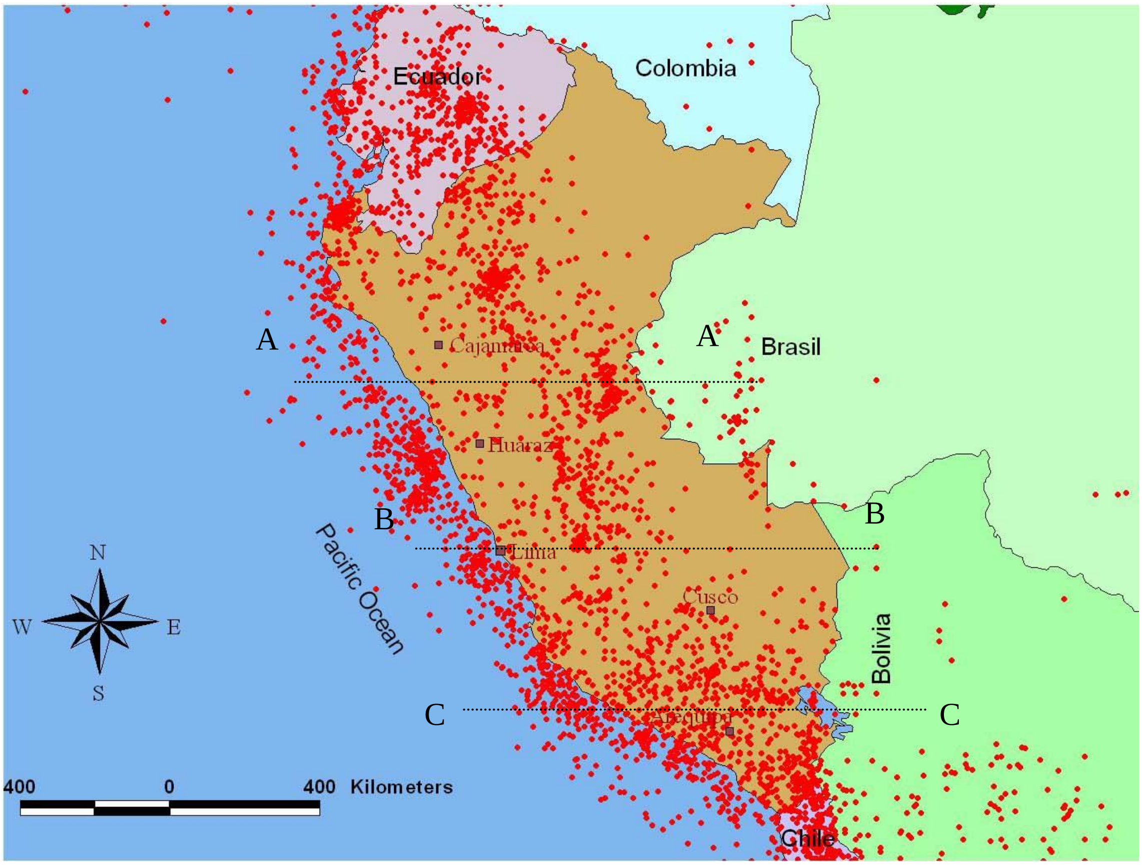


Fig. 1 Earthquake distribution near the coast of Peru

Fig. 2 shows the distribution of earthquakes in elevation for each section described in previous paragraph. Although the distribution pattern presents the same tendency for each zone with shallow earthquakes near the coast and deeper inland earthquakes, the depth distribution and amount of earthquakes for each zone are quite different.

Section A-A shows the distribution of shallow earthquake near the coast. Concentration of epicentres at focal depth from 100 km to 200 km also can be observed in here. Additionally, concentration of deep epicentres is observed in the zone of the Amazon jungle (east part) with depths of the order of 500 km.

In the section B-B the distribution of the earthquakes shows that in this zone the earthquakes have less that 200 km of depth or even less than that depth. The sallow earthquakes near the coast are closer to the coast line which means that the epicentres are closer to inland cities.

The section C-C shows more clearly the typical earthquake distribution of the subduction action of the marine plate, with deeper inland earthquakes. It can be noted that the number of earthquakes is larger in comparison with the north and central part of Peru.

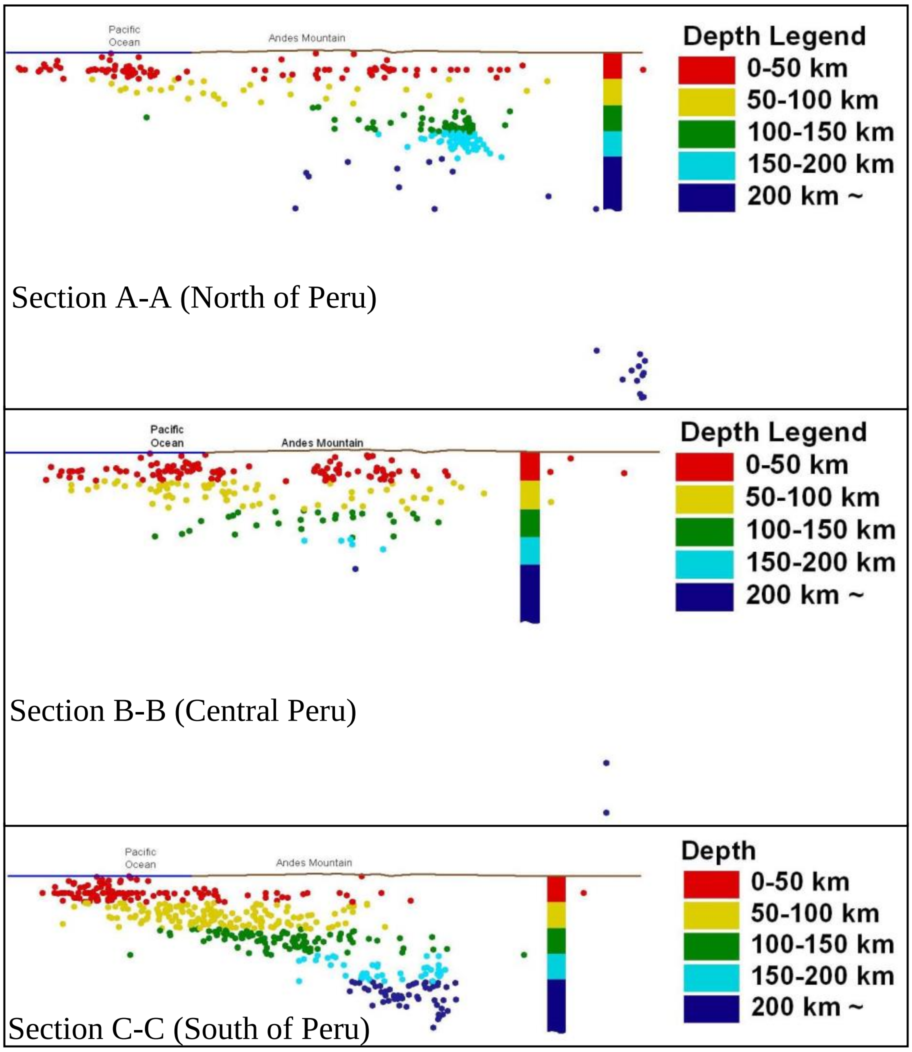


Fig. 2 Distribution of earthquakes in elevation

Seismic hazard analysis for representative sites of the Andean region of Peru (Cusco city), and the coast of Peru (Lima city) was performed by Cuadra et al (2003) and are shown in Figure 3. Hazard curve for Los Angeles city is included for comparison. Results of the probabilistic seismic hazard analysis can also be expressed in terms of the return period shown in Fig. 3, where peak ground acceleration (PGA) for different return periods with 10% probability of exceedance are plotted. It may be noted that the PGA for 100 year return period is around 0.25 g for the considered Andean region and for Lima (Coast of Peru) the PGA is 0.5 g. This higher level of peak acceleration may produce failure in buildings in general and the situation become critical for weak material like adobe constructions. In addition, the PGA levels in Fig. 3 represents rock or stiff soil conditions, while the actual level of shaking depends on local site conditions at specific heritage sites where the local site amplifications and other effects may be important.

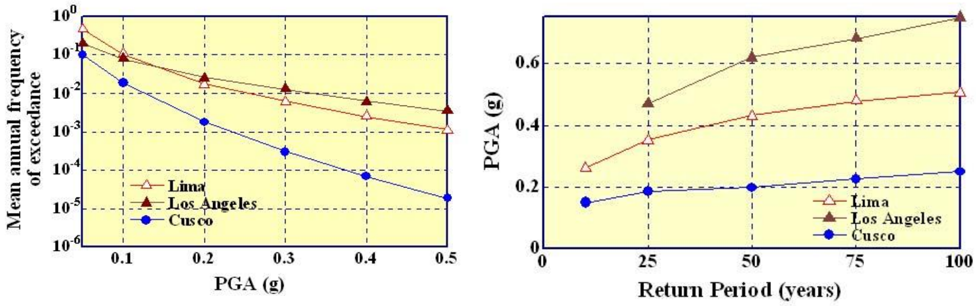


Fig. 3 Hazard curve and PGA versus return period for representative sites

3. HISTORICAL SITES IN PERU

Peru has many sites of cultural and natural heritage reflecting the pre-Inca era, Inca era as well as the subsequent era following Spaniard conquistadors in the 17th century. The distribution of these heritages can be observed in Fig. 4 and includes the world heritages declared by UNESCO which are marked by circles. Of the eleven Peruvian heritage sites in the UNESCO world heritage list, seven are considered cultural and two are considered natural. The remaining two are considered mixed category, meaning that the sites reflect the cultural as well as the natural heritage. Additionally to this UNESCO list, other architectural heritages located in the coast of Peru are included in Figure 4 and are marked by triangles. Most of these selected architectural heritages correspond to structures made of adobe. Descriptions of some important sites are presented in the following sections.

Fig. 4 Peruvian world heritages distribution

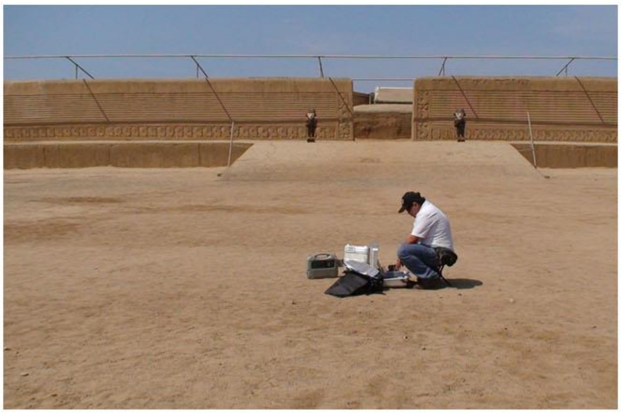
3.1 Chan Chan archaeological zone

Chan Chan is considered the largest old city of South America that was made of adobe. Chan Chan was the capital of a pre-Inca kingdom of Chimu. The remains of the city can be found in nine parts that are considered separated units or palaces because only around these places can be appreciated remarkable constructions. In Fig. 5 some views of adobe constructions can be observed.

The adobe constructions are quickly damaged by natural erosion due to the air, salt, humidity and rain and they require continuous conservation efforts. This zone is also subjected to the impact of El Nino current which affects climate world-wide. Some years like 1983 and 1998 this phenomenon was unusually strong, leading to torrential rain and flooding. As was shown previously the seismic activity in this north part of Peru are smaller in comparison to the southern and central parts. However, historical earthquakes distribution and hazard analysis shown that this area is not free of earthquakes and on the contrary occurrence of rarely earthquakes could strike and damage earthen structures like Chan Chan.

Fig. 5 Some views of Chan Chan adobe city

In this study some preliminary microtremor measurements were carried out to estimate the characteristics of the ground in Chan Chan. Results of the data analysis shows that the ground has a predominant frequency of the order of 1 Hz that could indicate that the city is located on a soft soil layer. To obtain this dynamic characteristic of the ground, the H/V spectrum ratio was calculated that is the ratio between the Fourier spectrum of the horizontal wave and the Fourier spectrum of the vertical wave. This H/V spectral ratio is shown in Fig. 6.



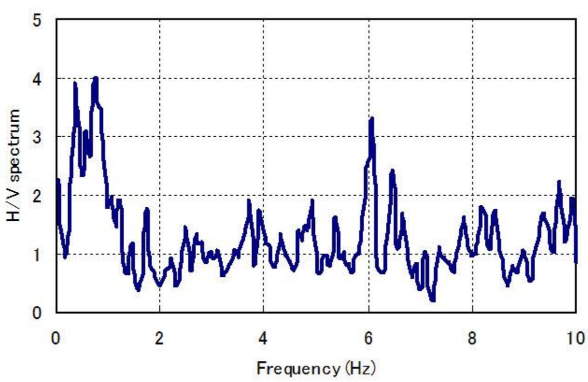


Fig. 6 Microtremor measurement and H/V spectrum for Chan Chan ground

3.2 Archaeological complex of Pachacamac

This complex was one of the main centers of religious cult, an oracle center of ancient civilization in the central coast of Peru. It is a pre-Inca heritage which origins date from 200 a. c. It is believed that one of the deities of this temple was the god of earthquakes. Their constructions are made of adobe which present condition shows the fragility of this kind of material to the action of natural hazards. Fig. 7 shows some view of the Pachacamac complex. The buildings in general are affected by the erosion due to the sand and also by the movement of the sand dunes that in some cases has destroyed and cover completely the buildings. It is difficult to infer the action of past earthquakes because the damage condition of the building could be the result of the action of earthquakes and the lack of appropriate maintenance. Another hazard to this complex becomes the rapidly development of the urban area near the complex that affect not only the landscape of the zone but the architecture heritage itself since construction materials are obtained from the historical place.

Fig. 7 Some views of Pachacamac archaeological complex

3.3 Lima historic centre

The city of Lima, the capital of Peru, was founded by Spanish conquistador Francisco Pizarro on January 18, 1535 and given the name City of the Kings. Lima played a leading role in the history of the New World from 1542, when Carlos V establish the vice royalty of Peru, until the middle of the 18th century. In 1988, UNESCO declared the historic center of Lima a World Heritage Site for its originality and high concentration of historic monuments constructed in the time of Spanish presence and at the beginning of the Republican era. The architecture of the buildings corresponds in general to typical Hispano-American baroque of the 17th and 18th centuries. Since its foundation the city has suffered the action of many earthquakes that have severely affected historical buildings and reconstruction works have been done keeping the originality of the buildings. However due to the age of buildings studies for retrofitting or strengthening are necessary. In this study a preliminary evaluation of structural condition of buildings is presented. As example a building that correspond to an old hotel is presented where ambient vibration measurements were performed to estimate the period of vibration. This building can be observed in Fig. 9. Walls are made of quincha that consists of a wooden frame with a mesh of cane that receives a mud plaster. The first story is made of adobe walls and the upper two stories are made of quincha. The building presents some partial collapse of interior walls and serious deterioration of the quincha walls.

Fig. 9 Views of a historical building at historic centre of Lima

Results of ambient vibration show a predominant frequency of the order of 3.3 Hz. Fig. 10 shows the predominant frequencies for NS and EW directions respectively. The NS direction was taken as the direction parallel to the façade and the predominant frequency is 3.37 Hz. In the EW direction that is perpendicular to the façade the predominant frequency is 3.21 Hz. These frequencies represent reasonable values for a building of 12 m of height however more detailed measurement are necessary to detect the local vibration of portions of the building that could indicate the condition of deterioration.

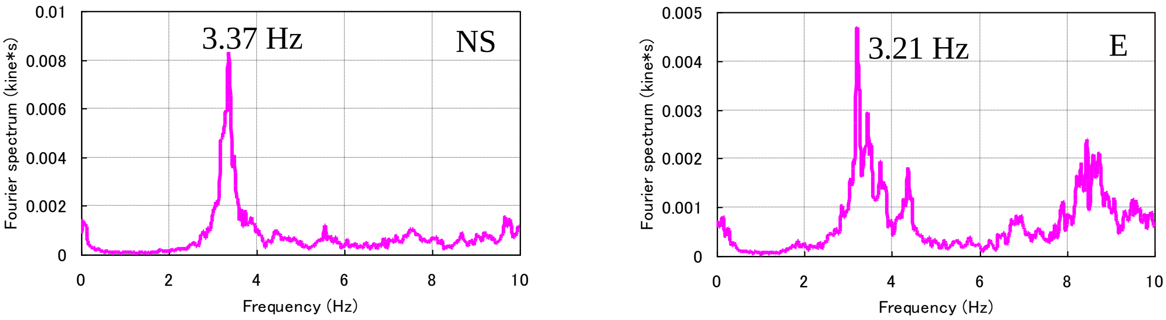


Fig. 10 Predominant frequency of selected historical building of centre of Lima

3.4 Stone masonry constructions

Field survey has been performed on selected part of Machupicchu citadel (Fig. 11) to evaluate the structural condition of historical constructions. Damages were detected in many buildings and, an evaluation to establish the causes of these damages was done. Slips of stone blocks are observed as gaps between adjacent blocks in stone masonry walls. In some cases the movement of blocks could be due the settlement of the underlying ground. However, in some cases there is not ground settlement and therefore it is supposed that the movement of blocks could be the result of the action of past earthquakes. The particular horizontal sliding between stone blocks at one wall corner of the Temple of the Three Windows could be consequence of strong seismic forces of past earthquakes.

Fig. 11 Stone masonry structures at Machupichu

Probable action of past earthquakes on the failure of these buildings or portion of these historic buildings can be inferred from the observation of the structural condition of gables walls. Most of them have collapsed and from detailed observation of apparently undamaged walls it can be observed that most of them have been reconstructed.
The evaluation of the settlement observed in the Main Temple conduces to think that it is probably due to the fracture of the subjacent bedrock in which the building is founded. Apparently, the bedrock is sallow and the fracture of this rock can be explained only by the action of large geodynamic forces.

4. CONCLUSIONS

Vulnerability of heritage architecture in Peru was discussed. The heritage architecture is exposed to the action of earthquakes as well as another kind of natural hazards and risk emanating from human activity. The adobe heritage architecture is mostly in a state of disrepair and therefore the seismic risk and other kind of risks are particularly acute. The discussion of earthquake hazard to which heritage architecture in Peru are subjected and the description of the state or structural condition of the buildings, provides an overview of the challenges involved in protecting the heritage architecture.

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