Structural properties of adobe dwellings in Cusco for seismic risk assessment

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ABSTRACT
According to the last national census, 35% of the Peruvian dwellings are made with adobe or *tapial* (rammed earth). In Cusco, a city located at the Peruvian highlands, around 75% of the building stock is constructed with earth. Besides, Cusco is relatively seismically active and thus seismic risk assessment studies are warranted. For example, on May 21, 1950, an earthquake seriously damaged almost all the buildings in Cusco, which a maximum estimated acceleration of 300 gals. This work looks at the structural properties of adobe buildings in Cusco for use in seismic risk assessment. The geometrical properties of typical dwellings from Cusco have been established according to a building-by-building survey carried out at the Catholic University of Peru (PUCP). Then, a database containing the principal geometrical properties of 30 dwellings has been created which has allowed the mean, standard deviation and probability density functions (PDF) to be defined for parameter such as storey height, wall length, etc.

Keywords: adobe dwellings, typology, structural characteristics

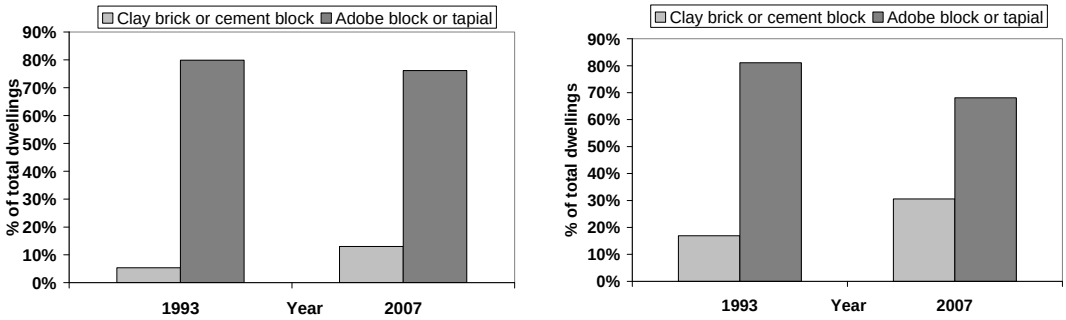
1. INTRODUCTION

The high seismic vulnerability of earthen buildings is due to an undesirable combination of the mechanical properties of dry earth: 1) earthen structures are massive and thus attract large inertia forces, 2) they are weak and cannot resist these forces, and 3) they are brittle and break without warning (Blondet *et al.* 2006). Adobe buildings are constructed with dry earth which is the least expensive construction material and often the only one available to much of the world's population in rural areas (Bariola and Sozen 1990). Furthermore, it has good thermal properties; it retains the warmth of the environment during the day and releases it at night and thus the house remains warm even in seasons with low temperatures. At the Peruvian coast, there is an important number of earthen dwellings, but their poor structural configuration (imitating constructions with other materials, big openings, thinner walls, etc.) makes them more vulnerable to earthquakes.

In Peru the total number of earthen dwellings (built in adobe or tapial) still forms an important percentage of the total number of Peruvian houses (INEI 2007). According to the last census, earthen buildings have decreased from 43% to 35% at of the a national level from 1993 to 2007. However, the region of Cusco (with more than 1,171,500 inhabitants and located at the Peruvian highland) maintains almost 76% of adobe houses (Figure 1a), though the percentage in the province of Cusco (which has more than 348,500 inhabitants) has decreased slightly from just over 80% in 1993 to around 68% in 2007 (Figure 1b). Despite this reduction, it is clear that in Cusco people build with adobe as a principal material.

At the Peruvian coast there are a lot of adobe houses but with different structural configurations that, in general, makes more vulnerable this type of buildings. For example, in Pisco (a city located at the Peruvian south), almost all the adobe dwellings collapsed during the last big earthquake in 2007, one

of the principal reasons was the high slenderness of its adobe walls and the lack of proper connection between walls to avoid the out-of-plane failure.

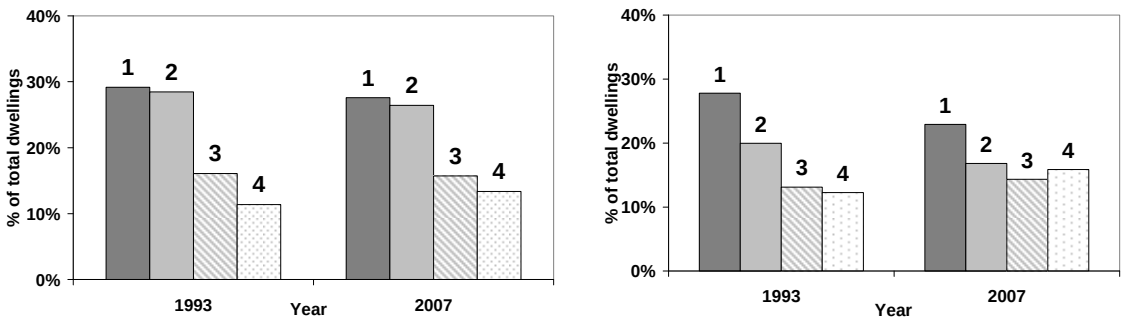


a) Region of Cusco, 293 584 dwellings b) Province of Cusco, 88 337 dwellings

Figure 1. Percentage of adobe and clay brick masonry buildings in 1993 and 2007.

According to Carazas (2001), the construction in the rural area of Cusco (corresponding to the city periphery) has a strong pre-Hispanic influence, namely 1-storey adobe dwellings with two rooms, one of which is used for social activities, such as cooking or eating, and the other is generally used as a bedroom (Figure 2). There is no statistical data about the quantity of adobe houses of one or more storeys in Cusco. However, it can be concluded from Figure 3 that the majority of adobe houses has 1 or 2 rooms. Indirectly, it may thus be concluded that these houses, or at least the majority of them, will have only one level. Considering this assumption, in the region of Cusco almost 60% of adobe dwellings have 1 storey (see Figure 3a).

Figure 2. Rural adobe houses (Carazas 2001).



a) Region of Cusco b) Province of Cusco

Figure 3. Number of rooms in adobe dwellings.

Considering the high concentration of adobe buildings in Cusco, as well as the moderate seismic hazard, this town has been selected by the Catholic University of Peru for a building-by-building survey to determine the structural characteristics of these buildings. Figure 4 shows some examples of

typical rural adobe houses in Cusco surveyed during a joint project between the Catholic University of Peru and SENCICO, a Governmental Institution.

Figure 4. Rural adobe houses in Cusco (Blondet *et al.* 2004).

This paper looks at how the structural data required for the displacement-based earthquake loss assessment methodology (DBELA) have been derived. The DBELA method makes a comparison between the displacement demand and the displacement capacity of a random population of buildings at increasing levels of seismic intensity (Crowley *et al*. 2004), this means the comparison between the seismic capacity with the seismic demand. The random population of adobe buildings used in DBELA is generated with Monte Carlo simulation based on probabilistic distributions of the geometric and material properties which are defined *a priori*. The Monte Carlo simulation method (stochastic modelling) is an analytical technique in which a large number of simulations are run using random quantities for uncertain variables and looking at the distribution of results to infer which values are most likely.

The displacement capacity of the buildings is estimated for different damage states as a function of the failure mechanism and the geometric and material properties of the buildings. The displacement capacities have been derived from experimental tests carried out in Peru (Blondet *et al*. 2005). The typical geometric properties of adobe buildings in Cusco are presented in Section 2, whilst the drift capacity of adobe buildings for in-plane behaviour, estimated from experimental tests, is presented in Section 3. The period of vibration of the buildings is also required in this methodology, as the displacement demand is function of this structural property. The equations derived to estimate the period of vibration are also presented in Section 3. A complete description of the procedure for evaluating the seismic risk of adobe dwellings can be seen in Tarque (2008).

2. GEOMETRICAL PROPERTIES

Blondet *et al.* (2004) carried out a building survey in Cusco and collected information from 30 adobe buildings as the dimensions of walls and bricks, number of rooms, number of openings, age of the building, type of soil, etc. With that data it was possible to define the mean values and standard deviations of the geometrical properties.

Table 1a shows the properties of the walls. It was found that the mean wall thickness of adobe buildings in Cusco is 0.44 m, and the mean wall height is 2.45 m for one storey buildings and 4.88 m for two storeys buildings. These mean heights have been calculated without considering the height of the gable. The thickness of the wall is fairly uniform amongst the buildings analysed, confirmed by the low standard deviation (0.04 m). It is important to remark that in other Peruvian cities, especially those located at the Peruvian coast, the wall thickness of the adobe dwellings is around 0.25 m. This result in slenderness values (height/thickness ratio) greater than 9, which increase the probability of collapse, principally associated to out-of-plane mechanisms. The adobe houses in Cusco have slenderness ratio values around 6 and thus may be less susceptible to out-of-plane collapse.

Table 1b shows the average dimensions of the adobe blocks. The mean length, width and thickness of the blocks calculated are 0.44, 0.21 and 0.15 m, respectively. Table 1c shows the mean and standard deviation values for the gables and the dimensions of the openings. Also, the average values of the length and width measurements for a typical adobe room are shown. The mean gable height has been found to be around 1.33 m, the dimensions of the doors are 1.08 m (width) and 1.80 m (height) and the dimensions of the windows are 1.07 m (width) and 1.00 m (height). Typically, the rooms have dimensions in plan of 4.53 x 5.38 m^2.

Table 1. Geometrical properties

a) Wall dimensions

	Thickness	Height (m)	
	(m)	1 storey	2 storeys
Mean	0.44	2.45	4.88
SD	0.04	0.21	0.38

b) Adobe blocks

	Length	Width	Thickness
	(m)	(m)	(m)
Mean	0.44	0.21	0.15
SD	0.04	0.02	0.01

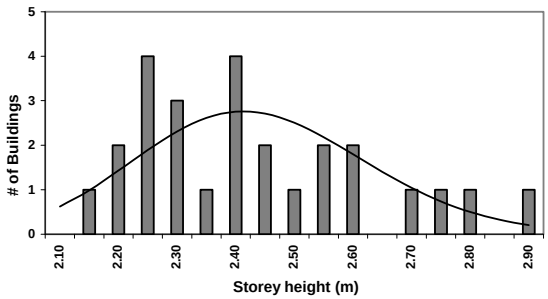
c) Gable, opening and room dimensions.

	Gable	Openings				Room	
		Door		Window		Length	Width
	(m)	Width (m)	Height (m)	Width (m)	Height (m)	(m)	(m)
Mean	1.33	1.08	1.80	1.07	1.00	5.38	4.53
SD	0.18	0.18	0.15	0.28	0.13	1.10	0.59

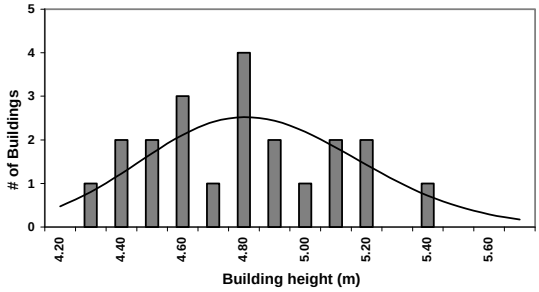
The variability of each of the parameters in this study (i.e. walls length, adobe bricks dimensions, etc.) can be represented by histogram plots which can then be fit to a probability density function (PDF). Figure 5 shows the histograms and the best-fit PDF for some of the geometrical parameters presented previously.

From the 30 adobe dwellings, there were 25 buildings of two-storeys and 5 buildings of one-story. The building height of 4 of the two-storey buildings was missing; this meant that data from only 21 buildings was used to produce Figure 5b. To evaluate the mean and standard deviation values for the height of the walls of one storey-buildings, data from the 2 storey-buildings was added; this resulted in 26 values of height used to produce Figure 5a.

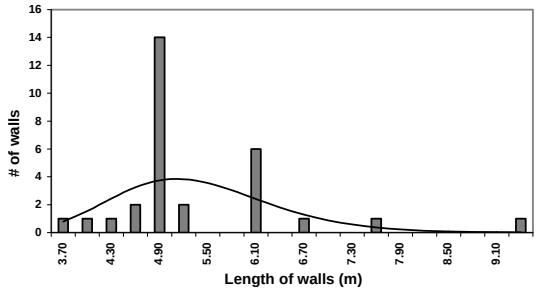
The normal or lognormal probability density distributions can represent fairly well the height of the buildings. The width of the windows and doors whilst the brick length and width probability distributions are fairly uniform. Neither the normal nor the lognormal distribution fit well the length of the walls in the direction perpendicular to the façade (Figure 5c), or the length of the walls placed parallel to the façade (Figure 5d). However, it is noted that a different histogram may be obtained if the data are grouped considering different interval sizes.



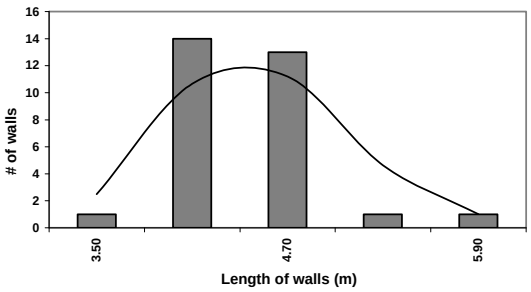
a) Height for 1-storey buildings.



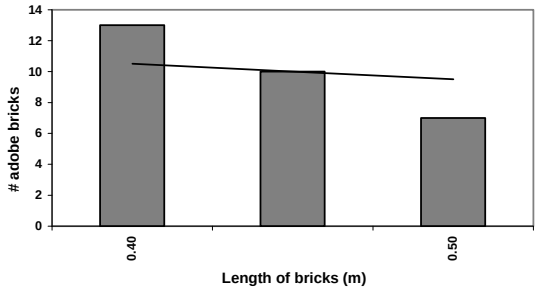
b) Height for 2-storeys buildings.



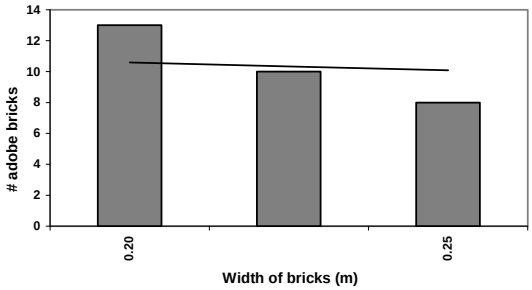
c) Wall length for walls located perpendicular to the façade.



d) Wall length for walls located parallel to the façade.



e) Brick length.



f) Brick width.

Figure 5. Histograms and PDFs of some geometrical properties.

3. MATERIAL AND DYNAMIC PROPERTIES

The material and dynamic properties are based on tests carried out at the Catholic University of Peru (PUCP). In 2005, a displacement controlled cyclic test (push and pull test) was carried out on an adobe wall by Blondet *et al.* (2005, Figure 6a). In 2006, a dynamic test was performed over the unidirectional shaking table of the PUCP on a full-scale adobe module (Blondet *et al*. 2006, see Figure 6b).

Based on the cyclic test performed on the wall specimen shown in Figure 6a, four limit states of damage have been obtained based on the grade of damage (Figure 7b). Until 0.05% drift, the structure can be considered as elastic (LS1), which means fully operational. After that level of drift, the structure can have some cracks but is still functional (LS2), until 0.1% of drift. Then, the life-safety performance (LS3) is reached at 0.26% of drift and, finally, the structure is considered near to collapse at 0.52% of drift (Tarque 2008). The last limit state does not necessarily means collapse of the structure; it can be specified that the cracks are not particularly serious unless the relative displacement across them becomes large, which means the overturning of the small blocks of walls formed by the cracks (Webster 2008).

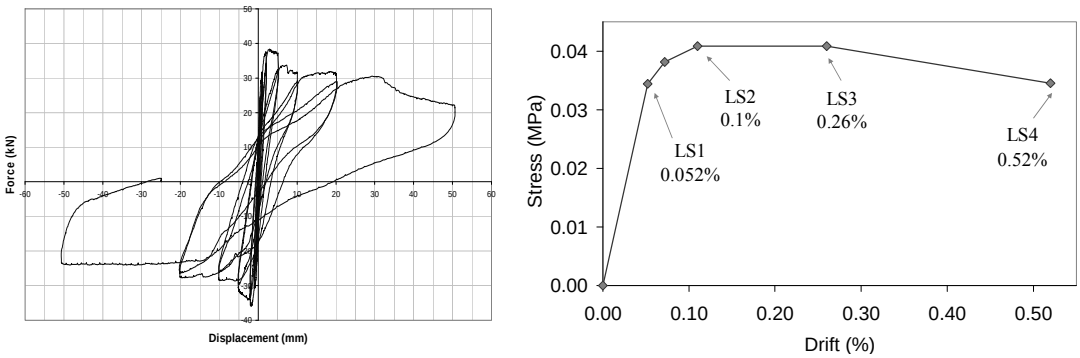
a) Cyclic test (Blondet *et al*., 2005) b) Dynamic test (Blondet *et al*., 2006)

Figure 6. Tests carried out at the Catholic University of Peru.

The elastic stiffness K was obtained from the capacity curve (Figure 7) and with this parameter it was possible to calculate the elasticity modulus E based on Equation 3.1 (cantilever beam subjected to flexural and shear deformations).

$$K = \frac{1}{\frac{H^3}{12EI} + \frac{H}{GA_v}} \tag{3.1}$$

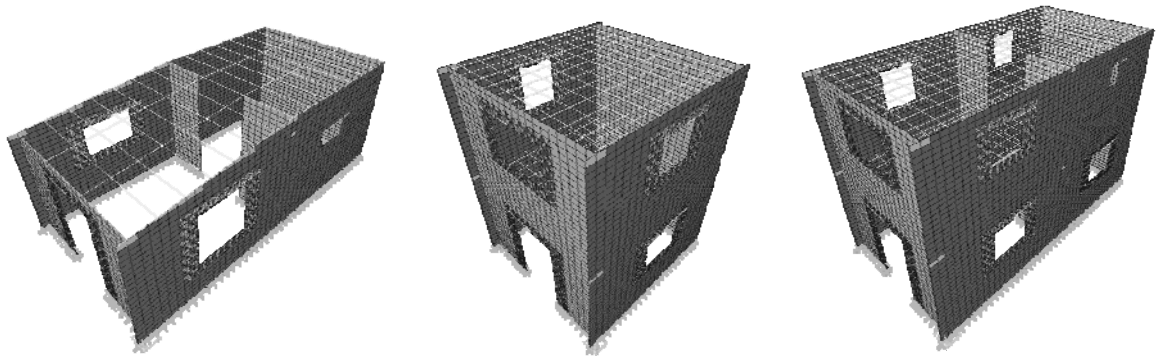
where H represents the wall height, I the moment of inertia of the section, A_v the shear area and G the shear modulus, which was taken as $0.4E$. The Young modulus was found to be around 135 MPa. With the weight of the wall (135 kN) and with the elastic stiffness it was calculated the elastic period of vibration with the expression $T = 2\pi(M/K)^{0.5}$. The period estimated for the wall is T_y= 0.15 s. From the dynamic test (Figure 6b), a period of vibration of around 0.16 s was obtained directly from a free vibration test carried out previously to the beginning of the dynamic test.



a) Hysteretic curve (Blondet *et al*. 2005) b) Envelope of the hysteretic curve

Figure 7. Capacity curve derived for the test results on adobe wall subjected to in-plane forces.

The periods of vibration obtained from the experimental test results were compared with the results of preliminary elastic numerical analyses performed with commercial finite element software for different configurations of adobe buildings (see Figure 8). A reduced Young modulus, $0.6E$, was used for the computation of elastic vibration periods, considering that at the first limit state the adobe walls were already cracked (Tarque 2008). Analytical models with different heights and with different configurations were developed to study the influence of these parameters in the variation of the vibration period. The vibration periods obtained with the experimental tests and with the analytical models are plotted in Figure 9, as function of the building height.



a) 1-storey building with 2 rooms b) 2-storey building with 2 rooms c) 2-storey building with 4 rooms

Figure 8. Analytical model for adobe buildings.

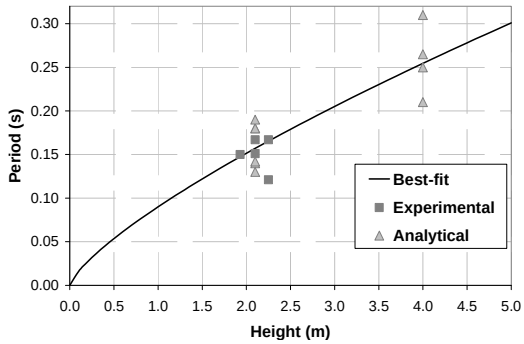


Figure 9. Vibration period versus building height (experimental and analytical data and best-fit regression curve).

To make a correlation between the period of vibration and the height of the walls (H), the following formulation was applied: $T=\alpha H^{\beta}$. From a best-fit regression analysis the values of α and β results in $T_y=0.09H^{3/4}$. The values of vibration period given by the correlation founded are higher than the formula proposed in many codes around the world for masonry buildings (which is often taken as $T=0.05H^{3/4}$), because this formula was obtained from the measured vibration periods of load-bearing wall buildings at low levels of ground shaking and has been calibrated to underestimate the period by 10-20% so that higher forces will be predicted from the design acceleration spectrum, which is inversely proportionally to period (Goel and Chopra 1998). It is important to remark that the period of vibration which has been derived in the current study correspond to a cracked period of vibration which is to be used for assessment, and thus a realistic prediction of the expected period of vibration is required.

4. CONCLUSIONS

Taking advantage of the building-by-building survey of 30 adobe dwellings carried out by the PUCP, a data base of the principal geometrical properties has been created. The mean, standard deviation and best probability density function has been found for each parameter (such as storey height, brick dimensions, wall length, etc) to describe how they vary within a population of adobe buildings. These statistics can then be used to create random hypothetical populations through Monte Carlo simulation of adobe buildings for use in seismic vulnerability assessment. The same procedure done in this study can be applied to another population of buildings with different typology construction.

Some interesting data which has arisen from this study includes the slenderness value of adobe walls from buildings located in Cusco, which is close to 6 and thus much lower than the values found in typical adobe buildings at the Peruvian coast region (Blondet *et al*. 2008).

Results from experimental tests and from analytical models of adobe buildings have also been used to study the elastic period of vibration of adobe buildings, as a function of its height, H, leading to the following relation: $T_y=0.09H^{3/4}$. This relation gives vibration periods of vibration of around 0.15s for 1 storey adobe buildings, and around 0.25s for 2 storey adobe buildings.

The geometrical data derived herein and the period of vibration equation has been applied in a seismic risk assessment for Cusco region, based on *DBELA* procedure and carried out by Tarque (2008). The results show a moderate risk to out-of-plane damage and higher risk for in-plane failure. Future studies should consider cost-benefit analysis, where the cost of repairing such damage is outweighed by the cost of retrofitting.

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