



Geotechnical and structural testing in an archaeological massive earthen pyramid: Huaca de la Luna

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Article disponible dans les actes du colloque Terra 2016:

JOFFROY, Thierry, GUILLAUD, Hubert, SADOZAI, Chamsia (dir.) 2018, *Terra Lyon 2016: Articles sélectionnés pour publication en ligne / articles selected for on-line publication / artículos seleccionados para publicación en línea*. Villefontaine : CRAterre. ISBN 979-10-96446-12-4.

SUMMARY

Huaca de la Luna is an archaeological complex built by the Moche civilization from 100 AD to 650 AD and is considered one of the major representative massive adobe constructions in Peru. Because of the importance of this monument, several in-situ and laboratory tests were carried out in different areas of this complex to evaluate its geotechnical and structural conditions. The aim of the research is to obtain accurate information to determine the characteristics of Huaca for further structural and risk studies. Experimental program results outline the foundation condition, mechanical characteristics of the adobe masonry and the diagnosis of some substructures. The most representative information for a proper structural analysis of the monument was gathered in this extensive field campaign and is presented in this paper.

1. INTRODUCTION

Peru is located in a region of high seismic activity and historically has been exposed to strong earthquakes. In addition, the north coast of the country has been affected by heavy rainfall events and flooding associated with the El Niño phenomenon. The archaeological complex of Huaca de la Luna (Figure 1a) is a monumental religious structure built from 100 AD to 650 AD in the north of Peru (Uceda and Morales, 2010). This complex is composed by six overlapped construction levels, denoted as A, B, C, D, E and F. Each level consists of three platforms and four squares.

The re-discovering process of Huaca de la Luna has left the structure vulnerable to different natural hazards. Furthermore, evidence of damage can be found in the actual site. Figure 1b shows a plan view of the complex with the hatched areas denoting the sectors of this monument where damage is present. Of particular interest are the areas with localized crack patterns at the NW corner and at the SW corner. Due to colonial treasure hunters, the structural stability of the Huaca has been affected by the several tunnels and cut along the north façade they produced in the past.

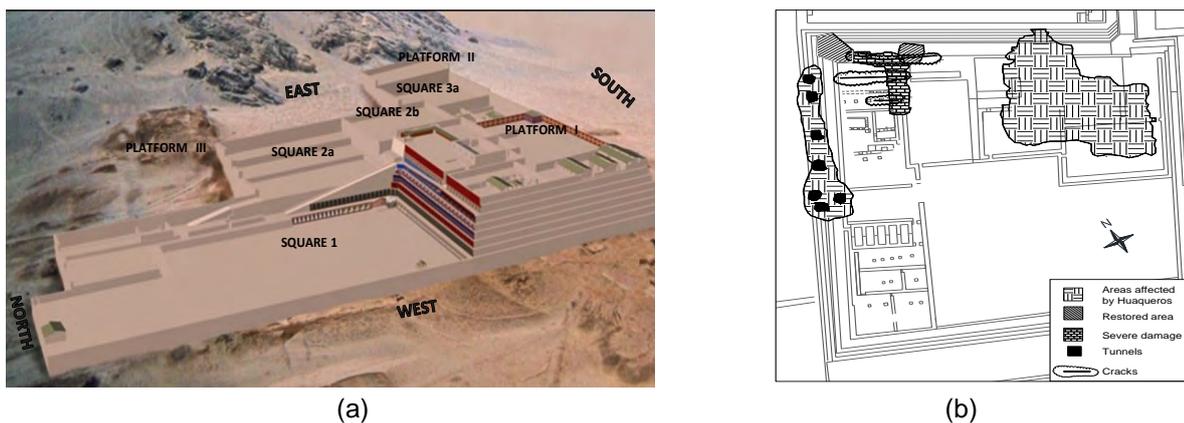


Figure 1. Huaca de la Luna: (a) general outline (b) observed damage (Zavala et al., 2015)

2. GEOTECHNICAL AND GEOPHYSICAL SURVEYS

A large field investigation program involving geotechnical and geophysical tests was performed at Huaca de la Luna in 2014-2015. The geophysical and geotechnical program at this site included eleven Multichannel Analyses of Surface Waves (MASW) (Park et al., 1999) and Seismic Refraction test lines, four Seismic piezocone penetrometers (SCPTu)

soundings, two handauger borings and four plate load tests. This geotechnical program and its interpretation are described briefly in this section.

The MASW test lines were performed with different lengths, adapting them to the available area in the field. Five of these lines were done on Square 1 (see Figure 1a), which is located on the lowest part of the north façade, and three lines were performed on the urban zone which adjoins the west façade of the complex. The remaining three lines were done on Square 3A, on the south east area of the Huaca, where the bedrock layer is referred to be at a shallower depth based on the geology and closer to the surface. The four SCPTu soundings were performed on the north and west façade, reaching a maximum depth of approximately 12 m. Hand auger boring was used to extract some samples and to supplement previous tests. All the tests were used to produce an east-west and north-south profile.

In general the SCPTu results indicate that the foundation soils of the affected area comprised by medium dense to dense sand layer of about 5.5 m in thickness, underlain by an intermediate layer of gravel, followed by dense to very dense sand layer with a depth ranging from 6 to 11 m, which were underlain by a hard layer (presumably consisting of granite bedrock). The interpreted soil profile based on the SCPTu tip resistance, consist of four sand layers. Layer 1 has an average tip resistance ranging from 70 to 110 bar (medium dense sands). Layer 2 average tip resistance ranges from 175 to 240 bar (dense to very dense sands). Layer 3 average tip resistance ranges from 225 to 250 bar (very dense sands). Layer 4 average tip resistance ranges from 210 to 375 bar (very dense sands) and is underlain by a hard layer where refusal of the tip was met. Details can be found in Zavala et al. (2015).

The results of the hand auger boring and visual classification of the recovered soil samples indicate that the first layer on boring B-1 (near the north façade) is composed by silty sand, the next layers are sand and gravelly sand. On the boring B-2 (west façade) the superficial layer is poorly graded sand followed by silty sand and fragments of crushed adobes. These results complement the SCPTu results above.

Shear wave velocities profiles (V_s) were obtained from MASW, Seismic Refraction, and SCPTu tests. The values from different tests were compared in order to evaluate the main area of this study. Layer 1 has average shear wave velocities from 200 to 300 m/s. Average shear wave velocities of layer 2 ranges from 250 to 350 m/s. Average shear wave velocities of layer 3 ranges from 300 to 400 m/s. In layer 4, the average shear wave velocities ranges from 350 to 500 m/s. Average shear wave velocities ranges from 400 to 600 m/s in layer 5 and is underlain by a hard layer with shear wave velocity higher than 600 m/s. The last layer is considered a bedrock according to the shear wave velocity and references from other studies (Olona et al., 2010; Miller et al., 1999).

Figure 2 shows stratigraphic profiles for the northern and western façade which were interpreted using the SCPTu tip resistances and shear wave velocities from MASW, Seismic Refraction and SCPTu tests. Both profiles show the 5 layers which slope downward from east to west, generally following the slope of the hard layer (bedrock) outcrop east of the Huaca. The foundation soils in the NW corner area are comprised of medium dense (Layer 1) to very dense sands (Layers 2, 3 and 4), weathered rock (Layer 5) and are underlain by a hard layer that could be the bedrock.

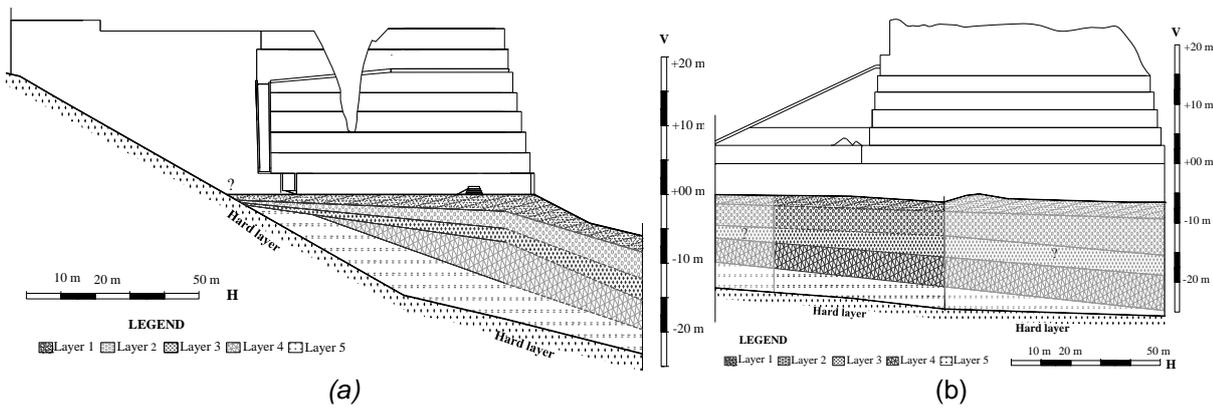


Figure 2. Soil stratigraphy profiles for the (a) the Northern façade and (b) Western façade

3. MECHANICAL CHARACTERIZATION OF THE STRUCTURAL SYSTEM

Mechanical characterization of the material of several structural elements of the Huaca de la Luna was carried out which consisted in the evaluation of adobes, mortar and masonry. The assessment of the components of the structural system (adobe and mortar) was done by means of compression (Figure 3a), flexural (Figure 3b), and splitting tests (Figure 3c). In the case of the adobe masonry, only compression tests were performed (Figure 3d).

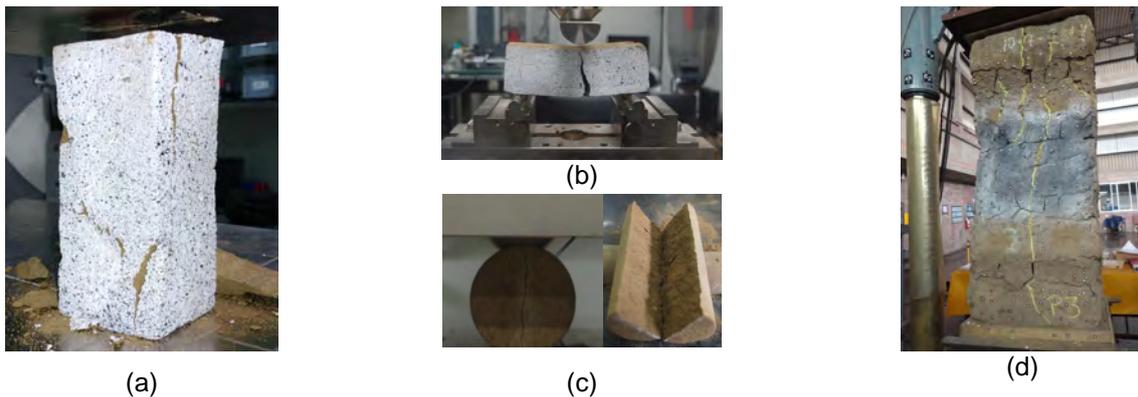


Figure 3. Mechanical tests (a) compression (b) flexion (c) splitting (d) masonry compression

Original adobe specimens and mortar pieces from the Huaca de la Luna were used for the determination of mechanical properties. Prismatic adobe specimens for compression and flexural tests of adobe were cut while cylindrical samples were re-molded for splitting. Mortar specimens were casted in molds, prismatic specimens were prepared for compression and flexion and cylindrical for splitting. For masonry characterization three prisms were built up using 5 adobe units (Figure 3d).

In all tests, the applied load was controlled by displacements, 0.50 mm/min for compression and 0.25 mm/min for flexion and splitting in the characterization of adobe and mortar. In the compression tests of masonry, displacement was applied at a constant rate of 0.25 mm/min. For the determination of the elastic properties, deformations of adobe and mortar specimens were tracked using a digital image correlation (DIC) system during compression and flexural tests. The deformations of the masonry prisms were measured using a four linear variable differential transformer and the DIC system (Ramirez et al., 2015).

The tests results of mechanical characterization tests are summarized in Table 1. The modulus of elasticity (E) was obtained from the compression tests strain-stress (Ramirez et al., 2015; Aguilar et al., 2015). The compressive strength was determined as the ratio

between the maximum force registered and the sectional area. Modulus of rupture (f_b) from three point bending and the splitting tensile strength (f_s) were calculated using expressions from the elastic mechanics.

Table 1. Mechanical properties of Huaca de la Luna components*

		E (MPa)	σ (MPa)	f_b (MPa)	f_s (MPa)
Components	Adobe	901 [43%]	1.28 [18%]	0.53 [26%]	0.25 [23%]
	Mortar	3174 [98%]	2.33 [32%]	1.03 [22%]	0.38 [25%]
Masonry	Prism	107 [25%]	0.36 [14%]	-	-

*Values in brackets parenthesis represent the variation coefficient

4. MECHANICAL CHARACTERIZATION OF SUBSTRUCTURES THROUGH SONIC AND OPERATIONAL MODAL ANALYSIS TESTS

Sonic pulse velocity tests (RILEM, 1996) were carried out on some substructures of this archaeological complex aiming at performing a qualitative evaluation. Two columns, one from Hypostyle Hall (C-1) and one from the Unit 16 (C-4), were assessed using direct testing. The direct sonic test consists on the determination of the velocity of mechanical P or S waves traveling from opposite points. The information of velocity is then used for the creation of 2D images, which reproduces the internal structure of an object. These images are associated to the heterogeneity of the material or the presence of cracks and defects (Binda, et al., 2000).

In the experimental program carried out in this work, an area of 0.45 m of width and 1.00 m of height was evaluated in each column using two accelerometers with a frequency range up to 15 KHz and a hand held steel ball impactor, as shown in Figure 4a. This area was divided in a rectangular grid of six rows and four columns spaced by 0.20 and 0.15 m, respectively. The grid was drawn from the center of the column to the lateral edges and the distance of the first row from the ground was approximately 0.90 m.

In C-1 the average velocity of the measured P-waves was 480 m/s, and the minimum and maximum velocity was 277 and 986 m/s, respectively. The mean velocity in C-4 was 614 m/s and the range of velocities varied from 357 to 1031 m/s. These results were very important to evaluate the uniformity/homogeneity of each element, as clearly shown in Figure 4b.

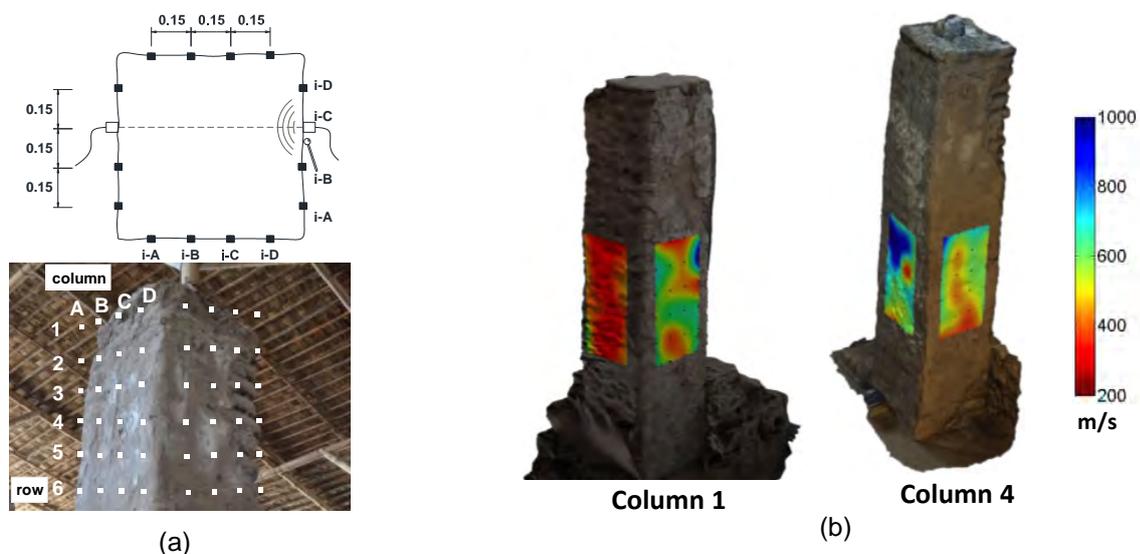


Figure 4. Direct sonic tests results: (a) test setup and grid, (b) resultant velocities in C-1 and C-4

The dynamic properties of four columns of Huaca de la Luna were identified through Operational Modal Analysis (OMA) tests. This paper presents only the results of the same columns C-1 and C-4 described in the previous Section. High sensitive piezoelectric accelerometers and high resolution data acquisition equipment were used for the signal acquisition (Figure 5). The Identification of the dynamic properties was carried out using the Enhanced Frequency Domain Decomposition (EFDD) and data-driven Stochastic Subspace Identification (SSI-data) techniques. The modal response of C-1 and C-4 are presented in Figure 5. As shown, the first two modes are translational and the third represents a torsional movement. More information about the dynamic behavior of the columns can be found in Chácará et al., (2014).

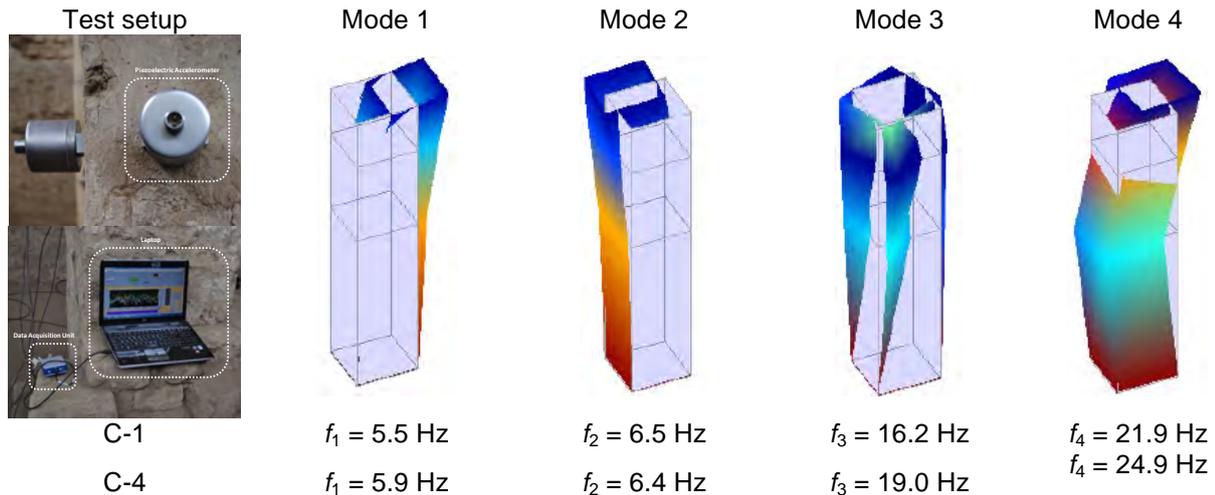


Figure 5. Modal shapes and frequencies of the adobe columns of Huaca (Chácará et al., 2014)

5. SUMMARY AND CONCLUSIONS

The results of the performed field and laboratory tests will be used in the ongoing structural assessment of Huaca, comprising the main geotechnical and mechanical characteristics of this monument. This analysis includes the seismic hazard analysis, settlement analysis and dynamic soil-structure interaction under simulated seismic ground motions. Future work is aimed at implementing advanced finite element models and performing predictive structural analysis.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge DGI-PUCP project 89-2014 for providing funding for this research. The authors would also like to acknowledge the support of CONCYTEC for the funding of the graduate students performing this work. Finally, the authors thank the Material and the Structures Laboratory of PUCP for the access to their installations and testing equipment.

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