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Investigations on the structural behaviour of archaeological heritage in Peru: From survey to seismic assessment

Rafael Aguilar [a,*], Rui Marques [a], Karim Sovero [a], Carol Martel [a], Fernando Trujillano [a], Ruben Boroschek [b]

[a] Department of Engineering, Civil Engineering Section, Pontificia Universidad Católica del Perú PUCP, Av. Universitaria 1801, San Miguel, Lima 32, Peru
[b] Department of Civil Engineering, University of Chile, Beauchef 850, Santiago de Chile, Chile

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ABSTRACT

The conservation of archaeological heritage is of major importance for preserving the scientific, ethnographic and artistic values of past cultures. Once archaeological sites are exposed after being buried for centuries, they are subjected to natural hazards, which should be studied with up-to-date techniques. Moreover, conservation works are primarily focused on aesthetic aspects or on solving localized problems. In earthquake-prone areas, it is of extreme importance to carry out structural analysis studies for assessing the actual behaviour of archaeological constructions, and for proposing adequate intervention measures. This paper presents an extensive study on structural behaviour of archaeological building remains in Peru, based on in-situ non-destructive testing as well as on numerical approaches. The case of the Chokepukio Archaeological Site is presented, which was built between 1000 and 1450 AD in the Pre-Columbian era, with a mixed masonry of stone units and earthen mortar. The paper begins with a comprehensive description of the historical, architectural and structural aspects of the archaeological site. The possibility of applying operational modal analysis tests is then explored with reference to a representative wall of Chokepukio. The results of the experimental field campaign are used to develop calibrated finite element models of the wall, and to indirectly estimate mechanical characteristics of the masonry. Basing on the investigations performed, potential failure mechanisms are identified for the wall and validated by pushover analysis. Finally, the mechanisms are evaluated through kinematic limit analysis, to proceed with the seismic assessment.

1. Introduction

Archaeological heritage buildings are like a constructed calendar of the history of civilizations, and thus are of high importance for the preservation of cultural, ethnographic and artistic values of past folks. Worldwide, archaeological remains represent a significant fraction of the heritage building stock. Much of these building remains, which are mostly made of masonry, have been discovered through archaeological excavations developed without consideration of structural aspects. Moreover, the exploration works introduce new hazards that can occur in open spaces, such as erosion due to water and wind, and particularly seismic events. Thus, the conservation of archaeological building remains requires, beyond a static stabilization or aesthetic operations, deep structural studies to assess its behaviour in case of exceptional loading events.

Peru has a great legacy of archaeological building remains, from typical earthen constructions in the coast to stone masonry remains in the Andean region. On the other hand, the Peruvian coast is located in the Pacific Ring of Fire, which makes this country a very relevant case regarding the development of a worldwide approach for the preservation of archaeological building remains. Recent seismic events such as the 2010 Chilean and 2003 Iranian earthquakes evidenced, once again, the high seismic vulnerability of historical constructions, in which archaeological building remains are included. Understanding the structural behaviour of this kind of constructions is particularly complex due to the difficulty for characterizing the geometry, materials and damage state, for identifying the structural system, as well as for creating reliable numerical models [1].

The International Council on Monuments and Sites (ICOMOS) has published different strategies for studying historical constructions. These strategies evidence the need for a deep knowledge of the monument under study, which can only be obtained through extensive experimental and diagnosis campaigns by means of laboratory and on-site investigations [2]. In this context, non-destructive testing is an important tool, since it allows the evaluation of constructions without endangering their structure.

* Corresponding author. Tel.: +51 1 6262000x4610; fax: +51 1 6262000x2813.
E-mail address: raguilar@pucp.pe (R. Aguilar).

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Vibration-based testing, namely Operational Modal Analysis (OMA), is a powerful non-destructive technique for the estimation of the structural dynamic properties of a construction. On the other hand, the structural evaluation requires adequate methods and tools for modelling and analysis, particularly regarding the seismic assessment. For this purpose, several approaches can be used concerning the nature and complexity of the construction, such as continuum finite element models, structural component methods or rigid block analysis, e.g. [3–7]. However, there are few studies applied to masonry remains and archaeological heritage, e.g. [8,9].

For this last kind of structures, the seismic assessment may require a multiple-view analysis approach, using different numerical methods for validating one against the others, and in which the Finite Element (FE) simulation is usually the reference for comparison, e.g. [8,10]. However, the development of a reliable FE model requires a calibration of the actual condition of the structure, regarding material parameters, boundary conditions and existing damage. This is usually made based on experimental in-situ vibration tests, trying to approximate the experimental modal properties by the numerical simulation, through a successive process of updating the model variables. In effect, calibration through vibration tests is an important issue in seismic analysis, e.g. [11].

This paper aims at the structural evaluation of archaeological heritage buildings, with application to the Chokepukio Archaeological Site in Cusco, Peru. The study includes on-site inspection, experimental testing, and numerical modelling and analysis, performed to assess the seismic vulnerability of the remaining traces of Chokepukio. After a brief description of the archaeological site, details of the OMA tests carried out on a representative wall of Chokepukio are given. Then, the optimization process of the FE model for the wall is presented, and finally, a pushover analysis is reported together with a kinematic limit analysis to proceed with the seismic assessment.

2. The Chokepukio Archaeological Site

The Chokepukio Archaeological Site is located 30 km from the city of Cusco, in the Andes of Peru. A wide variety of remaining structures made of stone masonry and mud mortar was found in the archaeological site. The seismic hazard at the region is high since the archaeological site is located in an area with active faults and Cusco itself is affected by the subduction of the Nazca plate.

Archaeological investigations in Chokepukio by McEwan et al. [12] evidenced that the original structures were built between 1000 and 1450 AD. Furthermore, artefacts were found in the site corresponding to Lucre and Killke cultures, which are considered ethnicities of transition between Wari (650–1000 AD) and Inca (1425–1532 AD) cultures.

Chokepukio presents a particular architecture of walls forming enclosures around open spaces (known as 'kanchas'). McEwan et al. [12] divided the site in three principal areas according to construction features and occupation periods, namely Sectors A, B and C (see Fig. 1a). Sector A, which is the one studied here, presents the highest density of standing structures (twelve 'kanchas' at least) and its walls enclose substantial areas (2600 m^2) with small rooms connected amongst them. Sectors B and C correspond, respectively, to the beginning of the Inca occupation and post-Wari culture, and are more degraded. Isometric views of typical walls in each sector are presented in Fig. 1b–d.

The constructions at Chokepukio were built using andesite stone, which is an extrusive igneous rock named after the Andes. The masonry is composed of irregular stones interposed with mud-mortar joints of thickness ranging between 2.5 cm and 10 cm. The mortar is a mixture of local soil, clay, straw, and cactus resin. Unfortunately, there are no reported studies about material mechanical parameters of the local andesite stone or masonry textures. Effectively, this gap needs to be addressed in future studies.

The height of the constructions ranges from 8 m to 10 m and each wall seems to be constructed in stages with growth in length and height, as evidenced by marked transitions amongst stone courses. Walls were built with multi-leaf arrangement and are 2 m width in average. In general, the walls present trapezoidal or rectangular niches at different heights. In some cases, the original earthen coatings are still visible on walls and niches.

One particular feature at Chokepukio is that higher walls have transversal buttresses, to improve vertical stability, and probably also to provide earthquake resistance. However, most of buttresses are partially in ruins, making the walls more vulnerable. In order to know the soil characteristics and foundation conditions, pit excavations were carried out near one wall located in the southeast corner of Sector A (see Fig. 2a and d). There it was possible to find the foundation of the wall, which is 3.0 m in depth and includes footings to increase the wall stability, see Fig. 2c and f.

3. Experimental diagnosis tests

In-situ experimental investigation was based on OMA [13], which was used as a vibration based non-destructive method to obtain the dynamic modal properties of the structure (frequencies, damping and modal shapes).

Rainieri and Fabbrocino [14] summarize the available techniques for OMA. These techniques consider the measured response of a structure under the unmeasured ambient excitations. Even if the input is not measured, it is assumed that the ambient excitation is banded with a bandwidth large enough to excite most of the response controlling modes. In general, the technique assumes a white noise ambient excitation to identify the modal response parameters. OMA is especially appropriate for civil engineering structures with high dimensions and special characteristics, where the application of impacts or shakers is too expensive or not feasible. Vibration based evaluation of existing constructions has become a deeply investigated topic, e.g. [15–18]. However, there are still few applications to archaeological heritage, e.g. [9,11].

OMA tests were carried out near the building remains located at the southeast corner of Sector A, namely on a couple of walls which present the particularity that are shored one against the other with timber struts (see Fig. 2a, b, d, and e). This sector was selected as case study due to the well preservation of the remaining structures, e.g. in the studied walls the original plaster is still on the interior face. For this study, only the front wall in Fig. 2 was instrumented, which presents variable geometry (thickness varies from 1.2 m to 1.8 m at the base and from 0.4 m to 0.6 m at the top), and average length and height of 20 m and 9 m, respectively. The wall presents two vertical parts with different stone masonry patterns. The bottom part is built with large stones and thin mud-mortar joints, while the top part is made of smaller stone units and thick mud-mortar joints. As shown in Fig. 2a–c, the change on masonry patterns coincides with the change on section in the height of the wall (at level +6.10 m).

For the experimental tests, sixteen measurement points were set in the wall in order to obtain an appropriate characterization of its dynamic response, see Fig. 3a. Due to the availability of a portable Data Acquisition System (DAQ) with a limited number of measurement channels, only four accelerometers were used for the tests. With this limitation, the test planning considered seven setups with two reference nodes (located at the expected higher modal amplitude points) and two roving sensors. The sensors layout was designed in such a way that the behaviour of the bottom and upper part of the wall could be properly measured. Sensors were criteriously installed in two rows at the bottom part of the