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SEISMIC DAMAGE TO STONE STRUCTURES IN MACHU PICCHU

C. H. Cuadra[1], K. Tokeshi[2] and J. G. Rojas[3]

[1] *Associate Professor, Dept. of Architecture and Environment Systems, Faculty of Systems Science and Technology, Akita Prefectural University, Japan*
[2] *Assistant Professor, Dept. of Architecture and Environment Systems, Faculty of Systems Science and Technology, Akita Prefectural University, Japan*
[3] *Professor, Faculty of Civil Engineering, National University of Cusco, Peru*
Email: carlos@akita-pu.ac.jp

ABSTRACT :

The Inca citadel of Machu Picchu is the most famous historical site in Peru; site which was declared as world cultural heritage by UNESCO in 1983 and also as one of the New Seven Wonders of the World in 2007. All of its constructions were made of stone masonry. The citadel was constructed by Inca Pachacutec and was abandoned after collapsing the Inca Empire by the year 1540 AD. During almost four centuries, the citadel endured and survived under a thick rain forest, until it was discovered by Hiram Bingham in 1911. However, it is important to analyze the probable causes of structural damages of the constructions to preserve them. To evaluate the current structural conditions of the buildings, the characteristics of failures are discussed in this paper, through field survey, micro vibration measurements and dynamic analysis. The field survey on damages consisted of a detailed observation and evaluation of a group of selected buildings. Also, micro vibration measurements were performed on the ground and on some buildings to estimate their dynamic characteristics. It was observed that for a specific soil condition, the failure in some buildings could be the result of the action of past earthquakes.

KEYWORDS: Stone masonry, Machu Picchu, Micro vibration, Equivalent elastic modulus, Vibration mode, UNESCO cultural heritage, Structural damage

1. INTRODUCTION

According to the UNESCO World Heritage list by July 2008, 878 sites have been registered. These heritages are classified as natural properties (174), cultural properties (679) and mixed properties (25); which are distributed in 145 countries. Depending to the damages that can suffer due to the human action or due to natural disasters, these world heritages could be lost. When these facts occur, the affected sites are inscribed on the List of World Heritage in Danger, and special actions for preserving these heritages are demanded by UNESCO.
Machu Picchu was categorized as mixed site (natural and cultural heritage), and at present, it is not included onto the List of World Heritage in Danger due to reasonable conservation actions. However, Machu Picchu is located in Peru; a country with great seismic activity due to the subduction of the Nasca tectonic plate beneath the continental South American plate. Cuadra *et al*. (2004), performed a seismic hazard analysis for the zone of Machu Picchu, obtaining a maximum with PGA of 255 Gal for a return period of 100 years. Failures in stone buildings or collapse of some structural components could occur even for this intermediate earthquake ground motion (Cuadra *et al*., 2008).
In this research, a field survey on selected structures of Machu Picchu has been performed to understand the probable causes of failure of these stone structures. Microtremor measurements were carried out on these buildings and at the ground surface near buildings. Structures built of fine shape polygonal stones were targeted for this research. The understanding of current damages in these buildings could be useful to predict its seismic vulnerability and to adopt protection measures.

2. CHARACTERISTICS OF STONE BUILDINGS

Three types of stone masonry can be distinguished in the Inca stonework, as shown in Figure 1. The first style is a roughly shaped stone fitted with mud mortar, as shown in Figure 1(a). The second style is a finely shaped masonry with polygonal units fitted without mortar, as shown in Figure 1(b). The third style is a finely shaped masonry of rectangular blocks forming horizontal layers as shown in Figure 1(c).

(a) Roughly shaped stone (b) Polygonal masonry (c) Rectangular masonry

Figure 1. Types of Inca stone masonry

In previous research (Cuadra *et al*., 2008), the equivalent Young elastic modulus for the first and the third style was studied. In this research, the second style was chosen to complete the study on the equivalent Young modulus of elasticity, and also to study the failure of this type of constructions in Machu Picchu. The targeted buildings and its overall location in Machu Picchu are shown in Figure 2. The Main Temple and the Temple of the Three Windows are located in the Sacred Plaza sector. Details of the Main Temple and the Temple of the Three Windows can be observed in Figure 3. The Main Temple shows damages of displacements between stone blocks of the north wall due to the settlement of the east wall (Figure 3 (a)). In the case of the Temple of the Three Windows, relative horizontal displacements of stone blocks can be observed (stone blocks on the left of Figure 3 (b)).

Figure 2. The main temple and the temple of the 3 windows in the Sacred Plaza sector

(a) Main Temple (b) Temple of the Three Windows

Figure 3. Details of the Main Temple and Temple of the Three Windows

2. MICROTREMOR MEASUREMENTS

Microtremor measurements were performed in the Main Temple and in the Temple of the Three Windows. In the case of the Main Temple, 3 transducers (two horizontal component sensors and one vertical component sensor) were set at the top of wall and at the ground level, respectively. For the Temple of the Three Windows, only horizontal component sensors were set on the structure and over the ground. These constructions are located on a terrace (see Figure 2).

Figure 4 shows the H/V spectral ratio obtained from microtremor measurements at the ground of Sacred Plaza. A predominant frequency of 23.7 Hz was estimated, which would mean that depth of the bedrock is shallow. Usually, the natural frequency of the ground ranges between 1 Hz for soft soil deposits and 10 Hz for hard soil deposits. Therefore, the estimated predominant frequency of 23.7 Hz indicates that the thickness for soft soil layer would be very thin (around 1 m) and that the bedrock would be close to the ground surface. In consequence, these buildings would be founded directly on the bedrock. The soil settlement failure observed apparently in Figure 3(a) would correspond to a failure in the bedrock. In that case, it is probable that some mechanical action on bedrock has produced the cracking of the rock, and as consequence, it has been the cause of settlement in the east wall of the Main Temple.

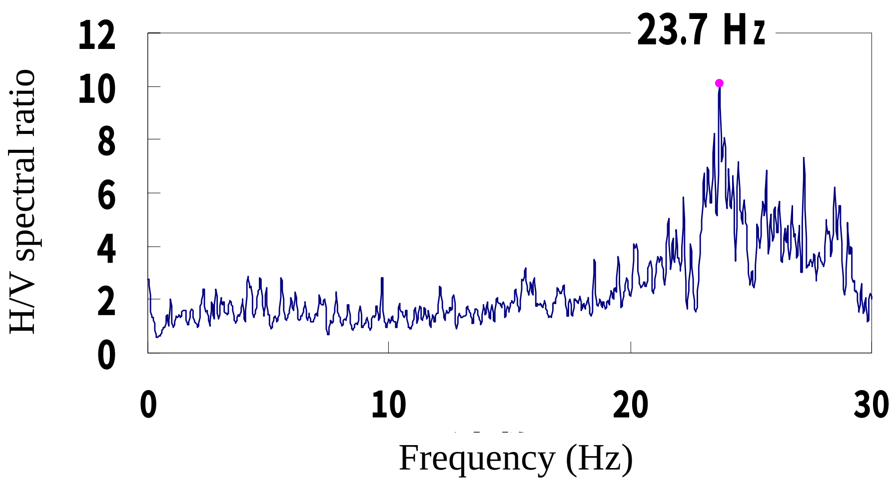

Figure 4. H/V spectral ratio at the ground of Sacred Plaza

In the case of the Temple of the Three Windows, two horizontal components in NS direction and EW direction were measured, separately. Two sensors were located at the ground near building; one at the external ground (Ch. 9) and another sensor at the inner ground (Ch. 6) of the building. Also, one sensor was located at the central window (Ch. 8) and another sensor at the top of the building (just above the central window) (Ch 7). Figure 5 displays the locations of observation points.

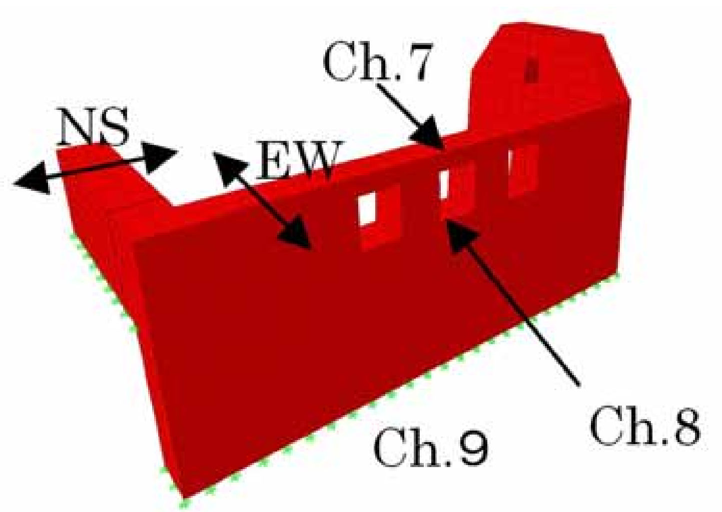

Figure 5. Micro vibration measurements at the Temple of Three Windows

To estimate the dynamic characteristics of the Temple of the Three Windows, the transfer functions between Ch. 9 and Ch. 7 and between Ch. 8 and Ch. 7 were computed, which results along the EW direction are shown in Figure 6. According to these results, the predominant frequencies of the west wall is 6.84 Hz when considering the transfer function from the external ground surface to the top of the wall (Ch. 7/Ch. 9). When the transfer function from the inner ground surface to the top of the wall is considered, the predominant frequency is 17.1 Hz (Ch. 7/Ch. 8).

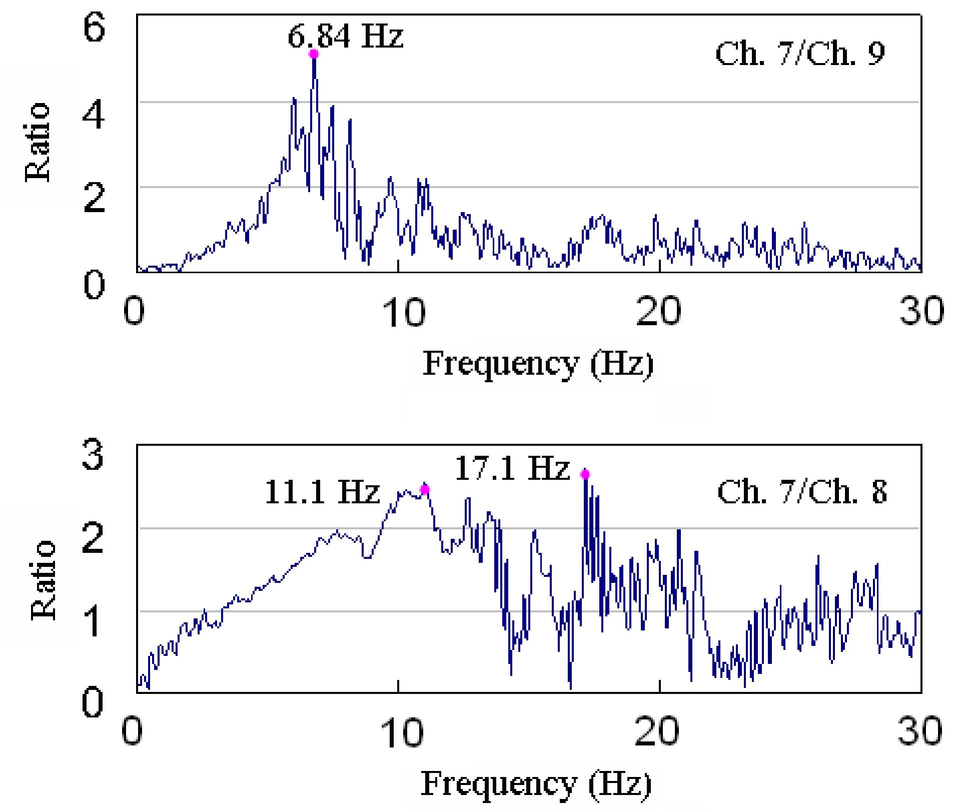

Figure 6. H/V spectral ratio along the EW direction in the Temple of the Three Windows

3. FINITE ELEMENT MODEL

Since the ground levels of the external side and the inner side of the Temple of the Three Windows are different, two models were considered in the FEM analysis. The first model assumes that the east wall does not have contact with the inner ground, as shown in Figure 7(a). The second model considers that the wall is restrained by the inner ground, as shown in Figure 7(b). The walls were modeled using solid elements, and the elastic linear analysis was applied to compare the results with those obtained by micro vibrations. The appropriate value of the modulus of elasticity was determined by inverse analysis of the values of predominant frequencies estimated from transfer functions of micro vibration measurements. The value of 1.3 kN/mm^2 was obtained for the equivalent elastic modulus, giving good agreements between proper frequencies from FEM and predominant frequencies from micro vibration measurements. Table 1 shows a comparison of the results.

Table 1. Vibration modes estimated for the Temple of the Three Windows (Unit: Hz)

Mode	Micro vibrations	FEM
1st Mode (Model of Figure 7(a))	6.84	6.93
2nd Mode (Model of Figure 7(b))	17.10	17.30

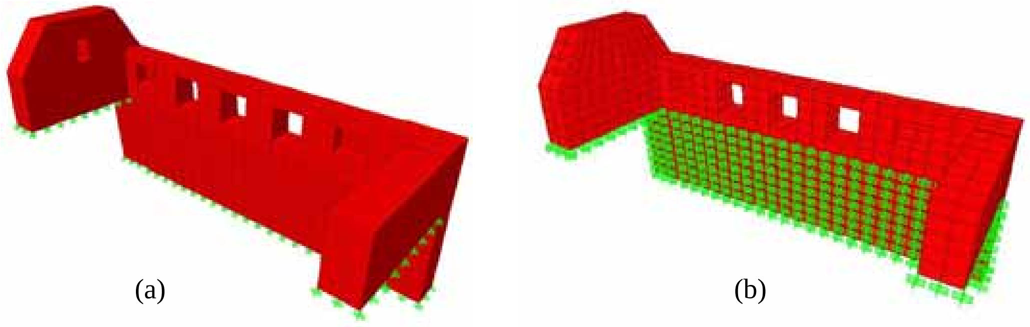

Figure 7. FEM models considered for the Temple of the Three Windows

The equivalent modulus of elasticity obtained for the polygonal shaped stone masonry is between the equivalent modulus of 0.9 kN/mm^2 for roughly shape stone masonry and the equivalent modulus of 1.8 kN/mm^2 for rectangular shaped stone masonry. The smaller value for roughly shaped masonry can be explained due to mud mortar was used. Larger equivalent elastic modulus for polygonal stone masonry could be expected, but according to the results, larger equivalent elastic modulus for rectangular fine shaped stone masonry was obtained.
Finally, the horizontal sliding between stone blocks in the Temple of the Three Windows could be consequence of strong seismic forces of past earthquakes.

4. CONCLUSIONS

Microtremor measurements performed in two temples of the Sacred Plaza of Machupicchu provided valuable information for evaluating the dynamic characteristics of Inca stone heritage structures.
The dynamic vibration modes of the Temple of the Three Windows were estimated from predominant frequencies of transfer functions of microtremor records. The equivalent elastic modulus was estimated by inverse analysis of vibration modes of two FEM models. According to the results, the equivalent elastic modulus of 1.3 kN/mm^2 could represent an approximate value for polygonal shaped stone masonries.
The settlement observed in the Main Temple is probably due to the fracture of the subjacent bedrock in which the building is founded.
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.
Further detailed discussions are currently underway by the authors.

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