Evaluation of the dynamic characteristics of typical Inca heritage structures in Machupicchu

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Abstract

As an initial step to evaluate the seismic vulnerability of Inca constructions at the Machupicchu citadel, dynamic characterization of typical buildings units has been undertaken. This forms a part of the outcome from the field study program, which included microtremor measurement of free field and typical constructions, planned and undertaken by the authors. In this paper, the results of the microtremor measurements are discussed in relation to the analytical procedure to be adopted to estimate the dynamic characteristics of the Inca stone structures. The analytical results are compared with the measurehte th98 0ure

citadel endured and survived under a thick rain forest, until discovered by Hiram Bingham in 1911. Probably, the reasons Machupicchu endured through the centuries is because the Incas used proven technology and a high standard of care in the building process of stone structures. In this research, an attempt to estimate the seismic behavior of the stone structures of Machupicchu in a rational manner is described. For this purpose, the results of field measurement of micro vibrations of selected structures and ground were utilized in the analytical modeling and simulation of seismic behavior.

2 Microtremor measurements and results

All microtremor measurements were performed in the urban sector. In Figure 1 the location of the measurements are indicated by encircled numbers and a brief description of the purpose of each measurements is given as follows.

Figure 1: Location of microtremor measurements

① Plaza (square): Ground vibration measurement. At this site, measurements of the vertical components of the ground vibration were carried out. The sensors were laid in a triangular array system of 30 meter sides. The array measurement is planned for F-K spectral analysis to obtain the characteristic Rayleigh wave dispersion curve, from which the shear wave velocity profile of the ground is estimated by inverse analysis.
② Terraces of Intihuatana: Vibration of terraces structures. In this case, horizontal

components of the vibration of the terraces were measured. North-South (NS) direction and East-West (EW) direction were measured separately. Sensors were located at top, intermediate and lowest part of the terraces.

③Temple of Three Windows: Structure vibration. Horizontal components of microtremor were measured on the structure and over free field ground at this important part of the Machupicchu citadel. Two horizontal components in NS direction and EW direction were measured separately. Two sensors were located on the ground near the building, one in the external part and another one in the interior of the building. Also, one sensor was located on the central window and another one on the top of the building above the central window.

④ Principal Temple: Structure vibration. This structure shows evidence of ground settlement on its east wall. In this case the two horizontal components and the vertical component were measured at top of the wall and at ground level.

⑤ Temple of the Sun: Structure vibration. This structure consists of natural rock foundation, where the naturally located rocks are cut to shape with further addition wall over in-situ rock to provide continuous structural shape and stability. On top of the wall, a circular wall has been constructed which gives this complex the designation as temple of the sun. Three components of microtremors in the upper part and in the bottom part of the structure were measured simultaneously.

⑥ Building No 7 of Group 2: Gable wall and structure vibration. In this case horizontal vibrations were measured. The points of measurement were: the ground, the top of the gable wall, and the top of the normal walls. Measurements were done for the NS direction and EW directions separately.

⑦ Building No 2 of the Group of the Mortars: Gable wall and structure vibration. Horizontal vibrations of the structure and ground were measured in this site. The points of measurement were the top of the central wall, the bottom part of the gable wall, the central window of the central wall and the ground. Measured were carried out for NS direction and EW direction separately. The measurement at this structure is of special interest since its mode of vibration can be compared with the mode of vibration of the previous structures to analyze the restraining effect of the central wall on the behavior of the gable wall.

⑧ Terraces at low part of Group 13: Ground vibration. Here the horizontal vibration of the terraces was measured. The direction of measurements was transversal to the valley (right to left in the Figure 1). Measurements were performed here to analyze the behavior of the terraces since they are affected by landslides that may also be triggered by earthquakes. The measurement was performed simultaneously in four consecutive platforms.

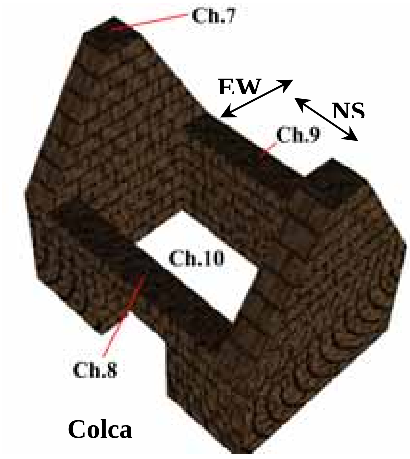
The measurements at building No 7 that here is called as “Colca”, and at building No 2 of the group of the mortar that is called as “Huayrana”, are used to estimate the dynamic characteristic of these stone masonry structures.

Details of these two selected structures are show in Figure 2. The Colca building has dimensions of 5 m. wide, 7 m large and a height of 6.5 m from ground to top of the gable wall. The Huayrana building has 7.7 m wide, 8.8 large and 6.5 m of height.

Colca **Huayrana**

Figure 2: Selected buildings for analysis of Inca's stone structures

The location of the sensor on the Colca and Huayrana are indicated in Figure 3. Channels 7 to 10 were measured simultaneously during 500 seconds. Then stable portions of the records were selected to perform the Fourier analysis that permits to estimate the natural period of vibration of the structures.



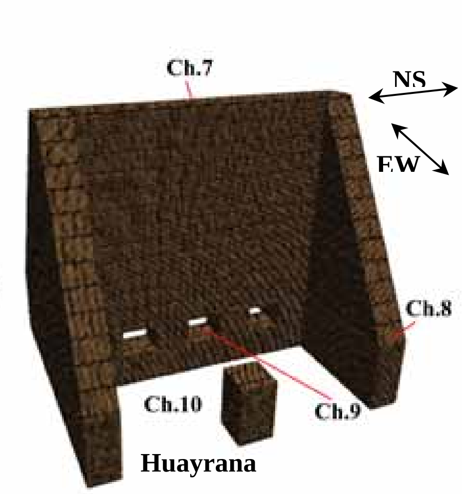


Figure 3: Location of microtremor sensors at Colca and Huayrana buildings

The results of the Fourier analysis are shown in Figure 4. The Fourier amplitude spectrum at each measured point of the structure was divided by the one at the ground level, to obtain only the vibration characteristics of the structure. It can be observed from Figure 4 (a) that the value of the predominant frequency in the EW direction of Colca building ranges from 8 to 12 Hz. In case of the NS direction, a clear peak at 5.5 Hz is shown in Figure 4 (c). This peak corresponds to the out-of-plane vibration of the gable wall. In the case of Huayrana, the central wall restrains the triangular gable walls, however due to the large dimension of this

equivalent elastic modulus of the order of 0.9 kN/mm^2 could be used for this type of construction.
In Figure 6 shows the first mode of vibration for both structures. It is confirmed by this analysis that the main modes of vibration corresponds to the gable wall in case of Colca and to the central restraining wall for Huayrana.

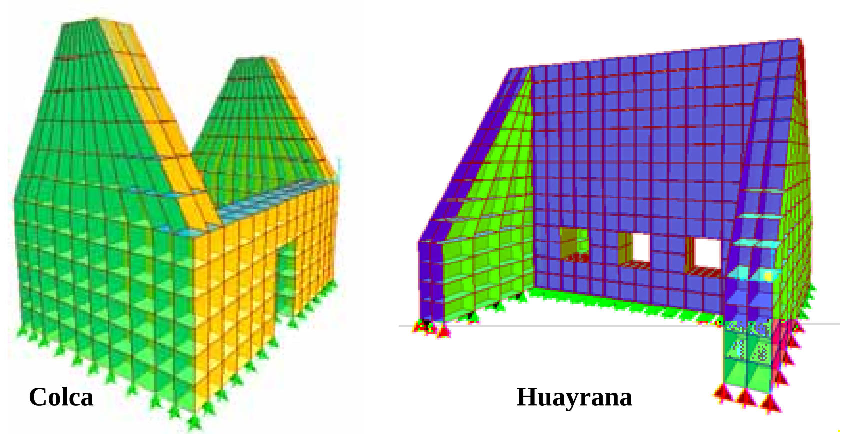


Figure 5: Finite element model for the selected buildings

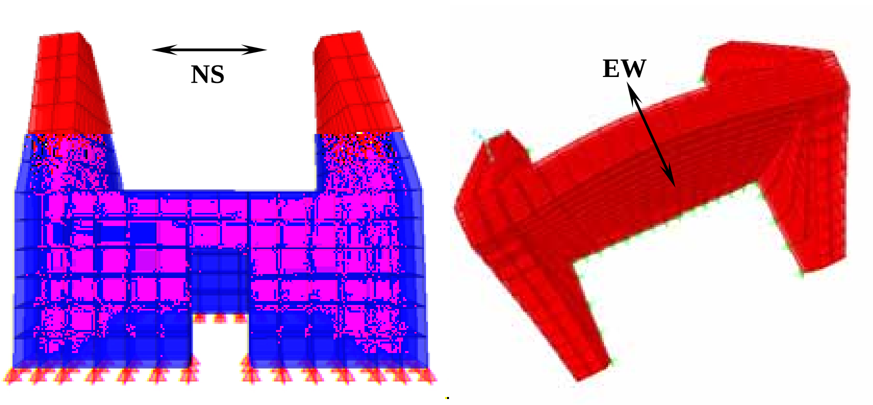


Figure 6: Shape modes of vibration of the selected buildings

The equivalent elastic analysis will not represent the real behavior of the stone structure in case of large earthquakes, since the stone units are working together mainly by friction. However, this analysis will permit to identify the dangerous zones of the structures, since the elastic analysis will give tension stress that in the actual behavior can not be absorbed by the structure, and therefore, this zone of tension stresses could signify the zone where the failure of the structures may start. As illustrative example, the two selected buildings were analyzed to the famous El Centro earthquake motion. Then, a plotting of the stress distribution when maximum stress occurs is shown in Figure 7. It can be observed in Figure 7 (b) that in case of Colca, the gable wall presents concentration of tension stresses at the bottom part of the gable and therefore the overturning of this portion of the structure is probable. In the case of Huayrana, the large dimension of the central restraining wall permits the behavior as a slab that originates tension stresses due to the bending of the wall as id observed in Figure 7 (c).

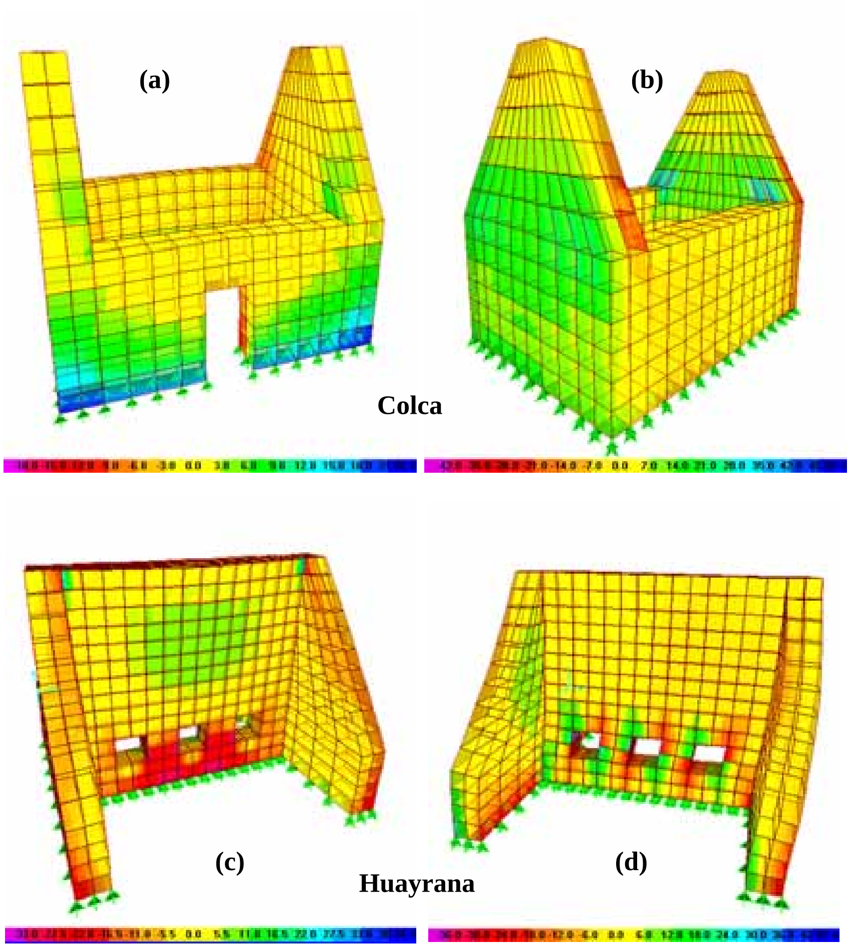


Figure 7: Vertical normal stress distribution for El Centro input motion

4 Conclusions

Microtremor measurements performed in representative stone structures of Machupicchu provided valuable basis for evaluation of the dynamic characteristics of such type of heritage structures.

Using the finite element method for analysis, the equivalent elastic parameters were estimated based on the results of field measurement. Accordingly, it was seen that an equivalent elastic modulus of 0.9 kN/mm^2 could be used for analysis of this type of structures.

Using the equivalent elastic parameters, the probable mode of failure was identified in the selected structures during an earthquake motion. This analysis can be repeated for other structures of Machupicchu where microtremor measurements were not performed. More realistic analysis may be performed by earthquake motions recorded near the site, whenever possible.

These findings are part of the ongoing collaborative research initiative at Akita Prefectural University and more detailed investigations are currently underway.

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