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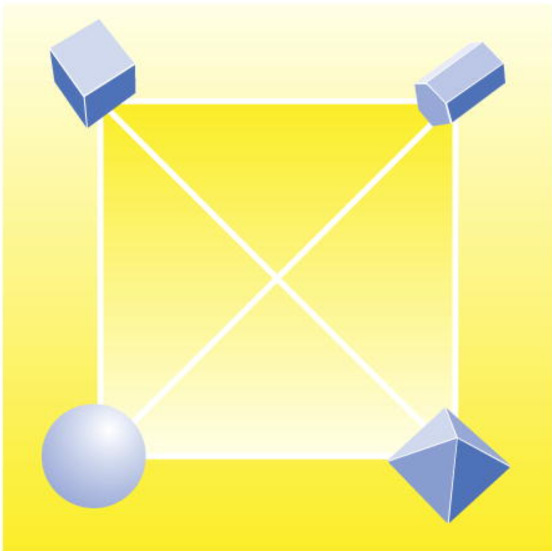

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Earthquake risk to Inca's historical constructions in Machupicchu

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Abstract

The citadel of Machupicchu is probably the most famous Inca heritage site in Peru. Considering the seismically active region, this research is an attempt to perform a seismic risk analysis of the heritage structures at Machupicchu. A systematic approach is adopted for this purpose. Characteristic seismicity of the region, where these historical constructions are located, is discussed based on the seismic hazard analysis. Evaluation of the vulnerability of the structures under the prevalent earthquake hazard is another important aspect essential for risk analysis. As a first step to proper understanding of the seismic behavior of these heritage structures, typical elements of Inca construction are studied by simple analytical models to verify basic aspects of structural integrity. The possibility that peak ground acceleration corresponding to even relatively low hazard may produce instability in some structural components like gable walls was noted. In view of this preliminary result, attempt was made to identify the dynamic characteristics of typical buildings units from more detailed investigation. This forms part of the outcome from the field study program, which included microtremor measurement of free field as well as typical constructions, planned and undertaken by the authors. The results of the microtremor measurements are utilized to estimate the dynamic characteristics of the Inca stone structures. That is, the analytical results are compared with the measurements to calibrate the analytical model. Since microtremor measurements involve very small displacements, the characteristics of stones structures thus obtained correspond to elastic behavior applicable to small strain condition. Based on this scheme, an approach has been proposed to evaluate the seismic behavior and hence the seismic vulnerability of these structures. The procedure also permits identification of the probable mode of failure of the structures concerned.

Keywords: Inca architectural heritage; Seismic hazard; Micro vibration; Finite element method; Fourier analysis

1. Introduction

About 500 years ago, the Inca culture reached the peak in its development, which was just before the arrival of Spaniard conquistadors. By the time, the Incas had integrated a vast empire that stretched from the Maule river in Chile to the northern Ecuador along the western side of the Andes mountain. This territory, as in present days, had been continuously exposed to natural disasters such as excessive rainfalls, earthquakes, landslides and floods. In spite of such impending disasters, the Incas were able to develop techniques of construction to withstand such natural forces. The awe-inspiring cities and road networks that remain intact to this day serve as witness to their acumen in construction.

The structural system of their construction involve various types, including adobe (sun-dried clay bricks), roughly shaped stones laid with mud mortar and finely shaped stones. They also used mud and clay as mortar for surface finishing. Finely shaped stone masonry was used for important building like temples, administrative structures and king's residences. In this type of construction, the adjacent stones are carefully shaped and fit snugly against each other without the use of mortar.

Machupicchu citadel is the most well known of the Inca's archeological sites. It was built before the arrival of the Spanish conquistadors and abandoned after the Inca Empire collapsed by the year 1540 AD. During almost four centuries, this citadel endured and survived under a thick rain forest, until discovered by Hiram Bingham in 1911.

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Now the site is one of the UNESCO world cultural heritage sites in Peru. The reason why Machupicchu endured through the centuries is probably because the Incas used proven technology and a high standard of care in the building process of stone constructions. In this research, an approach involving three basic steps to evaluate the seismic behavior of the stone structures of Machupicchu in a rational manner is proposed. Firstly the seismic hazard of the region involving the Inca territory is undertaken. The selected zone includes the city of Cusco (capital city of the Inca Empire) and the citadel of Machupicchu. The seismic hazard analysis is aimed at estimation of the characteristic seismicity in view of various ancient stone masonry structures located in the region. Then, typical elements of Inca construction are analyzed by a simple method to understand their structural behavior based on the study of their stability under various hazard levels. Finally a series of microtremor measurement is performed to estimate the dynamic characteristics of typical buildings and the ground. The results of microtremor measurements are utilized in calibrating the analytical models utilized to simulate seismic behavior.

2. Seismic hazard of Machupicchu zone

The west coast of South America is well known for its vigorous seismic activity originating mainly from the tectonic interaction between the Nazca plate and the South American Plate. Associated with this tectonic setting, other sources of seismic activity also include several regional or local faults.

The Peruvian Institute of Geophysics (IGP) has published the catalog for historical earthquakes for South America. From this catalog the earthquakes that affect the Peruvian territory are selected and plotted as is shown in Fig. 1a. The IGP catalog contains information about earthquakes from year 1471.

To understand the relative reliability of data from earlier age, the earthquakes corresponding to the Inca era and to the colonial era were separated. Earthquakes from before 1533 are considered to be from the Inca era, while those from 1534 to 1821 are regarded as those of colonial era. Distribution for these earlier earthquakes is shown in Fig. 1b. There are only four earthquakes reported for the Inca era, of which two are located near Lima, the capital city founded by the Spaniards. During the Inca era, the Pachacamac temple of the God of earthquakes, which was one of the venerated Inca Deity, was located near this region. Earthquakes during the colonial era appear to be located around main cities, indicating that earthquakes occurring far away from cities were probably not included in the record. Therefore the distribution of historical record appears biased and not completely representative of the seismic activity of the region during the earlier era. Besides, proper instrumental recording of seismic activity in Peru started only since 1963. Accordingly, only records for the last 20 years, comprising instrumental recording during 1983–2003, are considered for the hazard analysis.

2.1. Source identification

Fig. 2 shows the distribution of selected earthquakes from the IGP catalog that correspond to those obtained by instrumental measurements and with magnitude larger than 4.0. It may be noted that most of the earthquake epicenters are located around the coastline, showing tendency of fewer instances of occurrence in the inland direction. To

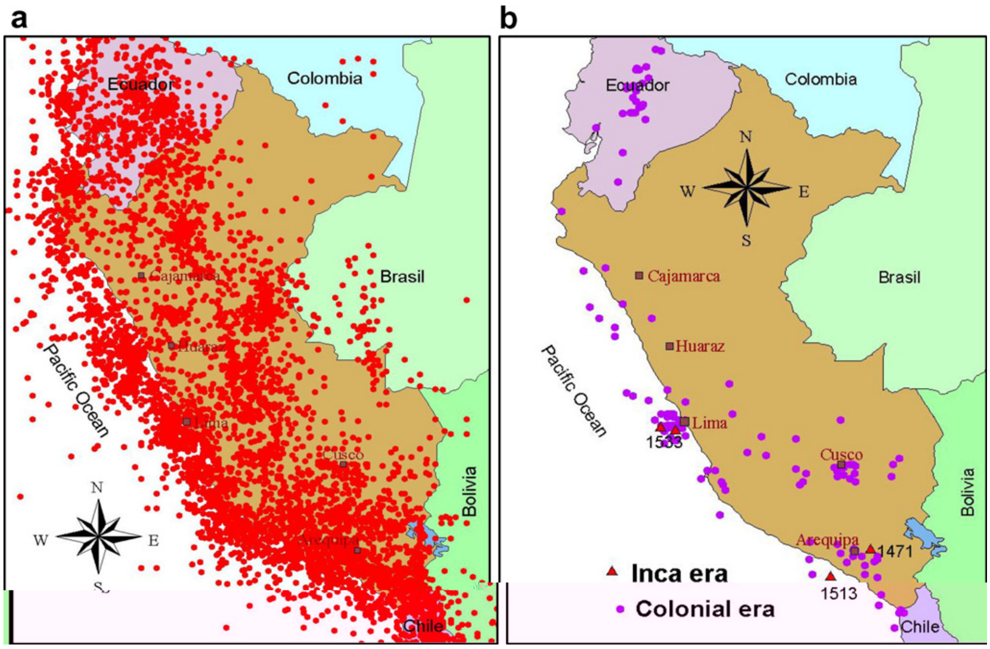

Fig. 1. Epicenter distribution of historical earthquakes: (a) from 1471 to 1982; (b) Colonial era and earlier.

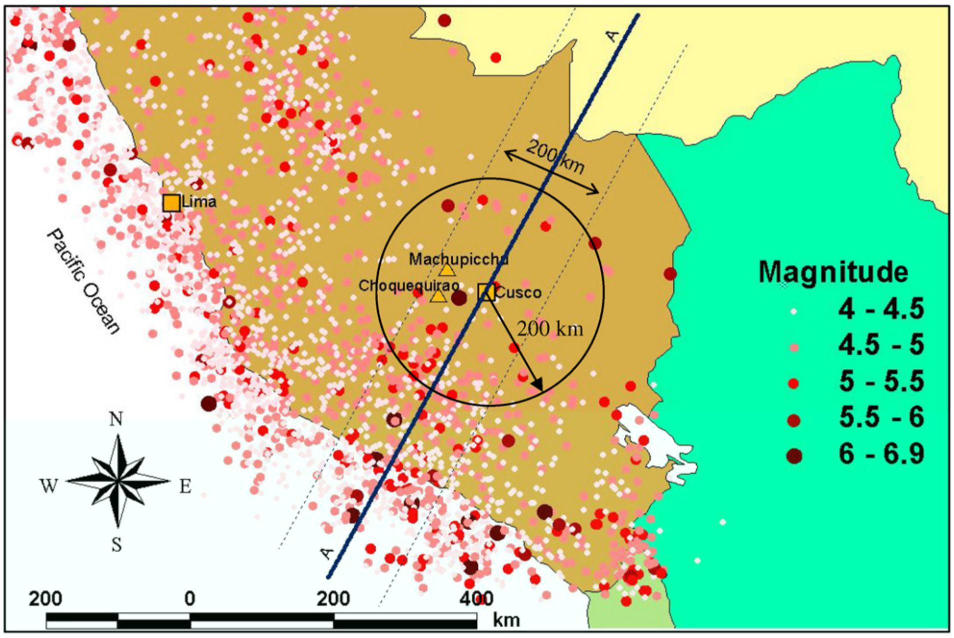

Fig. 2. Earthquake distribution around the zone of study.

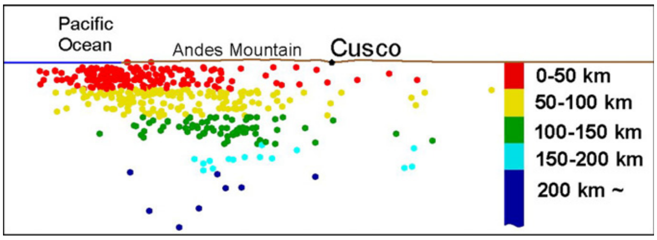

Fig. 3. Earthquake profile.

analyze the vertical profile or distribution in depth of the earthquakes, a 200 km wide zone centering on Cusco city and approximately perpendicular to the coastline was define as shown in Fig. 2. It may be noted that the zone also includes Machupicchu. To understand the mechanism of these earthquakes, the vertical profile of earthquakes within this 200 km wide zone was developed. The profile is shown in Fig. 3. The profile of earthquake hypocenters appears to delineate a fairly clear subduction zone, with shallower earthquakes in the Pacific Ocean coast and deeper ones inland. However, slope of the subduction zone tends to become almost horizontal below the central part of Andes mountain region. The horizontal trend in the shape of subduction zone plate boundary, however, occurs directly below the zone of concern in this study. Naturally, this means shallower depth to subduction zone earthquakes and consequently increased potentiality of local source earthquakes.

2.2. Source recurrence model

To perform the seismic hazard analysis, a circular zone of 200 km in radius with center at Cusco city is considered. That is earthquakes that have epicentral distance smaller that 200 km from Cusco are considered. This circular zone is also indicated in Fig. 2. As was noted from the profile in Fig. 3, two types of earthquake can be distinguished: shallow source earthquakes and deep source earthquakes. The shallow source is regarded here as Source 1, which includes focal depths shallower than 60 km. The deep source is designated as Source 2 and corresponds to earthquakes with focal depths of 60 km or more.

In order to obtain the magnitude–frequency relationship (Guttenberg–Ritcher recurrence curve), earthquakes with a magnitude larger than 4.0 have been considered. This is in consideration of the lower bound with engineering significance, that is, the earthquake magnitude capable of causing damages in the considered structures, in the hazard analysis. The curves for cumulative number of earthquakes larger than a magnitude divided by the interval of 20 years are plotted in Fig. 4.

The *b*-value parameter, that is the slope of the Guttenberg–Ritcher recurrence curve, is used to estimate the probability of magnitude [1]. The recurrence parameters have the relation $\log(\gamma_m) = a - b * m$, where m represent the magnitude. These values are shown in Table 1. The *b*-value for Source 1 is higher than *b*-value for Source 2, implying that the average occurrence of local or shallow earthquakes (Source 1) is less than that of average of deep of subduction type earthquakes (Source 2).

2.3. Attenuation model and hazard curves

Various studies for empirical evaluation of attenuation curve to estimate peak ground acceleration (PGA) or peak ground velocity have been performed by researchers in different parts of the world. These studies are based on data

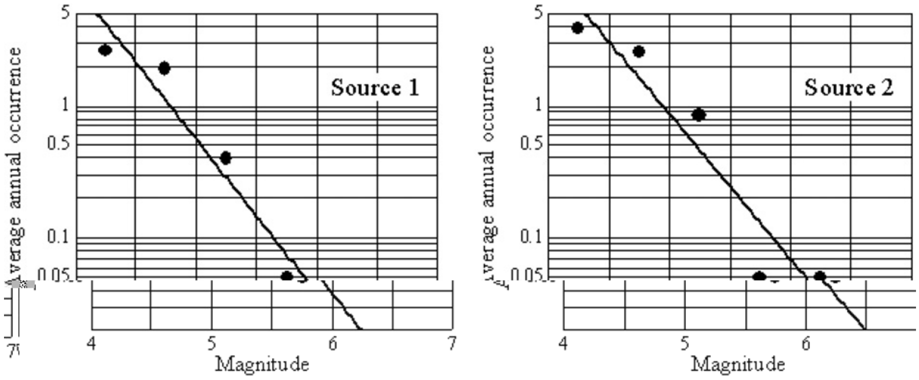

Fig. 4. Magnitude–frequency relationships.

Table 1
Parameters of recurrence

Source	*b*-value	*a*-value
Source 1	1.1649	5.5734
Source 2	1.0961	5.4185

of strong motion records and the proposed attenuation curves are derived by regression analysis. In this investigation, the PGA values are computed based on the relationships proposed by Chang et al. [2] since they attempt to make distinction between shallow crustal earthquakes and deep subduction zone earthquakes corresponding to Source 1 and Source 2 respectively considered in this research.

Based on the parameters of the recurrence model and the attenuation model, the annual hazard curve is estimated considering a large number of possible magnitude and distance combinations [3]. The results of the analysis are shown in Fig. 5. For comparison, the results of the seismic hazard analysis for Lima and Los Angeles [4] are also shown. The hazard curve for the region selected shows lower frequency of exceedance compared to Lima and Los Angeles, the difference being more remarkable for high PGA.

Attempt was also made to undertake the probabilistic seismic hazard analysis in terms of the return period, the result of which can be expressed as the hazard curve shown in Fig. 6. This figure shows PGA for different return period with 10% probability of exceedance. It may be noted that the PGA for 100 year return period is around 0.25 g for the selected region of Inca territory. Again, this value is lower compared with those obtained for Lima and Los Angeles. However, the Inca construction has already been in existence for several hundred years and it would be more logical to consider earthquake actions corresponding to a return period of several hundred years, which cannot be rationally evaluated based on the instrumental record of only about 20 years considered here. Besides, even lower level of acceleration may produce failure in Inca stone structures or in portions thereof. This aspect is discussed further in the next section.

2.4. Local site condition and vulnerability

The PGA levels represented in the probabilistic seismic hazard analysis correspond to the case of rock or hard soil sites. Depending on the nature of local soil condition at specific site, the acceleration may be further amplified,

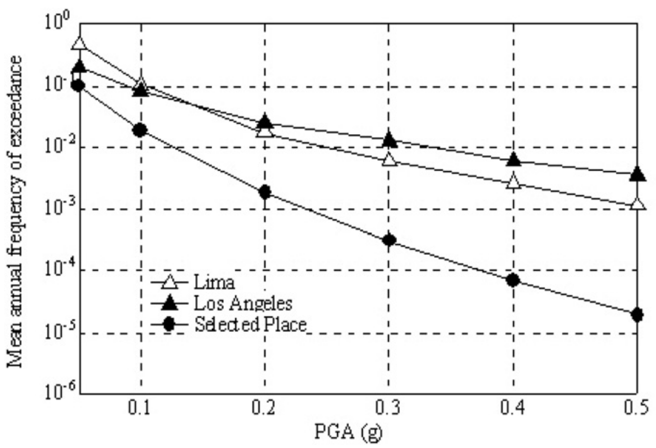

Fig. 5. Hazard curve.

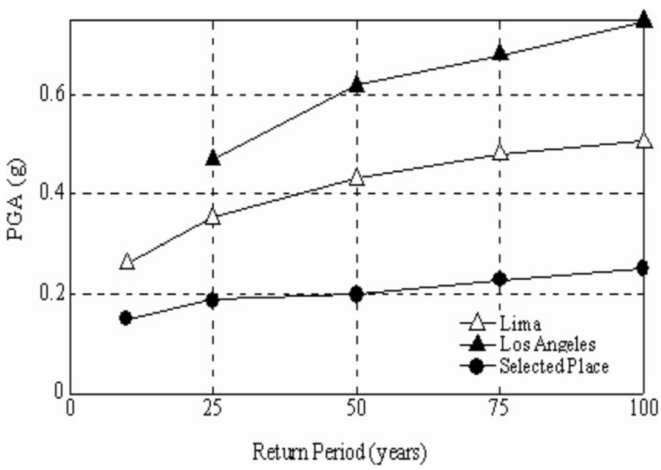

Fig. 6. PGA versus return periods.

resulting in a larger seismic action on structures. Consequently, another important step towards further investigation in future could be to determine the local ground characteristic to estimate the local hazard and to depict it in the form of microzonation. Another related aspect in this process is the need to account for the effect of topographical configuration of the region, which can also produce amplification of incoming earthquake motion.

It should also be noted that lower hazard for the selected Inca territory in comparison with other cities does not necessarily mean that the seismic risk is also lower. This is because the structures targeted in this study may be more vulnerable to comparatively lower level of hazard, resulting in higher risk.

3. Preliminary stability analysis of Inca's structural components

One of the typical structural components Incas used in their construction was what they called "cancha" that grouped single quadrilateral rooms to form a complex for specific purposes. Typical such structural components at the citadel of Machupicchu that may be considered for analysis are encircled in Fig. 7. These structures have rectangular shape in plan. It is assumed that the stone structures support the vertical load appropriately since the granite stone walls have sufficient compression strength. However, for the case of lateral movement during earthquakes, the structural resistance is expected to be mostly determined by the friction over joints or contact surfaces of the dry stone masonry elements.

It was shown by Cuadra et al. [5,6] that these structures can resist the inertial force generated by expected earthquakes. However some elements of these structures may suffer from instability, particularly in gable walls used to support the roof, contributing to potentially high vulnerability. Fig. 8 shows schematic details of the gables walls in zone B shown in Fig. 7. It can be observed that some gable walls remain intact while others have failed partially or completely. The possibility that the failures may have occurred during past earthquakes can not be discounted. When the structures had roofs over them, the gable walls are likely to have been more stable since the roofs provides out-of-plane support. However, if the roofs were not rigid

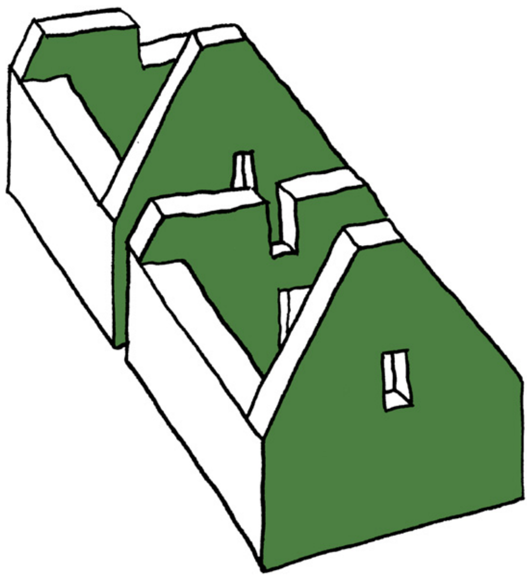

Fig. 8. Detail of gabble wall failure.

Fig. 7. Typical constructions in Machupicchu citadel.

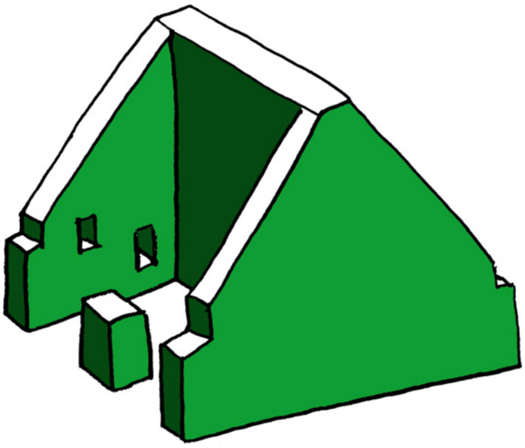

Fig. 9. Restrained gabble walls.

enough, the restraining effect may have been minimum. It is believed that the ancient Inca constructors understood this fact, because alternative way of construction can be observed in the encircled zone C, the details of which can be seen in Fig. 9. In this case a central wall that restrains the gable walls transversally has been used.

The stability of gable wall without restraining is analyzed by considering a lateral inertial force perpendicular to the plane of the wall. As a typical case, the base of the gable wall is taken as 6 m and two cases of height 3 m and 6 m are analyzed. It is assumed that the self-weight produces normal compression stress in the base of the gable wall. Accordingly, the lateral inertial force is considered as acting at the center of mass at one-third the height, producing an overturning moment at the base of the gable wall. If the stress due to the moment becomes larger than the compression stress, it means that tension stresses occur in the wall. However, due to the nature of material used and the way the stone wall is constructed [7], it is clear that

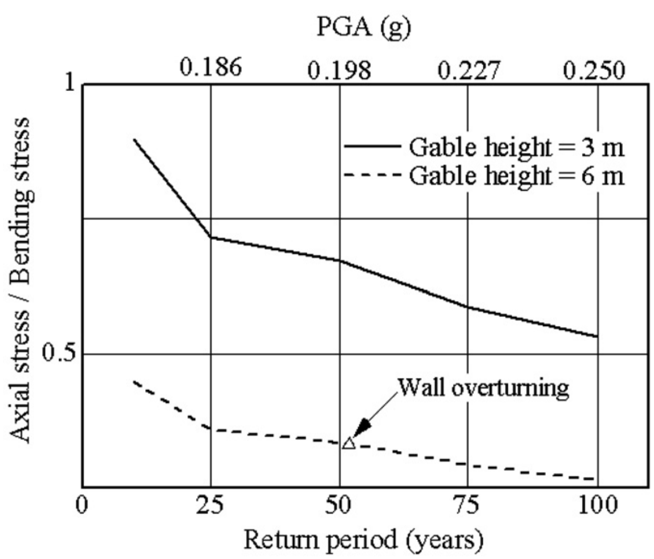

Fig. 10. Stability of stone gable wall under different PGA levels.

the tension stress is inadmissible if failure by tilting or overturning is to be prevented. To estimate the lateral resistance to seismic action, the mass of the wall and PGA corresponding to the seismic hazard analysis are employed. Fig. 10 shows the ratio between normal stress and bending stress versus different return period for various levels of PGA. In both cases the ratio between compression stress and bending stress does not reach 1.0. This means that for PGA levels corresponding to frequent earthquakes, failure might occur even under the action of relatively small earthquakes. If the gabble wall is considered as a rigid body to estimate the overturning failure, by considering the equilibrium of moments due to the horizontal seismic force and due to the vertical weight, it is found that for the gabble wall of 3 m height the overturning may occur for a 0.4 g of input acceleration while for the 6 m height this failure occurs for 0.2 g or earthquakes with 50 years of return period.

4. Microtremor measurements at ‘‘Colca’’ and ‘‘Huayrana’’

A series of microtremor measurements were performed at the citadel of Machupicchu, but only the results of microtremor measurements carried out at ‘‘Colca’’ and ‘‘Huayrana’’ are discussed here. These measurements are utilized for estimation of the dynamic characteristics of these two masonry structures shown in Fig. 11. The Colca is 5 m in width, 7 m in length, and 6.5 m in height from the ground level to the top of gable wall. Similarly, the plan of Huayrana is 7.7 m in width, 8.8 m in length, and 6.5 m in height.

Fig. 12 shows the points (indicated with channel numbers from 7 to 10) where microtremors were measured simultaneously for a duration of 500 s. The natural frequencies of the structures were estimated from the observed transfer functions of microtremors (Fig. 13). These transfer functions were obtained after dividing the corresponding Fourier amplitude spectrum of microtremors measured at various points on the structure by the one at the ground level. The Fig. 13a shows that the values of the predominant frequency in the EW direction of Colca vary from 8 to 12 Hz, while a clear peak at 5.46 Hz is seen for the NS direction in Fig. 13c, which corresponds to the out-of-plane vibration in the triangular gable wall. In case of Huayrana, the central wall restrains the out-of-plane movement of triangular gable walls. However, large amplification factor at around 5.52 Hz corresponding to measurement at top center of the restraining wall in EW direction is seen, probably due to the large dimensions of wall (see transfer function for Ch.7/Ch.10 in Fig. 13b). In case of NS direction, Huayrana shows lower amplification factors at around 8.2 Hz for all measured points (Fig. 13d).

From these observation results, it can be said that the first mode of vibration for Colca corresponds to the vibration of the gable wall in the NS direction with a predominant frequency at 5.46 Hz, and its second mode of vibration corresponds to the vibration of a transversal wall

Fig. 11. Selected buildings for analysis of Inca's stone structures.

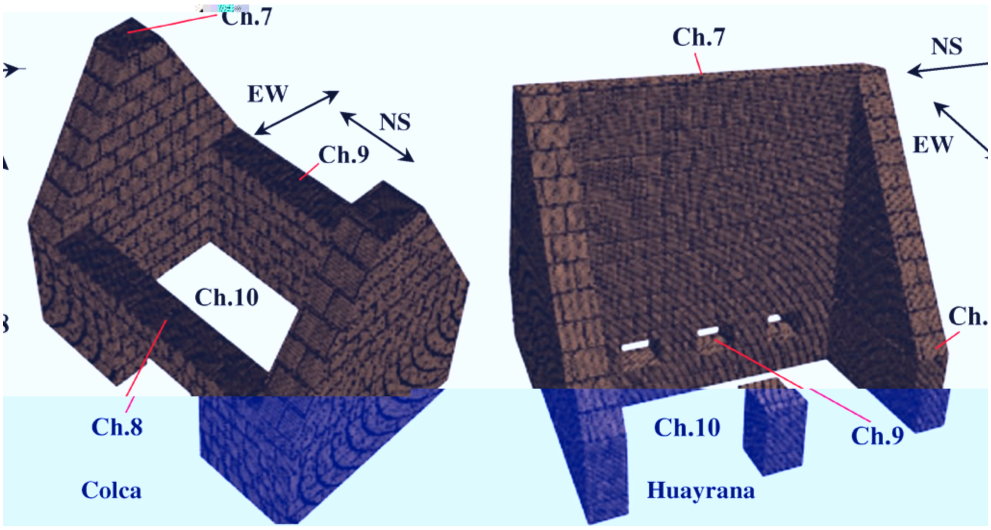

Fig. 12. Location of microtremor sensors at Colca and Huayrana buildings.

in the EW direction with frequency at 11.70 Hz. In case of Huayrana, the first mode of vibration corresponds to the vibration in the EW direction of the central wall at 5.52 Hz, and the second mode corresponds to the vibration of the structure in the NS direction at 8.34 Hz. These observed results are utilized for estimation of modulus of elasticity of the wall material using a three-dimensional continuum model.

5. FEM modeling and estimation of elastic modulus

Since microtremor measurement implies very small displacement responses, it is reasonable to assume that the vibration of the stone masonry structures correspond to elastic linear behavior. Accordingly, a scheme is proposed to estimate the equivalent elastic parameters of the stone masonry in both selected structures based on the dynamic analysis using the finite element method. The Fig. 14 shows the finite element meshes for Colca and Huayrana respectively. These models were developed based on the field measurements and observation carried out by authors. The number of parallelepiped solid elements, used for modeling consist of 704 for the Colca and 928 for the Huayrana. A Poisson ratio of 0.3 and density of 2.65 ton/m^3 are assumed and the inverse analysis is carried out to estimate the equivalent elastic modulus such that the modal frequencies of the models are as close to those obtained from microtremor measurements as possible. The equivalent elastic modulus of 0.863 kN/mm^2 and 0.983 were estimated for Colca and Huayrana, respectively. Fig. 15 shows the first mode of vibration for both structures. It is confirmed by this analysis that the fundamental modes of vibration correspond to the out of plane vibration of gable wall in case of Colca and to the out of plane vibration of the central restraining wall for Huayrana. The fundamental mode vibration frequencies for the elastic modulus obtained compare well with those observed from microtremor measurements, as shown in Table 2. Equivalent elastic modulus of the order of 0.9 kN/mm^2 could be considered realistically for this type of construction.

The equivalent elastic analysis will not represent the real behavior of the stone structure in case of large earthquakes,

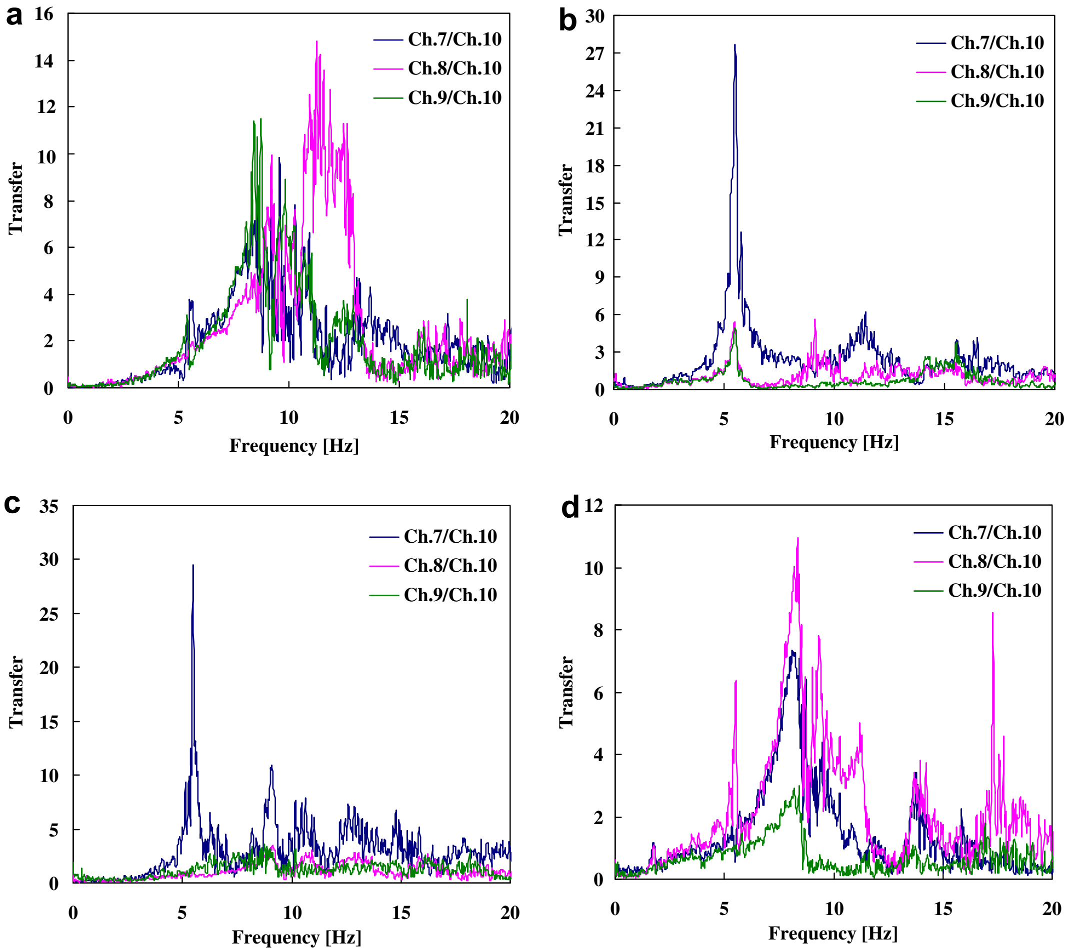

Fig. 13. Horizontal transfer functions from microtremor measurements.

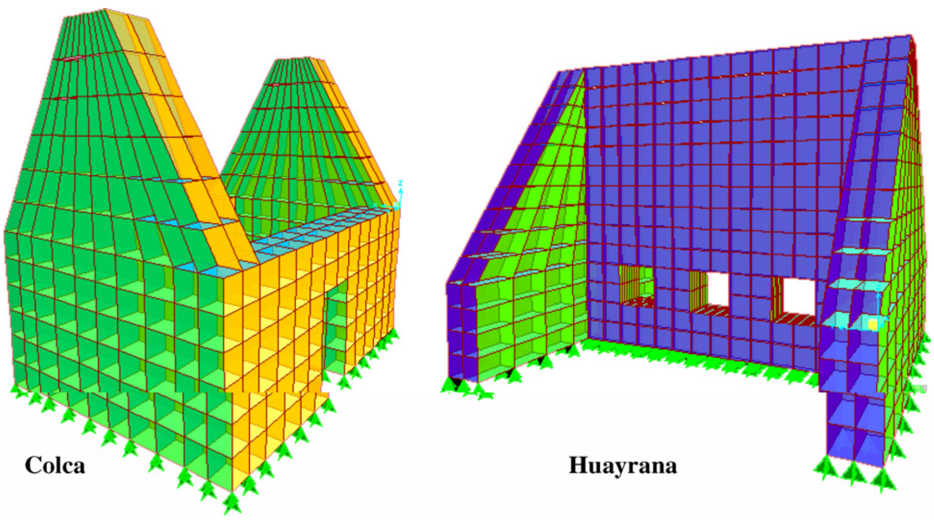

Fig. 14. Finite element model for the selected buildings.

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 can identify zones of tension stress. Since the structural system tends to rely only load transfer by compression, the zone of tension stresses could signify the zone where the failure of the structures may initiate during earthquakes. As an illustrative example, the two selected buildings were analyzed for stresses under the action of well-known El Centro earthquake motion. A plot of the maximum stress distribution is shown in Fig. 16. It can be observed in Fig. 16b that in case of Colca, concentration of tension stresses occurs at

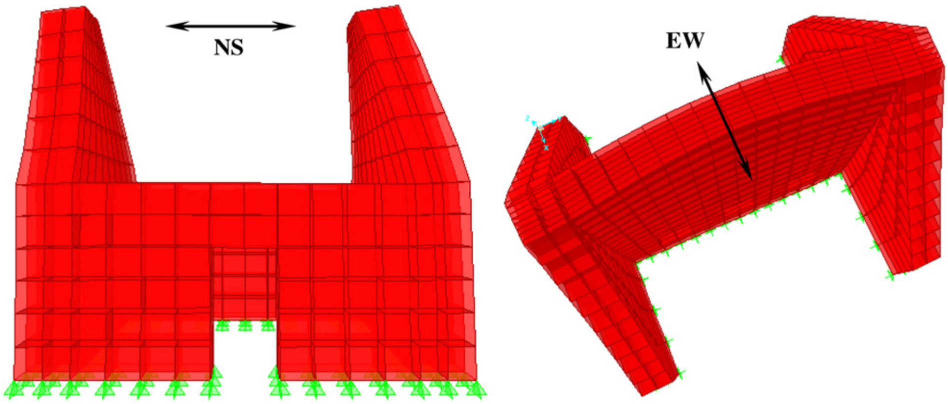

Fig. 15. Shape modes of vibration of the selected buildings.

Table 2
Comparison of frequencies (Hz) from observation and analysis

Vibration mode	Colca		Huayrana	
	Observation	Analysis	Observation	Analysis
Horizontal EW	11.70	11.24	5.52	5.50
Horizontal NS	5.46	5.50	8.34	8.07

the bottom part of the gable wall, indicating that the overturning of this portion of the structure is probable. In the case of Huayrana, the large central restraining wall tends to behave as a slab that develops tension stresses due to the transverse bending of the wall plane as may be observed in Fig. 16c.

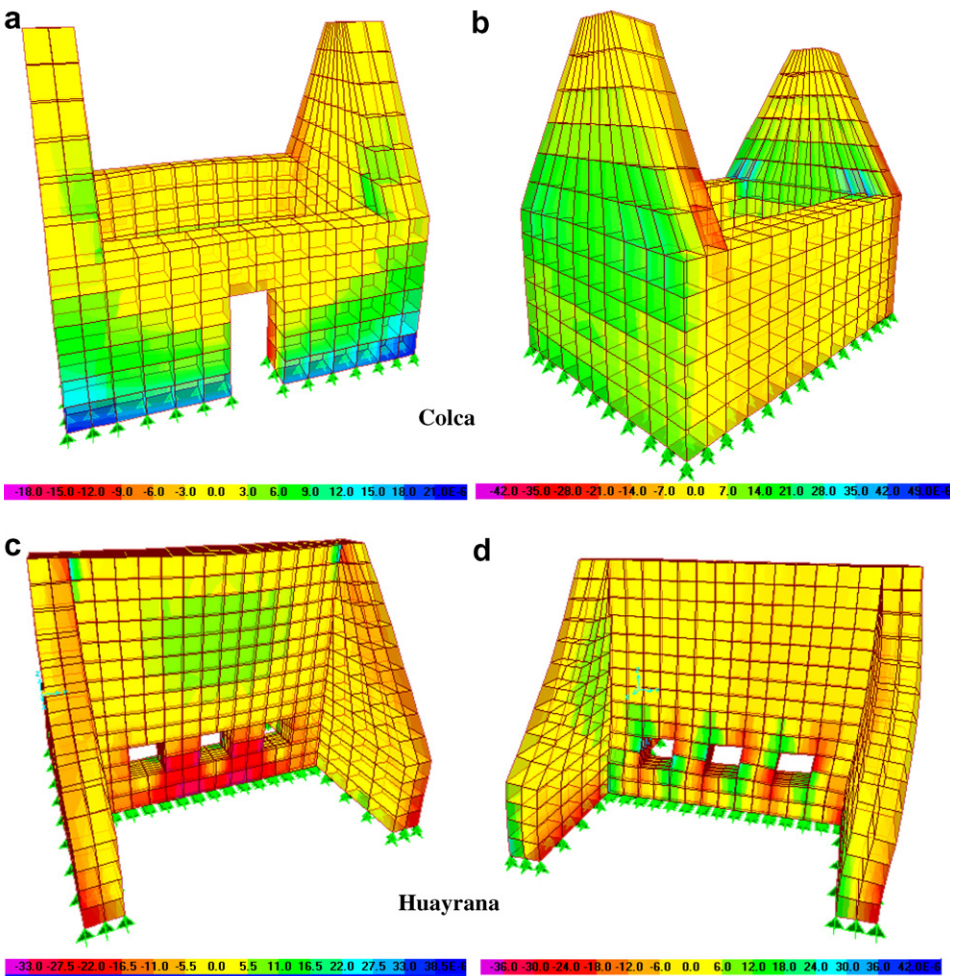

Fig. 16. Vertical normal stress distribution for El Centro input motion.

6. Conclusions

Seismic hazard analysis has been performed for Machupicchu citadel and results show that the seismic hazard is lower in comparison to hazard in cities like Lima and Los Angeles. However, a preliminary analysis of the vulnerability of some components of Inca stone structures shows that the PGA corresponding to this relatively lower hazard may produce failure in these structures, specially in elements like gable walls.

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.

Acknowledgement

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References

[1] Kramer SL. Geotechnical earthquake engineering. New Jersey: Prentice Hall; 1996, 07458.

[2] Chang T, Cotton F, Agelier J. Seismic attenuation and peak ground acceleration in Taiwan. Bull Seismol Soc Am 2001;91(5): 1229–46.

[3] Sunuwar L, Karkee MB, Tokeshi JC, Cuadra C. Applications of GIS in probabilistic seismic hazard analysis of urban areas. In: Fourth international conference on seismology and earthquake engineering, Tehran, I.R. Iran, CD-ROM, Paper No. SM21; May 12–14, 2003.

[4] Thiel C. Earthquake damageability criteria for due diligence investigations. The Struct Des Tall Build 11:233–63.S.

[5] Cuadra C, Karkee MB, Ogawa J, Rojas J. Preliminary investigation of earthquake risk to Inca's architectural heritage. In: Proceedings of the fourth international conference of earthquake resistant engineering structures, Ancona, Italy; 2003. p. 167–76.

[6] Cuadra C, Karkee MB, Ogawa J, Rojas J. An evaluation of earthquake risk to Inca's historical constructions. In: Proceedings of the 13th world conference on earthquake engineering, Vancouver, BC, Canada, CD-ROM Paper No. 150; August 1–6, 2004.

[7] Wright KR, Valencia A. Machu Picchu: A civil engineering marvel. Reston Virginia: American Society of Civil Engineers ASCE Press; 2000.