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AN EVALUATION OF EARTHQUAKE RISK TO INCA'S HISTORICAL CONSTRUCTIONS

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SUMMARY

Seismic hazard analysis is performed for a representative zone in Peru, including the city of Cusco, the citadel of Machupicchu and the archeological complex of Choquequirao, constituting the area with important Inca heritage. This is considered to be the first step towards developing a rational approach to seismic risk analysis of the Inca's architectural heritage. An evaluation of the vulnerability of some typical constructions to prevalent earthquake hazard is performed to evaluate the seismic risk of such heritage structures. As a first step to proper understanding of the behavior of these heritage structures, typical elements of Inca construction are studied by simple analytical model to verify basic aspects of structural integrity. The results indicate that peak ground acceleration corresponding to relatively lower hazard may produce failure in these structures or in some structural components like gable walls.

INTRODUCTION

The Inca culture reached the peak in its development about 500 years ago, 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 continuously been exposed to natural disasters such as excessive rainfalls, earthquakes, landslides, floods, etc. 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 involves the use of adobe (sun-dried clay bricks), roughly shaped stones laid with mud mortar, 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.

The Inca's stone structures have survived earthquakes that have occurred in the region. Attempt is made in this paper to investigate the behavior of typical Inca stone masonry wall component under the action of the earthquakes. For this, firstly the seismic hazard of a representative zone of the Inca territory is undertaken.

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The selected zone includes the city of Cusco (capital city of the Inca empire), the citadel of Machupicchu (the so called lost city of the Incas) and the archeological complex of Choquequirao. Cusco and Machupicchu are UNESCO world cultural heritage sites while Choquequirao is considered as the city where the last Incas taken refuge. The seismic hazard analysis aimed at estimation of the characteristic seismicity in view of various ancient stone masonry structures located in the region. Finally, typical elements of Inca construction are analyzed by simple method to understand the structural behavior. Basically, the investigation here is limited to stability of selected elements under the earthquake action evaluated from hazard analysis.

SEISMIC HAZARD OF THE SELECTED ZONE

The seismic activity of the west coast of South America is originated 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. The IGP catalog contains information of earthquakes from year 1471, however as was shown by Cuadra et al [5], the historical record in not completely representative of the seismic activity during earlier era. Then, for this study, records for the last 20 years, from 1983 to 2003, are considered. These selected earthquakes are instrumentally recorded.

Source identification

Figure 1 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.

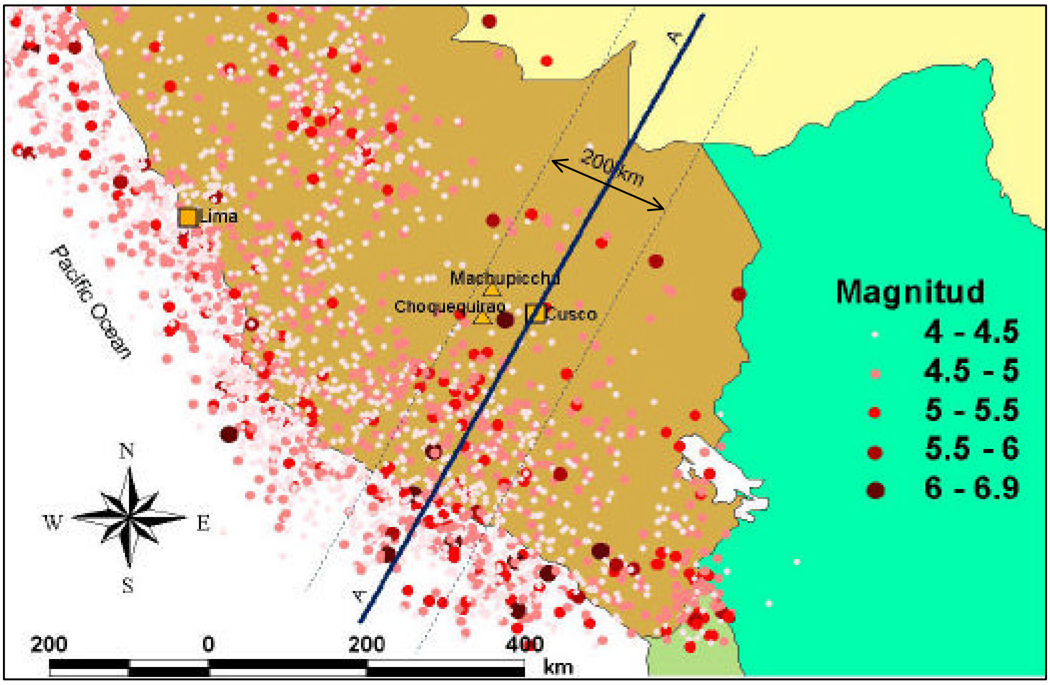


Figure 1. Earthquake distribution around the zone of study

A 200km wide zone centering on Cusco city and approximately perpendicular to the coastline is also shown in Figure 1. It may be noted that the zone also includes Machupicchu and Choquequirao. To understand the mechanism of these earthquakes, the vertical profile of earthquakes within this 200km wide zone was developed. The profile is shown in Figure 2. 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.

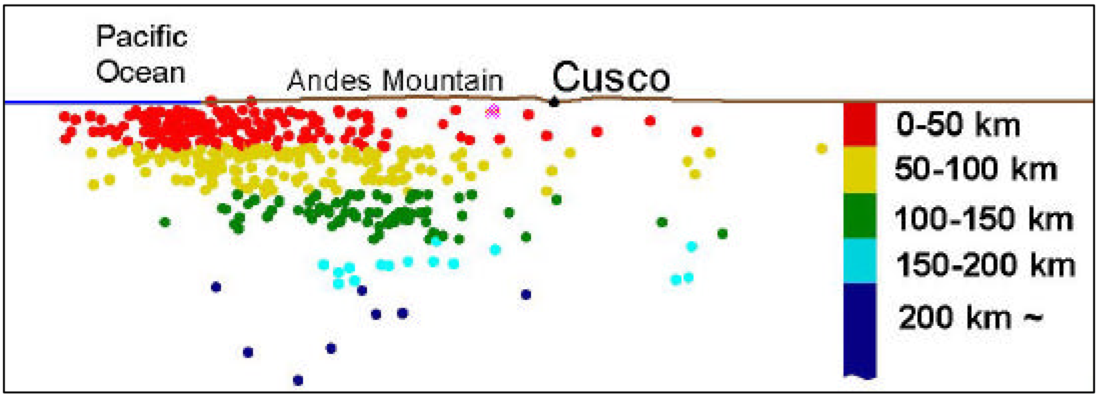


Figure 2. Earthquake Profile

Source Recurrence Model

To perform the seismic hazard analysis, the center of the triangle formed by Cusco, Machupicchu and Choquequirao is taken as the central point. Earthquakes that have epicentral distance smaller that 200 km from the mentioned center were considered. As was noted from the profile in Figure 2, two types of earthquake can be distinguished: shallow source earthquakes and deep source earthquakes. The shallow source is denominated here as Source 1, including focal depths shallower than 60 km. The deep source is called 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 used. This is in consideration of the lower boundary with engineering significance, that is the minimum earthquake capable of producing 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 Figure 3.

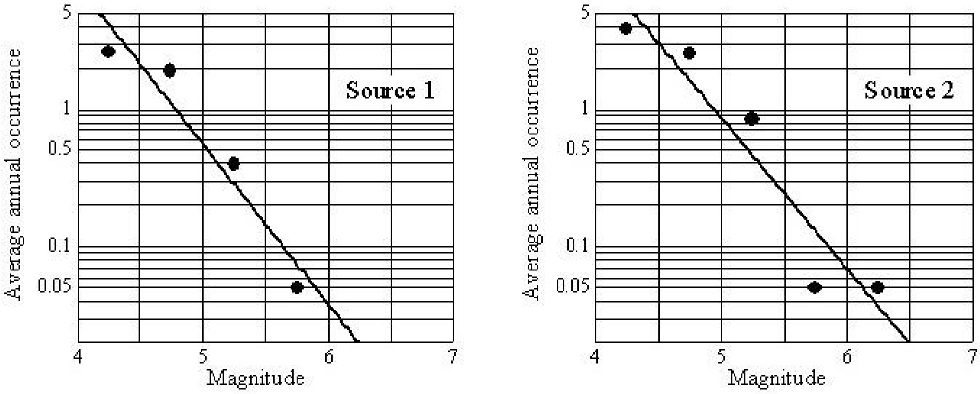


Figure 3. Magnitude-frequency relationships

The b-value parameter, that is the slope of the Guttenberg-Ritcher recurrence curve, is used to estimate the probability of magnitude (Kramer [1]). The recurrence parameters have the relation $\log(\lambda_m) = a\text{-}bm$, where m represent the magnitude. These values are shown in Table 1.

Table 1: Parameters of recurrence

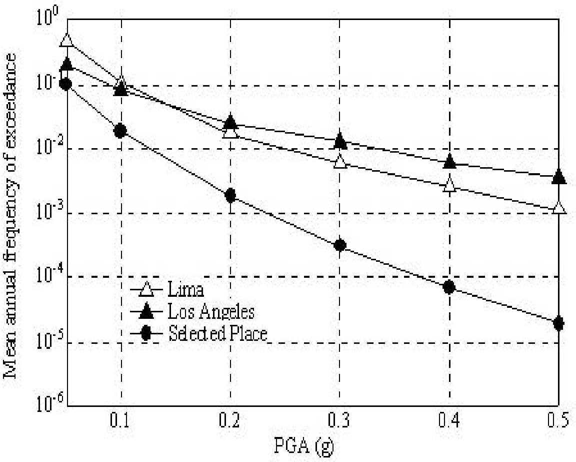
Source	b-value	a-value
Source 1	1.1649	5.5734
Source 2	1.0961	5.4185

Attenuation model and hazard curves

Researchers have performed many studies for empirical evaluation of attenuation curve to estimate peak ground acceleration (PGA) or peak ground velocity. These studies are based on data obtained from strong motion records and the attenuation curves have been derived by regression analysis. Here, PGA values are computed with the relationships proposed by Chang et al [2]. These relationships were chosen since they distinguish shallow crustal earthquakes and deep subduction zone earthquakes that is the case of present research for Source1 and Source 2 respectively.

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 (Sunuwar et al [4]). The results of the analysis is shown in Figure 4. For comparison the results of the seismic hazard analysis for Lima city and Los Angeles city are included. The hazard curve for Los Angeles is taken from Thiel [3]. The hazard curve for the selected place shows lower frequency of exceedance compared with Lima and Los Angeles, the difference being more remarkable for high PGA.

Considering the results of the probabilistic seismic hazard analysis in terms of the return period, the hazard curve can be expressed as is shown in Figure 5. 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 0.25g for the selected zone. 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 over 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 presented in the next section.



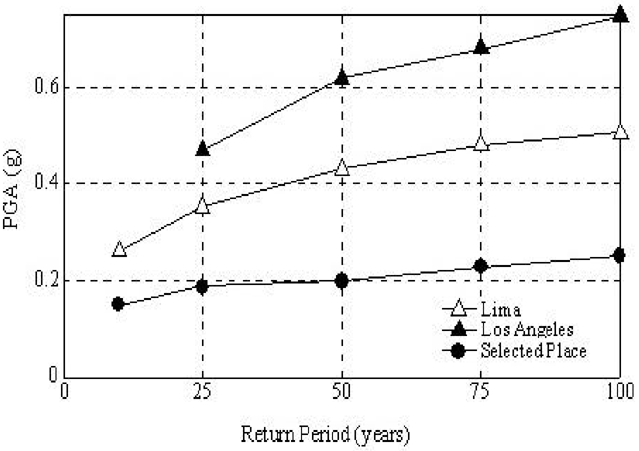


Figure 4. Hazard curve

Figure 5. PGA versus return periods

Local site condition and vulnerability

The PGA levels represented in the probabilistic seismic hazard analysis correspond to the case of rock or hard soil. According to the nature of local soil condition at specific site, this acceleration may be further amplified, resulting in a larger seismic action on structures. Consequently, another important step towards further investigation in the near future is 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 place 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 a higher risk.

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. A typical case that corresponds to the citadel of Machupicchu is taken for the analysis. The shape of this structural component that were taken for analysis are shown encircled in Figure 6. These structures have rectangular shape in plan. It is considered that the stone structure supports the vertical load appropriately since the granite stones have sufficient compression strength. However, for the case of lateral load produced by earthquakes,

the resistance of the structure is mostly determined by the friction between joints or contact surfaces of the stone wall elements.

Figure 6. Typical constructions in Machupicchu citadel

It was shown by Cuadra et al [5] that these structures can resist the inertial force generated by expected earthquakes. However some elements of these structures may present some instability, in special the gable walls that are used to shape the roof of the structure. Typical examples of such walls are encircled in Figure 6. These walls must be considered since they may contribute to potentially high vulnerability. Figure 7 shows a detail of the gables walls encircled in zone B of Fig 6. It can be observed that some gable walls remains complete while other have failed partially or completely. Probably the failure have occurred during past earthquakes. When the structure has its roof, the gable walls are more stable since the roof provide them out-of-plane support. However if the roof is not rigid enough the restraining effect is minimum. It is believed that this fact was known by the ancient constructors since alternative way of construction is observed in the encircled zone C, which detail is presented in Figure 8. In this case a central wall that restrains transversally the gable walls is used. This type of construction is observed also in the main constructions of the archeological complex of Choquequirao.

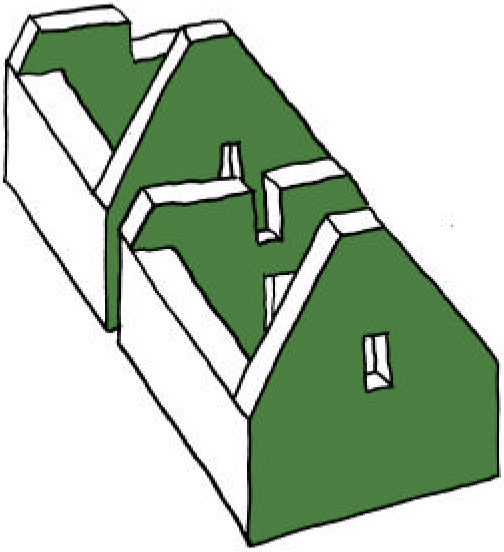


Figure 7. Detail of gabble wall failure

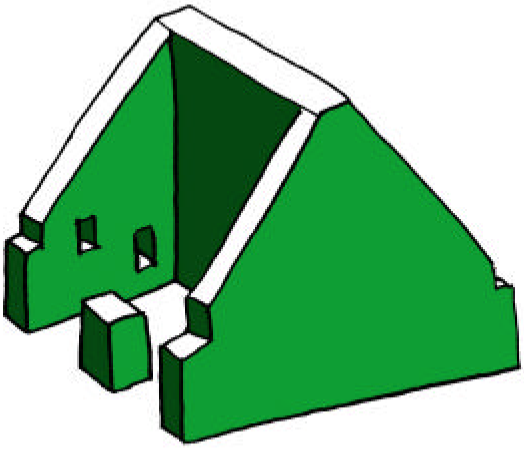
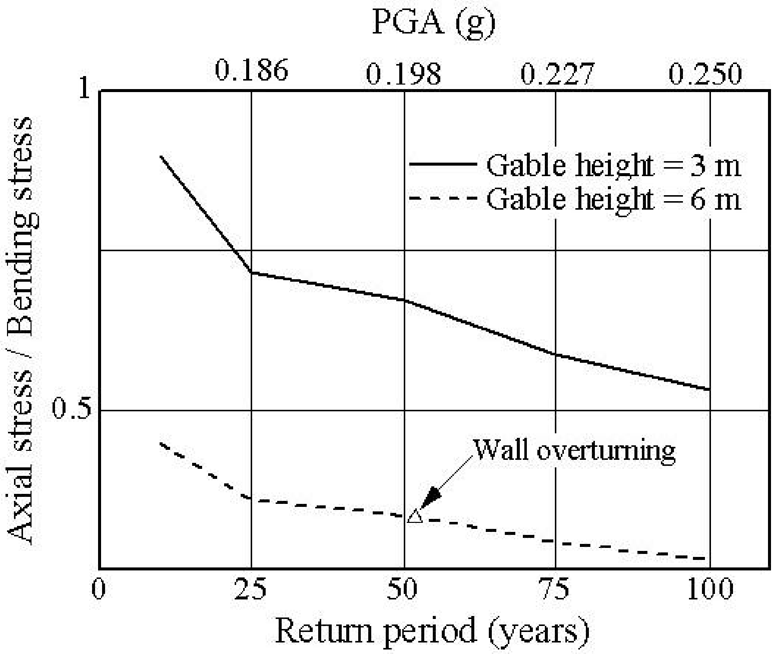


Figure 8. Restrained gabble walls

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 6m and two cases of height 3m and 6m are considered. It is assumed that the self-weight produces normal compression stress in the base of the gable wall. Then the lateral inertial force is considered as acting at the center of mass at one-third the height, such that this load produces 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, it is clear that the tension stress is inadmissible to prevent failure by tilting or overturning. To estimate the lateral resistance to seismic action, the mass of the wall and PGA corresponding to the seismic hazard analysis are employed. Figure 9 shows the ratio between normal stress and bending stress versus different return period for various levels of PGA. In both cases the ratio between axial 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 0.4g of input acceleration while for the 6 m height this failure occurs for 0.2g.

Figure 9: Stability of stone gable wall under different PGA levels

CONCLUSIONS

Seismic hazard analysis has been performed for the zone of Peru where Cusco, Machupicchu and Choquequirao, consisting of valuable Incas cultural heritage structure sites, are located. It appears that the actual seismic hazard for the zone may be lower when compared to the hazard in cities like Lima and Los Angeles. However, results of the preliminary analysis of some components of Inca stone structures to investigate their vulnerability indicates that the integrity of valuable heritage structures may be severely affected even under the PGA corresponding to this relatively lower hazard. It may be particularly so in case of structural elements like gable walls. 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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