Seismic Vulnerability of Santo Domingo Church, Cusco, Peru

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SUMMARY:
During the Inca's empire a complex of temples namely Coricancha was constructed in Cusco city which was dedicated primarily to Inti, the Sun god. At present, a small part of the Inca stonework is all that remains of the ancient complex. Most of the complex was demolished by Spaniard conquistadors in the 17th century to make way for the construction of Catholic Church of Santo Domingo on this site, using part of the Inca construction as the foundation. This complex is a fine example of how Inca stonework had been incorporated into the structure of a colonial building. The church has suffered the action of past earthquakes that destroyed its tower and this tower has been reconstructed always in its original shape. In this place, a series of ambient vibration measurements were carried out to estimate the dynamic characteristics of the structure and the ground. In this paper, the results of the measurements and corresponding interpretations are discussed. In addition, finite element method is used to formulate analytical model in order to verify the dynamic characteristics of the building. It was found that the predominant period of vibration of the church tower is comparable to the predominant period of the ground, and therefore, the tower appears to be more vulnerable to earthquake occurrence due to possible resonance phenomenon to be expected.

Keywords: Stone structures, Fourier analysis, Ambient vibration measurements, Seismic vulnerability

1. INTRODUCTION

Before the arrival of the Spaniard Conquistadors around the year 1535, the Inca culture reached the peak in its development, integrating a vast empire that stretched from the Maule river, in Chile to the northern Ecuador, along the western side of the Andes mountain range. 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 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. The Coricancha temple is the most representative structure of the finest stone masonry of the Incas. At present, a small part of the Inca stonework is all that remains of the ancient complex. Most of the complex was demolished by Spaniard conquistadors in the 17th century to make way for the construction of Catholic Church of Santo Domingo on this site, using part of the Inca construction as foundation. The church has suffered the action of past earthquakes that destroyed its tower and this tower has been reconstructed always in its original shape. In this place, a series of ambient vibration measurements were carried out to estimate the dynamic characteristics of the structure and the ground.

The results of the measurements and corresponding interpretations are discussed, and then finite element method is used to formulate analytical model in order to verify the dynamic characteristics of the building. It was found that the predominant period of vibration of the church tower is comparable to the predominant period of the ground, and therefore, the tower appears to be more vulnerable to earthquake occurrence due to possible resonance phenomenon to be expected.

2. DESCRIPTION OF SANTO DOMINGO CHURCH

It is believed that the original complex of Inca temples was dedicated to Inti, the sun god, and was formed by a group of constructions located around a central square, as can be observed in Figure 1, which is a view of a scale model. Each building was dedicated to one god respectively. The name of the god corresponding to each temple is indicated in Figure 1. These gods were Inti (sun), Killa (moon), Chasca (stars), Illapa (thunder, rainbow). Also, it is thought that the Incas believed in a creator god, called Wiracocha.

The Coricancha complex was built on a natural hill and between the rivers Shapy-Huatanay and Tullumayo. Its construction was ordered by the Inca Wiracocha around the year 1200 A.D., and later it was embellished or decorated during the reign of the Inca Pachacutec. The architectural distribution of the temples was done inside of a space that was circled by high walls. The shapes of the walls are trapezoidal and have a vertical inclination which is typical of the Inca's architecture. The stones used in this complex were extracted from the quarries Waqoto and Rumicolca that are located 20 to 30 km away from Cusco city. The stones used by the Incas were plutonic diorite rocks and calcareous rocks. According to the chroniclers the walls of the temples were covered with gold plates and on these plates there were a drawing of the corresponding god.

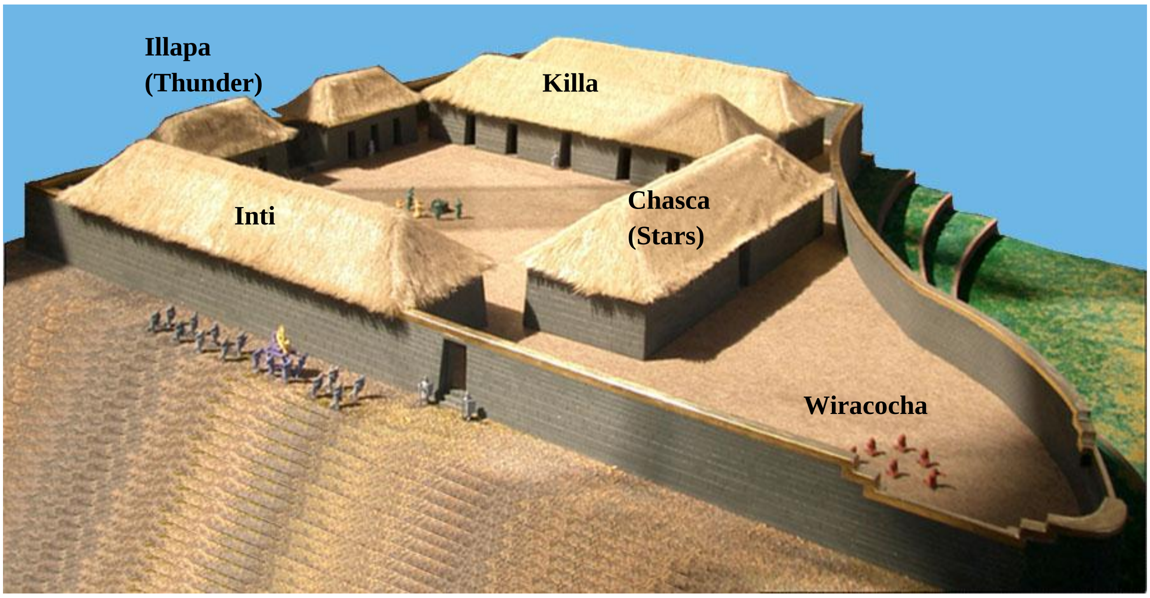

Figure 1. Scale model of the Coricancha complex

In the 16th century, the Christian Catholic Church was built over the Inca stone structure. For the construction of the church, the Spaniards destroyed some part of the temples that formed the complex and some parts were used as a foundation of the Catholic Church. In this way, the Inca stone structure was incorporated to the colonial construction resulting in a magnificent monument that shows a mixture of Spanish and Inca culture. The Figure 2 shows the plan view of the current building, where the black part represents the remaining Inca's walls and the gray part represents the colonial construction. The Santo Domingo Church is located at the upper part of the Figure and it can be appreciated that was constructed on the Inca base.

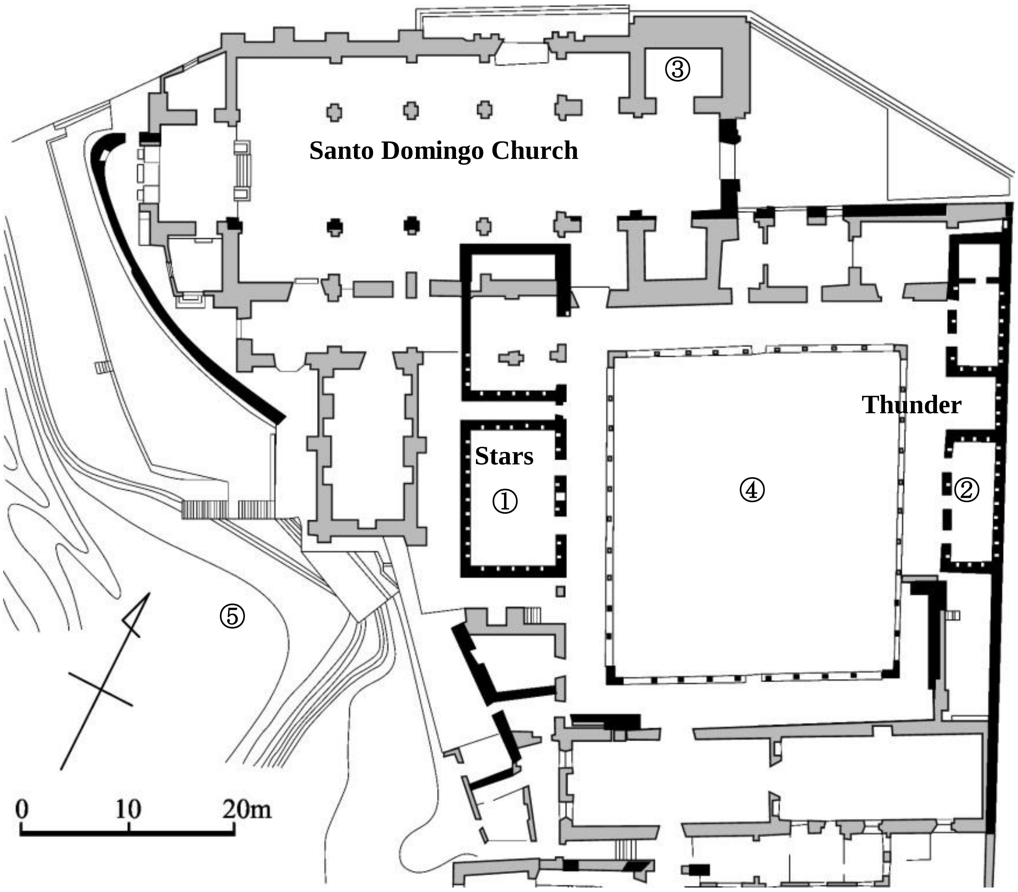

Figure 2: Location of Santo Domingo Church inside the Coricancha complex

3. AMBIENT VIBRATION MEASUREMENTS

A series of ambient vibration measurements were carried out in the complex that includes the Santo Domingo Church. The stars and the thunder temples, the tower of the colonial church and the inner at outer yards were selected for these measurements. These locations are indicted by encircled numbers in Figure 2. The meaning of the numbering and the purpose of the measurements are described as follows.

① Star Temple (Chasca): Structure Vibration. Measurements of horizontal vibrations in the two principal directions of the building were performed. The sensors were located on the floor level and at walls on all four sides. The sensors at the wall were located on the sill of rectangular offset on the inner wall face closest to center of the wall. The directions were designated NS and EW respectively. However, the actual directions are Northeast-Southwest (NS) and Northwest-Southeast (EW).

② Temple of Thunder (Illapa): Structure Vibration. In a similar manner to the temple of the stars, measurements of horizontal vibrations in the two principal directions of the building were performed. The sensors were located on the floor level and on walls on four sides. The sensors at the wall were located on the sill of rectangular offset on the inner wall face closest to center of the wall. Again, the directions were designated NS and EW, respectively.

③Tower of Santo Domingo Church (Figure 4): Structure Vibration. Three component of vibration were measured at the top and bottom of the tower. The directions for measurements are indicated in Figure 3.

④ Interior Yard (Ceremonial Fountain): Ground vibration measurement. At this site, array measurements of the vertical components of the ground vibration were carried out. The triangular array configuration of sensors on the yard consisted of approximately 25 meter sides triangles. The array measurement is intended for F-K spectral analysis (F: frequency, K: wave number) to obtain the Rayleigh wave dispersion curve, from which the shear wave velocity profile of the ground may be estimated by inverse analysis.

⑤ Exterior Garden (Sacred Garden of Sun): Ground vibration measurement. In a similar manner to the interior yard, array measurements of the vertical components of the ground vibration were carried out here. The configuration of sensors again consisted of triangular array with sides of approximately 30 meters. As noted above, array measurement is intended for F-K spectral analysis.

Figure 3: Tower of the Santo Domingo Church

4. ANALYSIS OF DATA

The analysis is focused on the behavior of the tower of the church since this portion of the structure is the most vulnerable part of the structure during earthquake as was observed during the earthquake that hits Cusco city in the year 1950.

Figure 4 presents the results of the Fourier analysis for the horizontal vibration of the Colonial tower. These directions NS and EW are indicated in Figure 4. The Fourier amplitude spectrum obtained at the top of the tower was divided by the one obtained at the ground level, to obtain only the vibration characteristics of the structure. It can be observed that the value of the predominant frequency in the EW direction is 2.7 Hz, and in the NS direction is 3.3 Hz.

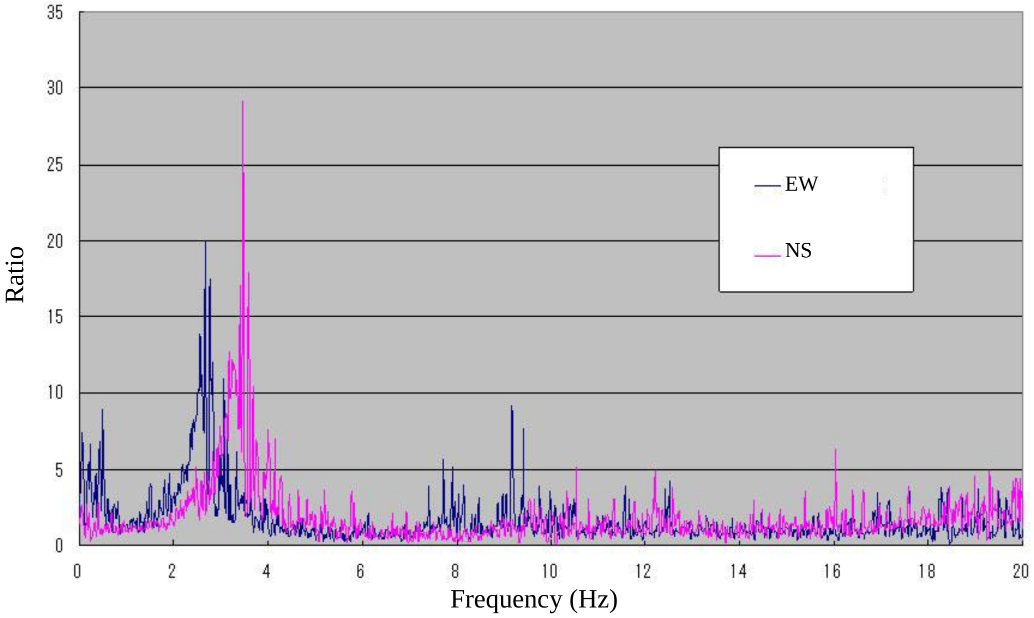

Figure 4. Fourier analysis results for the tower of Santo Domingo Church

Figure 5 presents the dispersion curve obtained from the FK analysis. This result permits to estimate the predominant frequency of the ground as 2.7 Hz. Then, if the result is compared with that obtained for the tower of the Colonial Church, it can be observed that the frequency of the structure and soil are similar, and therefore, the resonance phenomenon is expected to occur. This coincidence of the predominant frequencies could be the explanation of the repeatedly failure of the tower during past earthquakes.

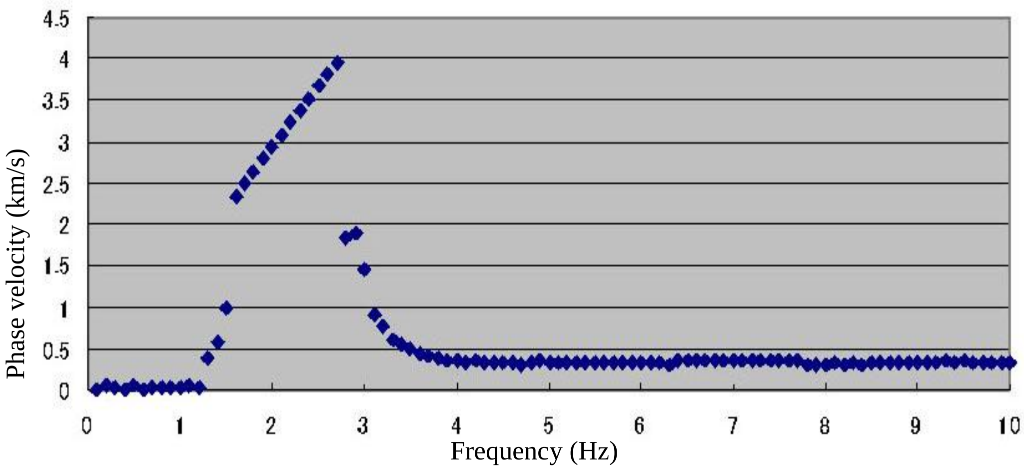

Figure 5. Rayleigh wave dispersion curve for Coricancha ground site

5. FINITE ELEMENT MODEL

To compare the characteristics obtained from ambient vibration measurements with analytical results, finite element method is employed to formulate the analytical model. The FEM model was constructed based on available data and based on direct measurements of the dimension of the building. As can be observed in Figure 6, the general shape of the Santo Domingo Church is reproduced in the model where only main openings (main door and windows of the tower) are considered. The columns and arches are modeled by means of frames, the walls are modeled by plate elements and the floors and roofs by are modeled by shell elements.

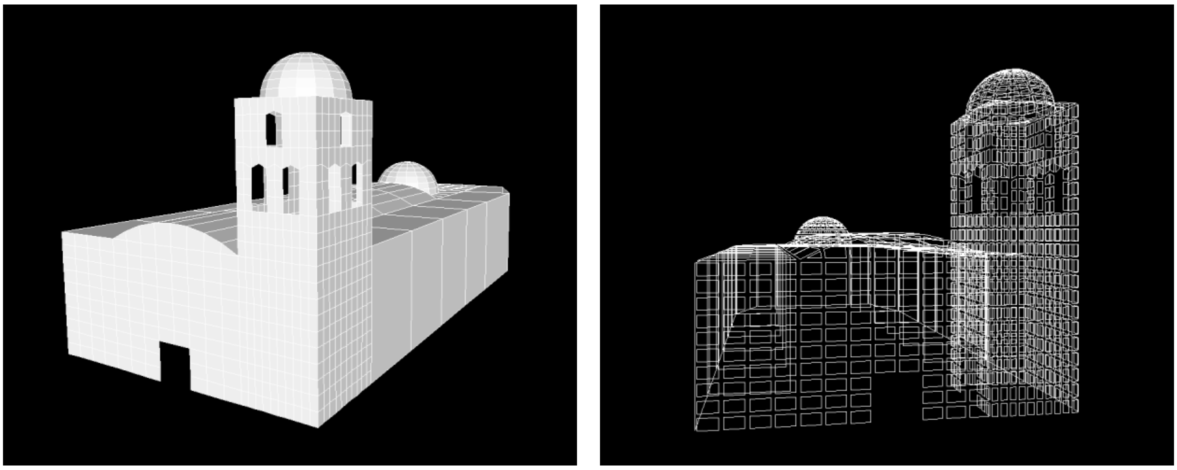

Figure 6. Finite element model of Santo Domingo Church

The material of construction is stone masonry and it is assumed that the mechanical properties of the masonry are dominated by the property of the mortar. The visual inspection of the walls and tower structure has shown that lime mortar has been used to lay down the stone blocks. Therefore low value of 0.5 Gpa is assumed as equivalent elastic modulus.

Modal analysis using the finite element method gives as a result that the first mode of vibration corresponds to normal mode in the EW direction (or in the longitudinal direction of the church) with a frequency of 3.66 Hz. The second mode corresponds to the vibration in the transversal direction with a frequency of 3.69 Hz. These modes of vibration are show in Figure 7 where the gray shadow indicates the undeformed shape of the church.

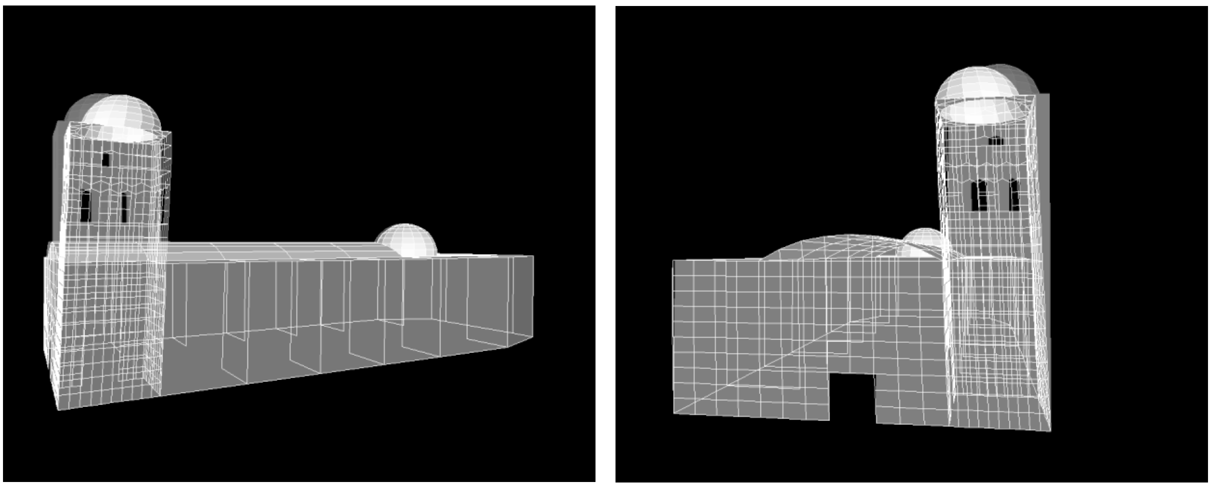

Figure 7. Modes of vibration of Santo Domingo Church

6. CONCLUSIONS

Ambient vibration measurements performed in the Santo Domingo Church have provided the basis for evaluation of the dynamic characteristics Colonial stone masonry structure. The measurement was focused on the behavior of the tower since it is the more vulnerable part of the building during earthquakes.

It was found that the predominant period of vibration of the church tower is comparable to the predominant period of the ground, and therefore the tower appears to be more vulnerable in case of earthquake occurrence because of the possible resonance phenomenon to be expected.

REFERENCES

C. Cuadra、 C. Zavala、A. Abe、T. Saito、S. Sugano；Vibration characteristics of traditional adobe-quincha buildings located at Lima historic centre、*8CUEE CONFERENCE PROCEEDINGS*、*8th International Conference on Urban Earthquake Engineering*、March 7-8、2011、Tokyo Institute of Technology、Tokyo、Japan。

C. Cuadra, Vulnerability of Machu Picchu citadel 100 years after its scientific discovery, *12th International Conference on Structural Studies, Repairs and Maintenance of Heritage Architecture*, STREMAH XII, Chianciano Terme, Italy, Sep. 2011

C. H. Cuadra, T. Saito, C. A. Zavala, and M. A. Diaz, The challenges of protect historical adobe constructions in Peru, *14th European Conference on Earthquake Engineering* (14ECEE), Ohrid, Macedonia August 30 – September 3, 2010. Paper Number: 392.

K. Sugiyama, C. H. Cuadra, and Y. Fujiwara, Characteristics of peak acceleration and attenuation during the 2008 Iwate-Miyagi earthquake, *14th European Conference on Earthquake Engineering* (14ECEE), Ohrid, Macedonia August 30 – September 3, 2010. Paper Number: 385.

C. H. Cuadra, Structural damages evaluation of a group of historical buildings in Machupicchu, *14th European Conference on Earthquake Engineering* (14ECEE), Ohrid, Macedonia August 30 – September 3, 2010. Paper Number: 506.

N. Igarashi, C. H. Cuadra, and S. Oshikiri, Dynamic properties of traditional wooden temples located in Yurihonjo city, Japan, *14th European Conference on Earthquake Engineering* (14ECEE), Ohrid, Macedonia August 30 – September 3, 2010. Paper Number: 392.

C. Cuadra, M.B. Karkee, J. Ogawa, and J. Rojas. An evaluation of earthquake risk to Inca's historical constructions. *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, August 1-6, 2004, CD-ROM Paper No. 150.

Sudhir R. Shrestha, Madan B. Karkee, Carlos H. Cuadra, Juan C. Tokeshi and S. N. Miller. Preliminary study for evaluation of earthquake risk to the historical structures in Kathmandu valley (Nepal). *Proceedings of the 13th World Conference on Earthquake Engineering,* Vancouver, B.C., Canada, August 1-6, 2004, CD-ROM Paper No. 172.

J. Ogawa, C. Cuadra, M.B. Karkee, and J. Rojas. A study on seismic vulnerability of Inca's constructions. *Proceedings of the 4th International Conference on Computer Simulation in Risk Analysis and Hazard Mitigation. Risk Analysis IV*, Rhodes, Greece 2004, pp 3-12.

C. Cuadra, M.B. Karkee, J. Ogawa, and J. Rojas. Preliminary investigation of earthquake risk to Inca's architectural heritage. *Proceedings of the Fourth International Conference of Earthquake Resistant Engineering Structures,* Ancona, Italy 2003, pp. 167-176.

S. L. Dimova. Modeling of collision in sliding systems subjected to dynamic excitations. *Proceedings of the Fourth European Conference on Structural Dynamics EURODYN99,* Prague, Czech Republic, 1999, Vol. I, pp. 175-179.

K. R. Wright and A. Valencia. *Machu Picchu: A Civil Engineering Marvel*. American Society of Civil Engineers ASCE PRESS, Reston Virginia, 2000.

Sunuwar, L., Karkee, M., Tokeshi, J., and Cuadra, C. Applications of GIS in Probabilistic Seismic Hazard Analysis of Urban Areas. *Proc. Of the Fourth International Conference of Earthquake Engineering and Seismology,* Tehran, Iran, 2003.