Geotechnical engineering in the Americas before Columbus

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ABSTRACT
A course called "Engineering in the Americas before Columbus" was developed in the Swanson College of Engineering at the University of Pittsburgh to introduce undergraduate students to the civil engineering methods employed by the Incas of Peru in the design and construction of their civil engineering structures that have remained stable in the face of time and natural hazards. The sites visited in Peru included Cuzco, Machu Picchu, Pisac, Moray, Ollantaytambo and the Qeswachaka suspension bridge. The students, working in groups, prepared reports presenting an in-depth investigation of a topic of particular interest.

RESUMEN
Un curso llamado "Ingeniería en las Americas antes de Colon" fue desarrollado en la escuela Swanson de Ingeniería de la Universidad de Pittsburgh para introducir al los estudiantes de pre-grado a los métodos de ingeniería civil empleados por los Incas del Perú en el diseño y construcción de sus obras de ingenieria civil que han permanecido estables a pesar del tiempo y las catástrofes naturales. Los lugares visitados por los estudiantes fueron Cuzco, Machu Picchu, Pisac, Moray, Ollantaytambo y el puente colgante de Qeswachaka. .Los estudiantes trabajando en grupos, prepararon un reporte bien detallado acerca de su investigación sobre un tópico de su interés.

1 INTRODUCTION

Traveling throughout Latin America one encounters stunning examples of pre-Columbian geotechnical engineering expertise. An example of this expertise is the agricultural terraces with their retaining walls built by the Incas of Peru at places such as Machu Picchu, Moray, Ollantaytambo, and Pisac. A course called "Engineering in the Americas Before Columbus" was developed in the Civil Engineering Department at the University of Pittsburgh to introduce undergraduate students to the methods employed by the Incas in the design and construction of these pre-Columbian structures, and to analyze why these structures have remained stable in the face of time and natural hazards. Factors which made pre-Columbian engineers so effective were analyzed using basic principles of civil engineering. This paper describes the format of the course and some of the findings reported by the students.

2 CONTENTS OF THE COURSE

2.1 Course Description

"Engineering in the Americas Before Columbus" consisted of preparatory lectures, discussion and exercises, and site visits (of ten days in total) to Cuzco, Machu Picchu, and the Sacred Valley in Peru where agricultural terraces and their respective retaining walls are located, as well as the Qeswachaka suspension bridge. The students were debriefed subsequent to the site visits. Students kept a journal recording relevant information collected during the site visits, and ultimately prepared a final report detailing and analyzing civil engineering features found at the sites included in the required field trips. The final report was prepared by students, working individually or in small groups of 3 to 5, presented an in-depth investigation of a topic of particular interest documented using a variety of media. The students shared, in written and oral formats, the results of their special report after the conclusion of the field trip.
By the end of the course the students: (a) had extended their basic understanding of fundamental principles of analysis and design of geotechnical engineering structures, (b) were able to use these principles to understand the design and construction of pre-Columbian geotechnical engineering structures, (c) had developed an appreciation of the engineering skills of pre-Columbian peoples; and (d) had gained experience in collecting, analyzing and presenting data in a variety of formats.
The Summer Semester of 2010 was the first time the course was offered. Eighteen civil engineering students enrolled and successfully completed the course.

2.2 Prerequisites for the Course

This course was open to engineering students with a basic knowledge of algebra, geometry, trigonometry, introductory physics, and calculus. The instructor and the students analyzed the design of pre-Columbian structures in South America from a civil engineering perspective.

2.3 Contact Hours for the Course

The course was composed of 45 contact hours. Of these contact hours, 30 hours form part of the field component of the course (6 days of 5 hours per day), and 15 contact hours of classroom instruction. The classroom instruction was conducted before the trip to Peru. One post-field trip session of 3 hours was held during which the students presented their projects, discussed their findings, and reflected upon their experiences,

2.4 Course Objectives

By the end of the course the students were expected to:

1. Have a basic understanding of fundamental principles of analysis and design of civil engineering structures;
2. Be able to use these principles to understand the design and construction of pre-Columbian architectural and civil engineering structures;
3. Develop an appreciation of the engineering skills of pre-Columbian peoples; and
4. Gain experience in collecting, analyzing and presenting data in a variety of formats.

2.5 Course Syllabus

- (a) Inca heritage: cultural background
- (b) Geology and environment of the Inca Region
- (c) Mathematics of the Incas: The Quipu and the Abacus
- (d) Construction materials, methods, and tools used by the Incas
- (e) Inca roads, the area covered by these roads, their method of construction, and the political importance of the roads for the Inca Empire
- (f) Introduction to Machu Picchu and Cuzco, the capital of the Inca Empire
- (g) Engineering planning and importance of Machu Picchu and Cuzco
- (h) Building foundations, retaining walls, and suspension bridges built by the Incas.
- (i) Comparison of structures that the Incas built that operated under tensile stresses and those built by the Europeans that worked under compressive stresses
- (j) Hydrology and hydraulic engineering in the Inca Empire
- (k) Drainage infrastructure of Machu Picchu
- (l) Assessing the accomplishments of Inca engineers and architects

2.6 Field Trip Schedule

Day 1: Tour of Cuzco with emphasis on engineering and architectural features of the city (i.e., the palace of Hatunrumiyuc, and the temple of Koricancha).

Day 2: Visit to the Inca Museum of Cuzco and lecture by Alfredo Valencia Zegarra, author of our textbook: *Machu Picchu a Civil Engineering Marvel*.

Day 3: Visit to the fort of Sacsayhuaman. Analysis of the history and engineering construction of this massive structure.

Day 4: Visit to engineering structures in the Sacred Valley at Pisac, Urubamba, Moray and Ollantaytambo.

Day 5: Visit to Machu Picchu. Analysis of its history and engineering features.

Day 6: Visit to the Qeswachaka suspension bridge.

2.7 Method of Evaluation

In addition to attending and participating actively in all classes, which involves engaging in discussions, responding to questions, and sharing observations and documentation from field trip work, students were required to complete the following:

(a) A journal documenting each site visit. This could include written information, observational drawings, and photographs relevant to class topics. Each entry should be a minimum of 2 to 3 pages in length. Journals were collected at the end of the term for grading purposes.

(b) Final report of a special investigation. Each student chose a topic of special interest to investigate throughout the course of the field trip, working alone or as part of a small group. Before departing for the field trip, students submitted their proposed ideas for review by the professor. The student conducted library and internet research pertaining to the topic, collected data from the field trips relevant to the topic, and analyzed the ideas involved based on the principles being learned in class. For example, a group of students chose to study retaining walls built by the Incas. The students then used field trip time to investigate the characteristics and uses of retaining walls encountered. Finally, they prepared a report including an analysis of the stability of these walls using the civil engineering principles learned in class. The final report was due at the end of the Summer Semester. The final report was 15 pages in length (including pictures and drawings). It was shared with classmates by each group as a short presentation (20 minutes) and was submitted to the instructor for grading purposes.

3 AN EXAMPLE OF A GEOTECHNICAL PROJECT CONDUCTED BY THE STUDENTS

3.1 Stability Analysis of a Retaining Wall in Machu Picchu

A group of participating students that visited Machu Picchu took photographs and measurements of a retaining wall forming part of the agricultural terraces at Machu Picchu. Figure 1 shows a view of the terraces from the agricultural sector of Machu Picchu.

Figure 1. Inca terraces with their retaining walls at Machu Picchu.

From the retaining walls shown in Figure 1, the students selected one in order to investigate its stability with respect to sliding and overturning. A photograph of the wall selected as well as its dimensions are shown in Figures 2 and 3.

Since is very difficult to obtain permission from the Peruvian government to conduct soil sampling at Machu Picchu, the soil and rock parameters were estimated in order to conduct the stability analysis. Table 1 shows the values assumed for the soil and rock properties.

Figure 2. Photograph of the Inca wall selected for the stability analysis

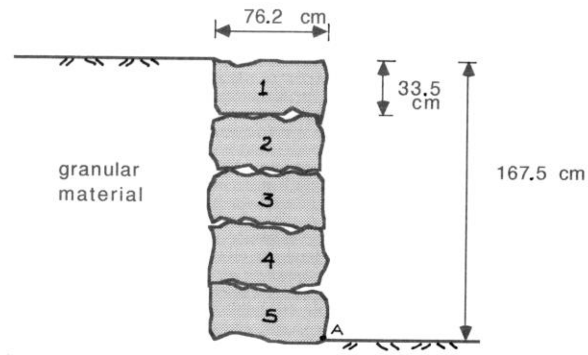

Figure 3. Dimensions of the Inca wall used for the stability analysis

Table 1 Engineering Properties of the Soil and Rocks

Properties	Soil	Rock*
Unit weight (γ)	15.71 kN/m^3	23.56 kN/m^3
Friction angle (ϕ)	40 degrees	
Interface Friction Angle between rock blocks (δ)		30 degrees

*Rock is Andesite

3.1.1. Sliding Stability of the Wall

The wall is made of blocks of Andesite placed one on top of the other as shown in Figure 3. The stability of the wall against sliding at any depth of the wall is provided by the frictional resistance between the rock blocks (5 blocks in the wall shown in Figure 3). For the stability analysis, the soil behind the wall was assumed to be a granular soil. Wright and Zegarra (2000) have been the only ones to have performed an excavation behind a retaining wall at Machu Picchu and found that the soil behind a retaining wall was mostly composed of sand and gravel with a small portion of the soil on top made of agricultural soil (Figure 4).

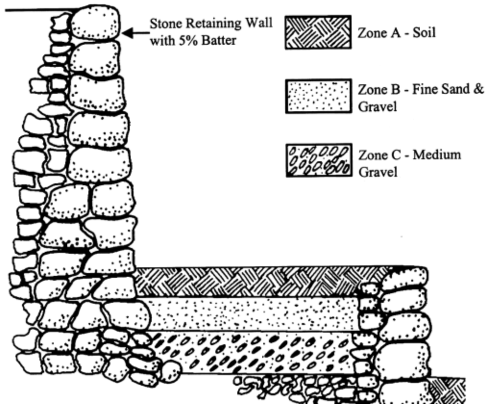

Figure 4. Parts of an Inca wall at Machu Picchu (Wright and Zegarra, 2000)

Inspection of the walls shown in Figures 1, 2, and 3 indicated that there was no cementing material holding the rock blocks together, and since most of the material behind the wall is a free draining granular material, the wall and the backfill was found to always release any water that comes from rain and irrigation. Therefore, the wall and the soil did not hold any water. Thus, for the stability analysis, the soils forming part of the backfill as well as the wall, were assumed to both be dry.

In addition, the wall and the backfill were assumed to be at rest. For this condition, the forces causing failure (F_c), and the forces resisting failure (F_R) were obtained from the following relationship without considering earthquake forces (Das, 1984),

$$F_c = (1/2)\,\gamma_{soil}\,H^2\,Ko = (1/2)\,\gamma\,H^2\,(1-\sin\phi) \qquad [1]$$

$$F_R = (V)(\gamma_{rock})\,\tan\delta \qquad [2]$$

where V is the volume of the rock blocks forming the wall.. For the analysis, each of the five blocks were assumed to measure 0.762 m in width, 0.335 m in height, and 1 m in length (normal to the plane of the paper) (Figure 3). The other terms in Equations 1 and 2 are defined in Figure 3 and Table 1.

If one considers the stability against sliding of just block number 1 in Figure 3 (H = 0.335 m), the values of F_C and F_R obtained using Equations 1 and 2 are equal to: F_C= 0.315 kN/m, and F_R = 3.47 kN/m. Thus the factor of safety against sliding for block number one is: FS= F_R/F_C = 11.

If one considers the whole wall (considering all the five blocks with H = 1.675 m in Figure 3, and assuming the blocks continue below the ground surface at point A), the values of F_C and F_R obtained using Equations 1 and 2 are equal to: F_C= 7.87 kN/m, and F_R = 17.36 kN/m. Thus the factor of safety against sliding for the whole wall is: FS= F_R/F_C = 2.2. Thus, the wall is stable with respect to sliding.

Near the Machu Picchu site there are two faults (Wright and Zegarra, 2000). Thus, for the analysis it is important to consider earthquake forces. One way to do this is to add to the value of the causing force (F_c) a force resulting from the earthquake as follows (Das, 1984)

$$F_c = (1/2)\,\gamma\,H^2\,(1-\sin\phi) + (0.15)\,(1/2)\,\gamma\,H^2\,(1-\sin\phi) \qquad [3]$$

where the factor (0.15) represents the fraction of the static force that has to be added in order to consider the effect of an earthquake.

Considering the whole wall (all five blocks), the value of F_C calculated using Equation 3 is found to be equal to 9.05 kN/m, with the value of F_R still equal to 17.36 kN/M. Thus, for the earthquake condition, the factor of safety against sliding is found to be FS= F_R/F_C = 1.92.
This high factor of safety value indicates that the wall is stable during earthquakes, which has been the case for the Machu Picchu terraces for more that 500 years.

3.1.2 Stability of the Wall Against Overturning

The wall shown in Figure 3 can overturn around point A when the static and earthquake forces given by Equation 3 are in effect. Thus, it is necessary to analyze the stability of the wall with respect to overturning. To do this we need to calculate first the moment created around point A (Figure 3) by the forces that cause failure, F_C from Equation 3. This moment will be called M_C and is equal to (Das, 1984),

$$M_C = [(1/2)\,\gamma\,H^2\,(1-\sin\phi) + (0.15)\,(1/2)\,\gamma\,H^2\,(1-\sin\phi)]\,(H/3) \qquad [4]$$

where H is the height of the wall (equal to 1.675 m as shown in Figure 3).

The value of the resisting moment (M_R) against overturning with respect to point A for the wall shown in Figure 3 can be obtained from the following relationship (Das, 1984),

$$M_R = [(V)(\gamma_{rock})]\,[\,0.762/2] \qquad [5]$$

where V represents the total volume of the five blocks shown in Figure 3. The other terms are defined in Figure 3 and Table 1.

If one replaces the values of the terms in Equations 4 and 5, the value for M_R = 11.46 kN-m/m, and the value of M_R = 5.05 kN-m/m. Thus the factor of safety against overturning FS = M_R/M_C = 2.26. This high factor of safety value indicates that the wall is stable against overturning during earthquakes, which has been the case for the Machu Picchu terraces for more that 500 years.

4 SUMMARY AND CONCLUSIONS

The walls at Machu Picchu and other areas where Inca walls are located (Pisac, Moray and Ollantaytambo) were found to be very stable. There are two reasons for this. The first one has to do with the drainage of water from the walls. Since is known that the water pressure behind a non-drained wall is about 3 times that produced by soil, it is of fundamental importance to drain the water from behind the walls. The Inca engineers knew this. The walls are freely draining, and the soil behind the walls is mostly made of sand and gravel (Figure 4). The rain water that percolated through the terraces at Machu Picchu flowed uninterrupted to the Urubamba River located at the bottom of Machu Picchu (Wright and Zegarra, 2000).

The second reason why the walls are stable has to do with the size of the blocks the Inca used to build their walls. The blocks were very large, especially in width (measuring between 76.2 cm and 1 meter as shown in Figure 3). This large width provided the inter-block frictional resistance necessary to overcome the pressure of the soil. Also, this large width provided the large resisting moment to overcome the overturning moment of the soil behind the wall.

Thus, the Inca engineers knew what they were doing and their ingenuity and methods of construction serve as an example to undergraduate students in civil engineering schools around the world.

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