A theoretical approach for testing the monuments of PUMAPUNKU, Bolivia

Authors: AHMED MUSTAFA, SANDRA RAMÍREZ

Teachers: G. Rus, J. Melchor, A. Callejas

Submitted as a final assignment for the course of
Evaluación No Destructiva Y Calidad En Estructuras, 2022

A theoretical approach for testing the monuments of PUMAPUNKU, Bolivia

1 Abstract

This work represents a proposed approach for a scientific determination of PumaPunku monuments characteristics, through conducting a nondestructive test broken down into two stages, first the ultrasonic method and second the Spectral Analysis Surface Waves (SASW). Leading to manufacturing of an assistant stone-softening substance, or an environmentally-friendly concrete.

2 Introduction

Based on some studies carried out, interest has been aroused in studying the monoliths of PumaPunku. French chemist Joseph Davidovits together with a group of scientists from Geopolymer Institute took samples of red sandstone and andesite from the area where is PumaPunku. For the first time, they analyzed them with electron microscopes, compared them with geological resources of the place and discovered the presence of carbon-based organic matter. “This organic element (andesite) is a geopolymer based on into carboxylic acid, therefore, was added by human intervention within the andesite sand to form a type of cement”

But the giant blocks of red sandstone posed another problem. This is a sedimentary rock composed of quartz grains and a clay binder. There are several possible sources and none corresponds to the archaeological monuments. Under the electron microscope, it was detected that it cannot be sourced from the area. So where from? Hundreds to thousands of kilometers? How are they supposed to transport the pieces?

Analysis by electron microscopy shows that the composition could be artificial. The hypothesis is that the Tiwanacotas created a kind of geological cement, from clay (the same red clay they used for pottery) and carbonate salts of sodium from the Cachi lagoon, south of the Altiplano desert. For gray sandstone rock, invented an organo-mineral binder based on natural organic acids extracted of local plants and other natural reagents, one of them the corn chicha. This binder was then poured into molds and hardened for a few months.

Davidovits explains that it is possible to soften these blocks due to the elements that can be contained in these.

From these studies, part of the hypotheses raised in this proposal. Whose goal is to verify the veracity of any of these hypotheses through the use of non destructive tests.

3 Hypotheses and objectives

3.1 Hypotheses

Two hypotheses are put into investigation. Which:

- The monoliths are softened stones by using natural methods(Submerged in a mixture of local plants for a period of time).
- The monoliths are a type of an organic concrete

3.2 Objectives

- Using the stone-softening method artistic sculptures or in road construction in remote places where the access of big machines is difficult.
- Using the organic mixture as a binder with durability and resistance characteristics similar to concrete with no or very little environmental impact.
- Verifying the validity of any of the hypotheses by using the non-destructive tests method.
- Comparing the results obtained from the proposed tests in order to satisfy the previous objective.

4 History

PumaPunku is a part of large site in Tiwanaku architectural complex site, located in the west of Bolivia, having over 1400 years of heritage. The name means "the gate to Puma", which was thought to be an important hub for the citizens or as a plaza for the governing body in the area. Due to lack of information about this mysterious site, many investigations and research tried to reveal some of its hidden secrets in order to understand the technology and the purpose of such monuments.

Figure 1: PumaPunku Site, Tiwanaku, Bolivia [1]

5 Method

5.1 Non Destructive Testing

Nondestructive testing (NDT) refers to a type of test and analysis technique used to evaluate the properties of a material, component, structure or system. NDT aims to the determination of the characteristic differences or welding defects and discontinuities without causing damage to the original part, sample, or buildings. NDT neither alters the shape nor the properties of an object. It does not produce any type of damage, or the damage is practically imperceptible. This type of test is used to study physical, chemical or mechanical properties of some materials. Common concepts and tests based on NDT:

- Visual inspection.
- Radiography.
- Eddy current method.
- Ultrasonic testing.
- Surface waves.

5.2 Ultrasonic testing

Ultrasonic testing [4] [3] is a method of nondestructive testing, based on the use of high frequency waves. This method allows the identification of the material properties, or the defects in it, through measuring some principal parameters.

A prime aspect or a technique for ultrasonic testing is the pulse-echo method. High-frequency waves are emitted into a test material through one of its faces and the reflected waves are received. The following steps represent the process of pulse-echo testing:

- A wave is sent into the test material through one of its faces by direct contact.
- The wave is received after being reflected.
- The travel time is measured, which it takes the wave to travel from the transmitter through the sample to the receiver (from one face to the other and back through the material itself).
- The velocity of the wave is obtained by dividing the value of the sample's thickness over the travel time's value.
- This velocity is as an initial step for the mechanical characteristics calculations, as will be shown in the next subsection of this chapter.

For the sake of having the ability to conduct such a test in this case, the assumption of having small fractured specimens besides the main site of PumaPunku is put into account.

An ultrasonic testing device is chosen, having specifications related to the already-put objectives.

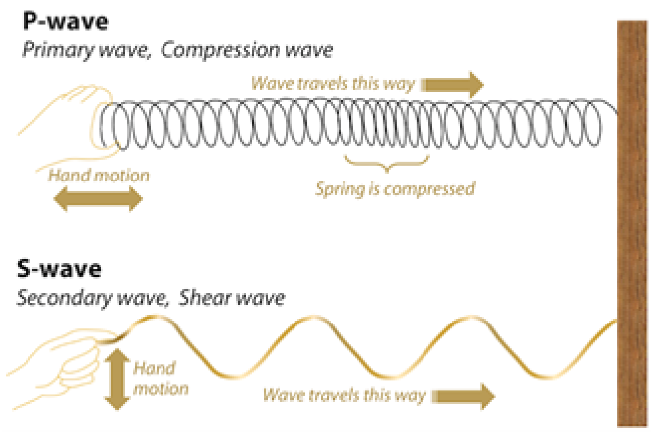

Figure 2: A scheme shows how P and S waves travel [11]

5.3 Olympus EPOCH 650

The Olympus EPOCH 650 detector [2] is capable of measuring many parameters, but in this case the traveling time of the wave through the sample is of importance.

It is assumed that the specimens from the PumaPunku site have dimensions with a more or less uniform thickness within the measuring bandwidth of the device.

Figure 3: Olympus EPOCH 650 Detector [6]

Testing procedure

1. Connect the detector to a computer or use it standalone.
2. Connect 5Hz transducers to the detector.
3. Calibrate the detector and its gates to an appropriate value so it can read from the transducer.
4. Apply some gel or couplant gel to the transducers.
5. Read the value before handling with the sample and record in seconds.
6. Put the test sample between the transducers and move them along the surface.
7. Read the value (traveling time) and record in seconds.

Analysis procedure [4,5]

The resulting time values are used to extract the mechanical properties of the tested sample, as follows:

1. Weigh the sample.
2. Measure the dimensions.
3. Calculate the volume of the sample:

$$V = L \cdot W \cdot T \tag{1}$$

   Where:

   V= Sample volume, in m^3

   L= Sample length, in m

   W= Sample width, in m

   T= Sample thickness, in m

4. Determine the density of the material.

$$D = \frac{M}{V} \tag{2}$$

   Where:

   D= Sample density, in Kg/m^3

   M= Sample mass, in Kg

5. Determine the velocity of the wave through the material:

$$C_p = \frac{T}{t_p} \tag{3}$$

$$C_s = \frac{T}{t_s} \tag{4}$$

   Where:

   C_p= Longitudinal wave velocity, in m/s

   t_p= Longitudinal wave travel time, in s

   C_s= Transversal wave velocity, in m/s

   t_s= Transversal wave travel time, in s

6. Calculate the Poisson's ratio:

$$\nu = \frac{0.5 \cdot \left(\frac{C_\mathrm{p}}{C_\mathrm{s}}\right)^2 - 1}{\left(\frac{C_\mathrm{p}}{C_\mathrm{s}}\right)^2 - 1} \tag{5}$$

Where:

ν= Poisson's Ratio

7. Determine the shear modulus:

$$C_\mathrm{s} = \sqrt{\frac{G}{\rho}} \tag{6}$$

So,

$$G = \rho \cdot C_\mathrm{S}{}^2 \tag{7}$$

Where:

G= The shear modulus, in GPa.

ρ= Material density, in Kg/m^3

8. Determine the Young modulus:

$$C_\mathrm{s} = \sqrt{\frac{E}{2 \cdot \rho \cdot (1+\nu)}} \tag{8}$$

So,

$$E = C_\mathrm{s}{}^2 \cdot [2 \cdot \rho \cdot (1+\nu)] \tag{9}$$

Where:

E= Young's modulus, in N/m^2

5.4 Spectral Analysis Surface Waves (SASW)

The spectral analysis surface waves (SASW) [5] method is based on the superficial Rayleigh waves. The installation of the tools to execute the SASW method involves one impulse source (Initiator) and two receivers connected to an analyzer. The next steps simplify the process of SASW testing method:

1. The initiator, for example a hammer, creates an impulse on the surface of a test sample.

2. The impulse, a wave, travels through the surface until it reaches the two receivers, which are situated at a fixed distance from each other.

3. The first receiver to receive the wave measures the so called input, and the second receiver measures the output.

4. A Fourier series is proposed to be used to perform the required analysis of the measured data.

5. Finally, the frequency response or transfer function is calculated. This is a measurement of the output-recorded values as a response to the initiator, in terms of phases of the output, as a function of frequency in accordance with the input values.

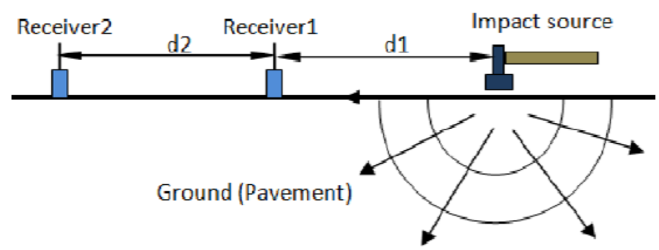

Figure 4: Test configuration of SASW method [8]

The resulting graph (acceleration vs. time) shows the velocity of each frequency (phase) of the Rayleigh waves. By translating the wave propagation theory into the terms of this case, the required mechanical properties could be obtained.

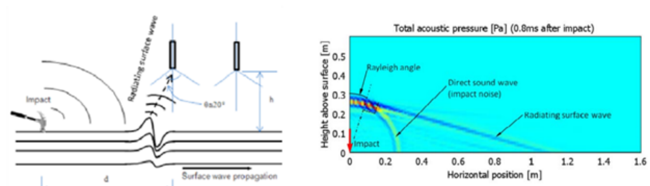

Figure 5: SASW wave propagation and its visualization using FEM [8]

Analysis procedure: [7,9]

$$V_\mathrm{R}(\omega) = \frac{X}{t(\omega)} \tag{10}$$

So,

$$\Delta t_{12}(\omega) = \frac{\varnothing_{12}(\omega)}{\omega} \tag{11}$$

Then,

$$\Delta t_{12}(f) = \frac{\varnothing_{12}(f)}{360 f} \tag{12}$$

As a result,

$$\gamma(\omega) = \frac{VR(\omega)}{f} = \frac{360X}{\varnothing_{12}(f)} \tag{13}$$

Where:

V_R= Rayleigh wave velocity, in m/s.

X= The distance between the receivers, in m.

t= Travelling time, in s.

Δt_{12}= The delay of time between the receivers, in s.

$\varnothing_{12}$= The angle of the frequency response spectrum between the receivers, in degrees.

ω= Angular frequency, degree/s.

f= Wave frequency, in Hz.

γ= Wavelength, in m. Therefore, and since the velocity

of Rayleigh wave is obtained, the P-waves (Longitudinal), the S-waves (Transversal), as follows:

$$v_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+v)}} \approx \frac{1+v}{0.87+1.12v} \cdot V_R \tag{14}$$

$$v_p = \sqrt{\frac{E(1-v)}{(1+v)(1-2v)\rho}} \tag{15}$$

$$v_p \approx \frac{1+v}{0.87+1.12v}\sqrt{\frac{2(1-v)V_R}{1-2v}} \tag{16}$$

$$E_d = 0.7632E_s + 22.604 \tag{17}$$

Where:

V_s= S-waves (Transversal), in m/s, S: stands for shear, perpendicular to the wave direction.

V_p= P-waves (Longitudinal), in m/s, P: stands for primary, parallel to the wave direction.

G= The shear modulus, in GPa.

E_d = Dynamic elastic modulus, in N/m^2.

E_s = Static elastic modulus, in N/m^2.

v= Poisson's Ratio.

ρ= Material density, in Kg/m^3.

5.5 Freedom Data PC

A device is selected to perform the aforementioned SASW, which is Freedom Data PC [10], with it accessories. This device have the ability to measure different parameters through different methods, such as ultraseismic, impulse-echo scanning and spectral Analysis of Surface Waves.

Description and capabilities

The Freedom Data PC is capable of measuring the required parameters without the need of drilling a hole into the sample. It functions upon the determination of the surface waves, Rayleigh waves, in relation to their velocities.

Freedom Data PC device for SASW testing and its accessories [10]

Since the velocity is obtained, the shear and Young's moduli of the material could be obtained though the application of the previous equations. It is important to note a feature of the device when dealing with soils or rocks, that as much depth required there should be accessible surface of the sample. As the manufacturer gave an example of a test reached a depth equal to 150 feet as the same area and dimension were available to access with the device.

The device could test some materials:

- Asphalt
- Concrete
- Wood
- Rocks, which is in this case.

Some of its prime features:

- System design allows for fast and accurate field measurements.
- System is compact, durable, and easily transported, allowing for multiple tests per day
- Real-time waveform display while testing.
- SASW measurements are accurate to within 5% for the determination of the thickness and stiffness of the top layer in a pavement system.
- Acquisition and modeling software are compatible and easy to use, yielding fast and accurate results.

A comparative table between the two proposed devices

OLYMPUS EPOCH 650	FREEDOM DATA PC
Velocity of the wave	Velocity of the wave and Acceleration
S-waves and P-waves	S-waves, P-waves and Rayleigh waves
Density	- - -
Shear modulus	Shear modulus
Young modulus	Young modulus
Poisson's ratio	- - -

Figure 6: Testing a rock using Freedom Data PC, based on SASW method [10]

6 Discussion

In the context of discussioning a research was implemented in depth about the case of PumaPunku, but in a chemical perspective. The research is done by Joseph Davidovits [2], 2019. The researcher claims that these monuments were cast in situ, where the people of Tiwanaku were able to create a geopolymer concrete by mixing some organic materials from nearby collecting sites, then soaking them in a mixture of plants extracts to soften their surfaces, in order to reshape them. This conclusions are supported by pure observation of the surfaces of some collected small specimens from the sites. However, this specimens were exposed to weathering conditions for hundreds of years, which may mean that they were disintegrated and mixed with their surroundings.

In this work, the hyptheses is divided into two, as first is that the mounuments are geopolymer concrete made from organic compounds, and second is they are volcanic stones were softened by using plants exrtacts.

In order to verfiy the these hypotheses, by following the methodology procedure and the devices' operating instruction, the possible results will be in favour of one of the hypotheses, based on the obtained mechanical proprties. That is to say if either the values are close to a geopolymer concrte or to a volcanic rock.

References

[1] Joseph Davidovitsa, Luis Huamanb, and Ralph Davidovitsa. "Tiahuanaco monuments (Tiwanaku/Pumapunku) in Bolivia are made of geopolymer artificial stones created 1400 years ago." In: Archaeological Paper# K-eng (2019).

[2] epoch 650 - ultrasonic flaw detector. URL: https://www.olympus-ims.com/en/epoch650/.

[3] A. Callejas G. Rus J. Melchor. Caracterización mecánica de materiales y detección de defectos med 2014.

[4] Grabendörfer. Ultrasonic Testing of Materials. 1990.

[5] Fernando Martınez-Soto et al. "Spectral analysis of surface waves for non-destructive evaluation of historic masonry buildings". In: Journal of Cultural Heritage 52 (2021), pp. 31–37.

1. www.wikipedia.org/wiki/Pumapunku
2. Tiahuanaco monuments (Tiwanaku / Pumapunku) in Bolivia are made of geopolymer artificial stones created 1400 years ago, Joseph Davidovits, 2019
3. WWW.Olympus-ims.com/en/epoch650/
4. Spectral analysis of surface waves for non-destructive evaluation of historic masonry buildings, Fernando Martínez-Sotoa, Fernando Ávila, Esther Puertas, Rafael Gallego, 2021
5. A Mobile Acoustic Subsurface Sensing (MASS) System for Rapid Roadway Assessment, Yifeng Lu, Yi Zhang, 2013
6. ACI 228.2R-13 Report on Nondestructive Test Methods for Evaluation of Concrete in Structures.
7. Catalouge of equipment for imaging the Civil Infrastructure - Olson Instruments, Inc.
8. www.paleolimbot.github.io/physical-geology/earthquakes.html