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Experiences and preliminary results of geophysical methods on historical statues

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Abstract. In recent years, geophysical applications have been significantly grown in rock mechanics field due to their versatility and reliability as diagnostic and/or monitoring tools. Since these methodologies are mainly non-invasive, they can be used for the investigation and characterization of the internal structure of historical artworks or for the monitoring of built cultural heritage, where the non-destructive feature is an indispensable prerequisite. Commonly, the artworks material properties are unknown or strongly altered due to time and physical/chemical agents. Moreover, their nature (mineralogic and petrographic) and origin (in terms of places where the material was exploited) is uncertain and difficult to allocate. Among the available geophysical techniques, seismic methods are useful for detecting the thickness or position of weathered layers, for estimating the physical properties of different materials and for providing information about cracking and degree of fracturing. In this paper, we present some experiences and preliminary results of geophysical characterization of two Tritons statues, discovered in the garden of the Royal Palace of Venaria (Piedmont Region, Italy). The statues were originally part of the Fountain of Hercules, destroyed in the 18th century during the redevelopment works of the Palace. Ultrasonic pulse velocity measurements were performed on each portion of the statues and 3D-imaging of the apparent P-wave velocity were carried out. The performed geophysical investigations were aimed at defining the overall material quality and detecting possible sectors with low resistance properties that might interfere with the coring operations, necessary for the reassembly of the statues. Results of these surveys were also useful for setting up a 3D-FEM model for simulating the material behaviour through an analysis of the forces and loads involved.

1. Introduction

The World Heritage List [1] counts 1154 heritage sites all over the world: many of these are natural or cultural sites that involve rock materials. Historical heritages require facing different and continuous challenges for evaluating their state of conservation and planning specific maintenance and restoration interventions, especially in the presence of severe natural and hand-made hazards or prolonged deterioration over time.

A detailed knowledge of the material properties and the internal structure is essential for quantifying material resistance, for the diagnosis phase and for the development and implementation of conservation and restoration measures [2]. Moreover, especially for artworks, the nature (mineralogic and petrographic) and origin (in terms of places where the material was exploited) of the rock material is commonly uncertain and difficult to allocate. Since it is impossible taking samples from cultural heritage to be studied in laboratory, non-invasive and non-destructive techniques are indispensable for this purpose.

The development of geophysical techniques, the improvement of their performances, of the resolution of sensors and devices and the increasing availability of user-friendly data/image analysis, and processing, softwares and routines have contributed to facilitate their use in cultural heritage [3-4]. Their non-invasive characteristics, their good resolution power from micro- to macroscopic investigations and their versatility made them perfect to be used both in small-sized [5-9] (columns, statues, sculptures etc.) and in situ targets (building facades or foundations) [10-14].

Among the available geophysical techniques, seismic methods, and in particular ultrasonic tests are the most used in the field of diagnostics on historical buildings and artworks [5-14]. This methodology is based on the evaluation of apparent propagation velocities of an ultrasonic impulse through the medium. The presence of altered material or fractures along the travel path causes an increase of the travel time and consequently reduces the apparent propagation velocity. Moreover, seismic velocities indirectly provide information on material stiffness and resistance, fundamental parameters for further analyses (e.g numerical simulations). The analysis of dense patterns of propagation paths allows for a comprehensive seismic characterization of the medium and consequently the detection of portions with lower mechanical properties.

Artworks have commonly complex-shapes and restrained dimensions: consequently, measuring seismic path distances becomes very important to accurately define seismic velocity distributions. For this purpose, photogrammetric techniques are essential tools for building 3D models from point cloud and texture mesh [5-6, 15-16].

In this paper, we present the results of the combination of ultrasonic pulse velocity measurements and photogrammetric analysis to evaluate the fracturing state of two Tritons statues, discovered in the garden of the Royal Palace of Venaria (Piedmont Region, Italy). The obtained 3D-imaging aimed at defining the overall material quality and detecting possible sectors with low resistance characteristics that might interfere with the coring operations, necessary for the reassembly of the statues.

2. Material and Methods

2.1. *The Tritons statues*

The two surveyed statues (Figure 1) represent two Tritons and were originally part of the Fountain of Hercules built between 1668 and 1670 in the gardens of the Reggia di Venaria Reale, renovated by the architect Amedeo di Castellamonte with the creation of terraces and "water games". The redefinition of the spaces of the gardens to a design by Michelangelo Garove in 1699 and the damage caused to the entire structure by the siege of Turin in 1706, marked the beginning of the dismantling of the fountain and its rich sculptural apparatus which dragged on until the mid-eighteenth century when was definitively destroyed to renew the garden. Part of these sculptures were relocated to other royal residences and others, the most damaged and the tritons that were in a fragmentary state, were buried in the fountain area [17].

Between the end of the last century and the beginning of 2000, as part of the overall recovery project of the Reggia di Venaria, archaeological investigations were also carried out at the site of the Fountain of Hercules with the consequent discovery of over 2000 stone fragments. Between 2005 and 2007 the archaeological restoration of the area was started pending a more in-depth intervention which began at the end of 2017 and is still in progress. As part of this project, the "La Venaria Reale" Conservation and Restoration Center is undertaking the restoration of a group of about twenty sculptures including the fragments of the tritons discovered during the archeological excavations. The conservation and recomposition of the fragments aim to relocate them on the edges of the fountain basin in the garden of the Royal Palace.

The intervention was designed with a multidisciplinary approach according to the criteria of minimum invasion and maximum reversibility, considering the state of conservation, the chemical-physical characteristics of the constituent material and according to the exhibition environment. A reversible intervention was essential to make possible the dismantling if in the future some missing fragments, not found in previous excavation campaigns, will be found.

The first Triton (named in the following as Triton A, Figure 1a) is divided into three separate pieces: the head and the left arm, the right part of the upper body and a portion of the tail. The head is characterized by metallic fragments around the triton's mouth, probably related to water pipes of the fountain. The second Triton (Triton B, Figure 1b) is divided into four separate pieces: the head and the right arm, the left arm, the pelvis and the tail.

No a priori information about the rock type was available: after an accurate historical research and visual inspection of the Tritons, it was hypothesized that they are made of "Verzino di Frabosa" marble. "Verzino di Frabosa" marble is a slightly impure marble (with a percentage of white mica and chlorite around 5-6%), with medium-fine grains and an anisotropic structure given by a relatively continuous schistosity (with centimeter spacing), highlighted by the presence of phyllosilicates. This marble was exploited in 1600s in the municipality of Frabosa (southern Piedmont Region). However, for verifying the petrophysical nature of the rock medium, devoted analyses should be performed on samples taken from the Tritons themself.

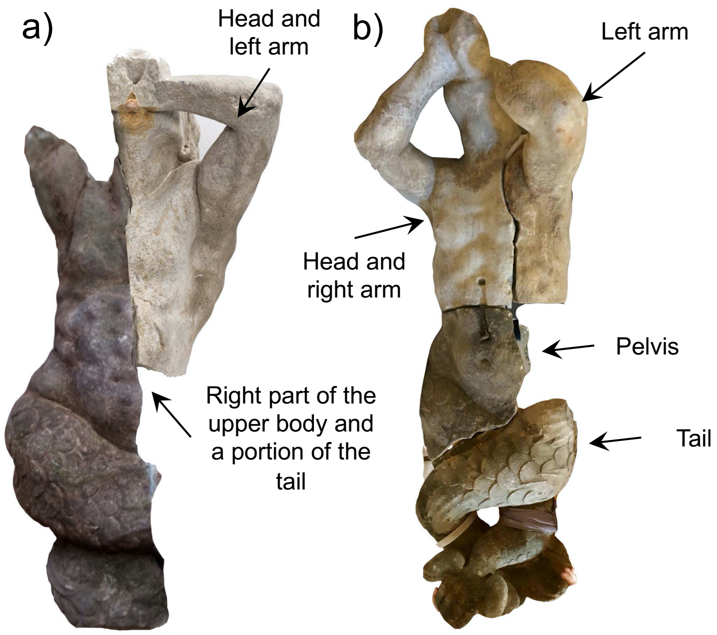

Figure 1. 3D view of the surveyed a) Triton A and b) Triton B.

2.2. *Photogrammetric survey*

The photogrammetric survey consisted in about 100 shots for each portion of the Tritons, acquired with a Nikon D810 professional camera and 35mm wide-angle lens. This detailed survey has produced very dense point clouds: each fragment was composed of about 10^8 points with an average distance among them of 0.8 mm. From those point clouds the 3D models were generated. These models have been later used, after intelligent decimation, for locating markers on the surfaces for the ultrasonic survey. The same virtual models were also helpful for aligning correctly each portion of the statues, thus avoiding to handle the real objects and so minimizing the risks of damaging the fragments. The alignment was performed by matching the fracture surfaces of the different Triton portions. The correct alignment in a

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virtual environment also granted to check the contact areas between pieces and any possible lack of parts.

2.3. Ultrasonic survey

On each portion of the Tritons, some of the markers used for the photogrammetric analysis (106 for Triton A and 194 for Triton B), were identified as positions for sources and receivers during ultrasonic tests. These points were selected to guarantee a sufficient ray coverage for obtaining an imaging of seismic velocity distribution inside the statues and particularly of the portions of the fragments facing each other. These points were then chosen for positioning the transmitter-receiver probes for P- and S- (where possible) wave velocity measurements (53 and 98 travel paths respectively for Triton A and Triton B). Measurements were denser especially around the expected most critical sectors of Triton portions.

The travel time analysis was performed by using an ultrasonic pulse instrument (PunditLab, Proceq) with two exponential probes having a nominal frequency of 37 kHz (Figure 2). For each seismic path, 10 ultrasonic traces were recorded, using a sampling frequency of 2 MHz. Manual picking of the first arrival times was performed. Determination of the P- and S- (where well-visible from seismic traces see Figure 2) wave ultrasonic velocity was then straightforward as the ratio between straight path dimension, measured directly on 3D model by using CloudCompare software, and travel time.

The combined measurement of both P- and S-wave velocities offers the opportunity to retrieve low-deformation (initial deformation phase of strain-stress curve) mechanical parameters, such as Young's modulus, E, shear modulus, G, and Poisson's ratio, ν, following:

$$G = \rho \cdot V_S^2 \tag{1}$$

$$\nu = \frac{V_P^2 - 2V_S^2}{2(V_P^2 - V_S^2)} \tag{2}$$

$$E = 2G(1 + \nu) \tag{3}$$

assuming an average material density, ρ, from reference value of Verzino di Frabosa marble (2700 kg/m^3).

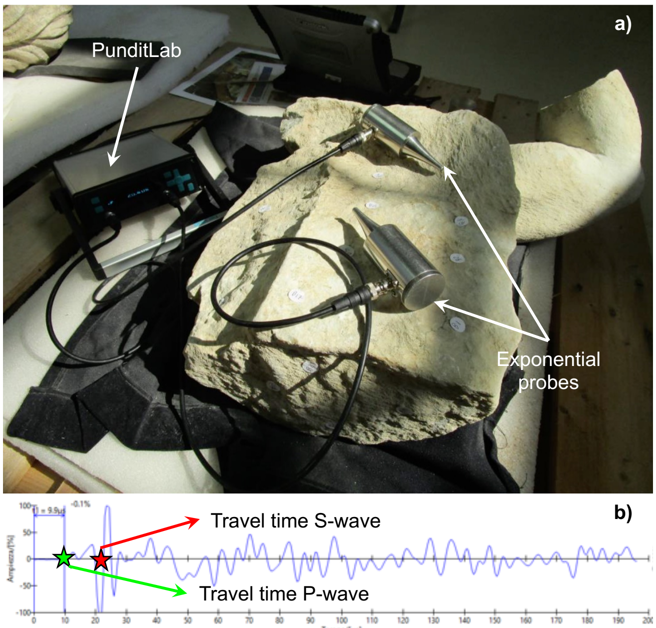

Figure 2. a) Ultrasonic pulse instrumentation and b) trace recording and analysis.

3. Results and Discussions

Figure 3 shows the comparison histogram between the apparent P-wave velocities measured on Tritons A (blue bars) and B (orange bars). As a general comment, Triton B has a wider velocity range compared to Triton A. This can be related to portions of the statue with both increased and reduced mechanical properties. The uncertainties related to first arrival time picking are very low as shown in Figure 4. Consequently, the repeatability of single measurements and the quality of acquired traces is excellent, proving that the velocity variability within statues is only related to alteration/fracturing of the material itself. However, most of travel paths fall around the mean values of the two distributions, respectively equal to 4827+392 m/s (Triton A) and 4595+990 m/s (Triton B). These values are fully comparable with marble stones.

A further statistical analysis was performed on the two distributions of Figure 3 for the definition of a self-explanatory color bar from green to orange colors (see Figure 5). Green color stand for velocity values greater than the 40th percentile of the distribution: on the other hand, orange stand for velocity values lower than 10th percentile.

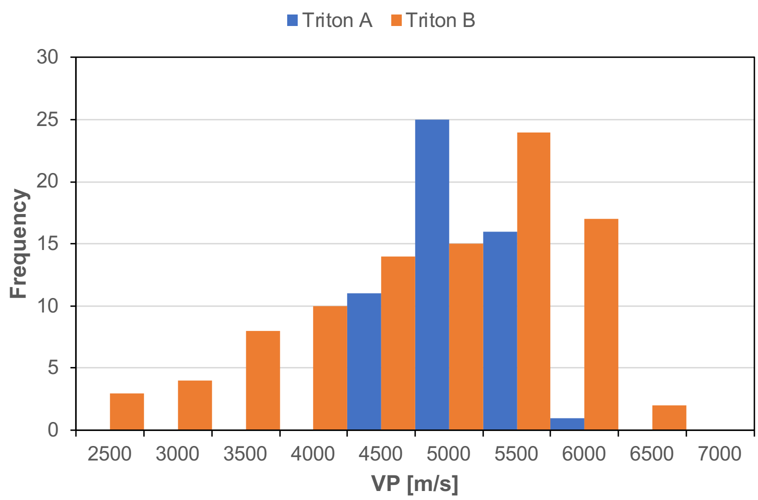

Figure 3. Histogram of the apparent P-wave velocity for Tritons A and B.

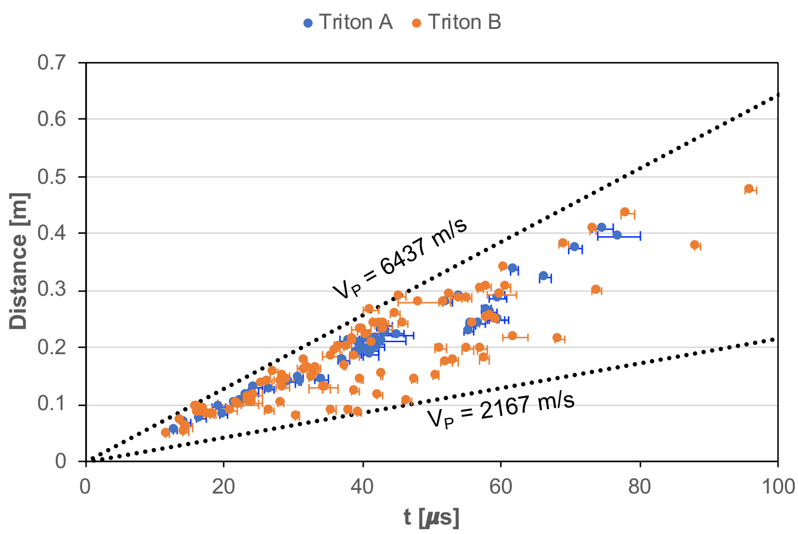

Figure 4. Distance versus time distribution. Where not visible, the error bar for time values is smaller than marker size.

The general observations made on figure 3 are also confirmed by analyzing the 3D-imaging of the apparent P-wave velocity carried out on Triton A (Figure 5a) and Triton B (Figure 5b).

The ultrasonic test yielded medium-high velocity values for many portions of the Tritons (green rays in figure 5), showing that the marble is sufficiently homogeneous and is quite well-preserved, in relation to the time it was buried underground.

Triton A (Figure 5a) shows four sectors with slight reduction of apparent velocities: two sectors are in the right part of the pelvis (points 1 and 2 in Figure 5a), one along the neck (point 3) and one in the internal portion of the upper body (point 4). As regards the two first sectors, velocity reduction can be related to superficial alteration of the marble, also confirmed by a localized blackening of the surface and the presence of a visible superficial fracture. The alteration around the Triton neck is possibly linked to water leakage occurred during the fountain operation. Instead, the velocity reduction in point 4 just involved superficial travel paths.

Analogously, in Triton B (Figure 5b) the areas with significant velocity decreases correspond to superficial portions of the various parts of the statue. No other specific low-velocity zones were observed. These low-velocity areas are consistent with failure surfaces, which probably underwent to a more rapid weakening due to post-failure alteration.

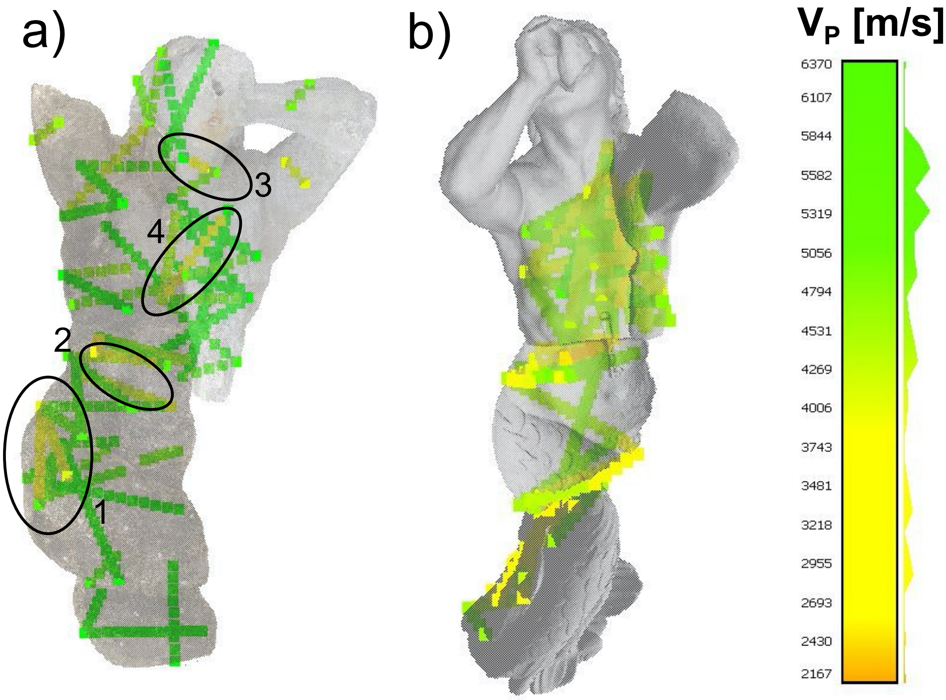

Figure 5. 3D-imaging of the apparent P-wave velocity carried out on Triton A (a) and Triton B (b).

By using Equations 1 to 3, stiffness parameters were estimated for both the Tritons. The results highlighted that Triton A has Poisson's ratio and dynamic Young and shear moduli respectively equal to 0.36, 39 GPa and 15 GPa. For what it concerns Triton B, stiffness parameters were also in good agreement with those obtained for Triton A (E=37 GPa, G=14 GPa and ν=0.36). Both the Tritons exhibited a quite high Poisson's ratio: these values can be both related to material characteristics (alteration) and also to difficulties in the S-wave velocity measurements due to the available instrument (some recorded traces by using exponential probes did not allowed the correct picking of S-wave arrival time since these probes are not specifically designed for S-wave generation).

Photogrammetric 3D model was used to virtually reassembly the Triton fragments. Usually, a traditional assembly system requires drilling holes to insert pins and sticking the surfaces with an adhesive resin, making the assembling irreversible. For these Tritons, an ad-hoc system was studied to tie the various fragments together with metal connecting elements to be inserted in the vertical recess on the back of the sculptures that originally contained the water pipes (Figure 6). These connecting elements were thought to be fixed to the fragments by means of pins inserted into the drilled stone. The hypothesised pins consisted of two main components: a threaded bushing, inserted and glued inside the fletching hole, and the actual threaded pin that can be easily unscrewed if disassembly is necessary.

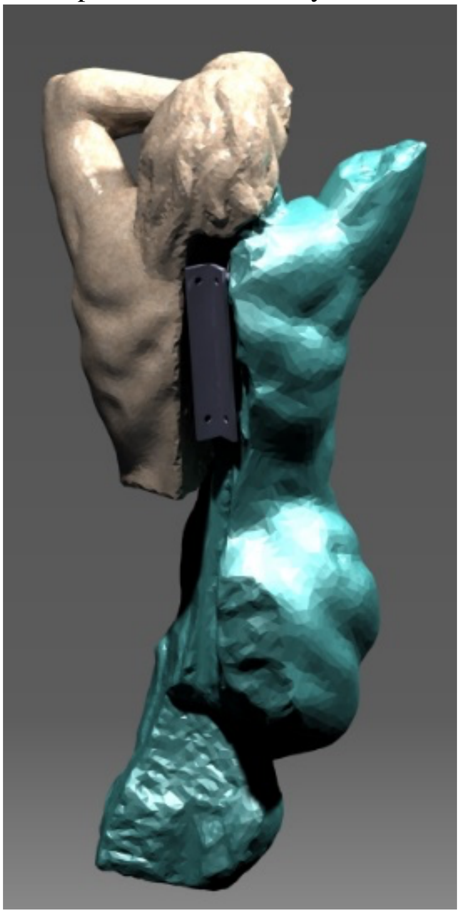

Figure 6. The reversible reassembly project with a metal connecting element fixed with removable pins

Future steps will be focused on combining the photogrammetric and seismic survey results to be used for the generation of a FEM analysis by associating the parameters relating to the nominal physical properties of the stone material and the results of the ultrasonic investigations relating to the state of conservation. In this way it will be possible to simulate the recomposition of the fragments and the behavior of the materials through an analysis of the forces and stresses involved.

4. Conclusions

This paper showed a fruitful combination of geophysical and photogrammetric techniques for the analysis of the integrity of two Tritons. In particular, the ultrasonic technique provides apparent velocity distribution that can be related to stiffness and resistance characteristics of the rock material. Photogrammetric processing revealed fundamental both for measuring correct ray dimensions and also for visualization and interpretation of the final results.

By coupling these processes, we obtained useful information on the overall material quality and detection of possible sectors with low resistance characteristics that might interfere with the coring operations, necessary for the reassembly of the statues. As a general comments, these methodologies proven the efficiency as non-destructive tests, indispensable prerequisite for the analyses of cultural rock artworks.

Even if these results have to be intended as a preliminary investigation, it is possible to deduce that:

- overall apparent velocity values indicate medium-high quality of the medium for both the Tritons, close to reference mechanical values for the hypothesised Vezino di Frabosa marble.
- Most of the weak zones (zone with statistically low velocity and elastic modulus values) correspond to superficial alteration, which affect limited rock volumes and should not interfere with coring operations during reassembly.
- In Triton B, lower apparent velocity values are located along the pre-existing failure surface between statue fragments. However, due to their superficial evolution, they have low influence on the overall mechanical characteristics of the statues.

Further analyses are already planned in the next future: 3D electrical resistivity tomography will be performed for locating detachments, voids and cracks and for better analysing the internal structure of the materials. Undoubtedly, the coupled interpretation of seismic and electrical measurements will provide a comprehensive characterization of the rock material.

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