NEAR SURFACE GEOSCIENCE 2015

Mo 21 B06

Photogrammetry and 3-D Ultrasonic Tomography to Estimate the Integrity of Two Sculptures of the Egyptian Museum of Turin

L. Sambuelli* (Politecnico di Torino), G. Böhm (OGS), C. Colombero (Università di Torino) & A. Filipello (Università di Torino)

SUMMARY

We present a fruitful combination of geophysical tests (Ultrasonic Measurements) and photogrammetric processing (Structure from Motion) for the analysis of the integrity of a couple of statues from the Egyptian Museum of Turin. Aim of the study was to investigate the persistence of the exterior widespread fractures within the sculptures. More than one hundred ultrasonic measurements were acquired on selected travel-paths across each statue, using an ultrasonic pulse velocity instrument. Dealing with complex-shape objects of restrained dimensions, it was very important to accurately define the three-dimensional coordinates of sources and receivers, in order to precisely measure their distances. A 3-D model of the statues was obtained from photogrammetric techniques. The acquired data were analyzed with both a statistical approach and tomographic processing, comparing the use of classical and staggered grids, in order to obtain the best fit of the local resolution. The final results revealed a valuable tool to guide the procedures for the mobilization, transport and restoration of the sculptures.

Introduction

The uniqueness of the masterpieces of our Cultural Heritage makes the detection of flaws in a solid material a very challenging issue. In this working contest, tests and analysis regarding the integrity of the medium must be carried out with non-destructive techniques, in order to preserve and not to affect the possible ongoing deterioration of the materials with time. An overview of the most common geophysical techniques applied to the non-destructive evaluation of monuments of the Cultural Heritage could be find in Martinho and Dionísio (2014). Among the available methods, the ultrasonic technique can be used in order to evaluate the degradation and to locate areas of structural weakness within the studied objects (Sambuelli *et al*., 2011; Capizzi *et al*., 2013).

In this work we present the results of the combination of ultrasonic 3-D tomography and photogrammetric techniques to evaluate the fracturing state on a couple of Egyptian statues: the whole body of Hathor (Fig. 1a) and a recovered part of the sculpture of Uahka II (Fig. 1b), preserved in the collections of the Egyptian Museum of Turin. Both the statues are made of fine-to-medium grained black diorite. The surveyed objects showed visible and widespread fracture traces on their surfaces. While Uahka II is only a single fragment of the original work, the complete statue of Hator seems to be the recomposition of disjointed original parts, reassembled together with the use of synthetic bonding resins. The major task of the study was to investigate the persistence of these discontinuities within the statues in order to make reliable decisions about the better restoration procedure and reasonable considerations about the risks of failure during mobilization and transport.

More than a hundred ultrasonic measurements were performed on selected travel-paths across each statue using an ultrasonic pulse velocity instrument. Dealing with complex-shape objects of restrained dimensions, it was very important to accurately measure the distances between the source and receiver points. From photogrammetric techniques we built a 3-D model of the statues consisting of a point cloud and a textured mesh. From the acquired data we performed a statistical analysis of the ultrasonic measurements together with tomographic processing, comparing the use of classical and staggered grids, in order to obtain the best fit of the local resolution.

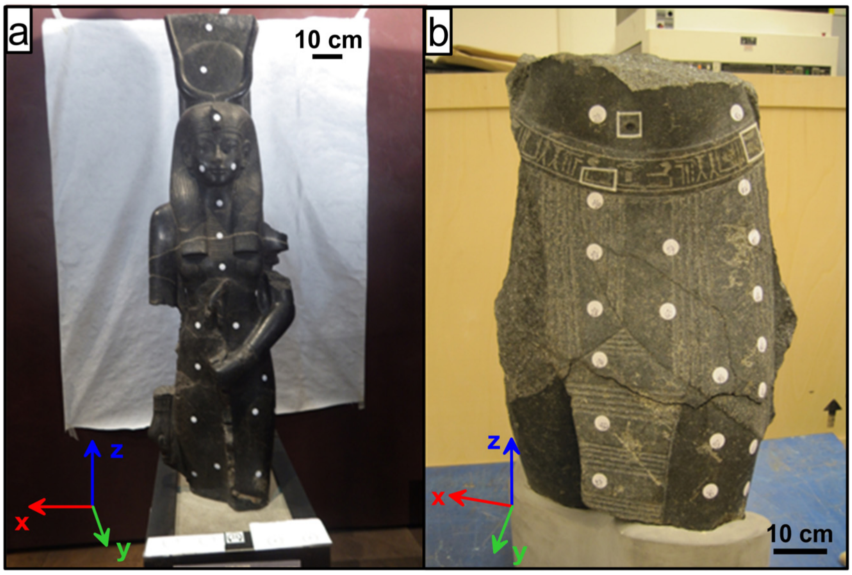

Figure 1 *The statue of Hator (a) and the remaining part of the sculpture of Uahka II (b). White round stickers correspond to the position of sources and receivers of the ultrasonic survey.*

Ultrasonic survey

Considering the need to apply the less invasive non-destructive investigation methodology, the small volume and the complex shape of the objects, we chose ultrasonic measurements to reconstruct the fracturing state of the two sculptures.

Firstly we identified a set of positions for sources and receivers on their surface with numbered stickers (82 points for Hator and 67 points for Uahka II), then we chose the couples transmitter-receiver (Tx-Rx) to investigate with ultrasonic measurements (161 travel-paths for Hator and 158 travel-paths for Uahka II). To perform the travel time analysis we used an ultrasonic pulse instrument (Pundit) with exponential probes having a nominal frequency of 50 kHz connected to an amplifier and an oscilloscope with a sampling frequency of 20 MHz. The Power Spectral Density of the recorded signals was computed to evaluate the dominant frequencies in the transmitted impulses and highlighted a main peak centered at 35 kHz, followed by a second less-energetic one at 55 KHz. Manual picking of the first arrival time was performed on each recorded trace.

The methodology is based on the reduction of the apparent propagation velocity of an ultrasonic impulse in a fractured medium. This velocity is simply obtained from the ratio between the distance (straight path from the transmitting to the receiving probe) and the travel time measured by the instrumentation. We based on the assumption that the presence of a fracture on the rectilinear path from the source to the receiver station would result in an apparent decrease in the propagation velocity of the ultrasonic impulses, since they have to follow a longer and no more rectilinear path to bypass the discontinuity. This results in a longer travel time which corresponds to a lower apparent velocity. Similarly, when passing through a fractured zone filled with synthetic materials, travel-times increase due to the lower propagation velocity in this medium with respect to intact rock. Analyzing the ultrasonic propagation on a dense pattern of paths we can get an estimation of the distribution of the velocities and consequently on the persistence of fractures inside the body.

3-D Model from Photogrammetric Analysis

In order to obtain the accurate locations of the source and receiver points of the ultrasonic survey we generated a 3-D model of the statues from photogrammetric processing. This technique is called Structure from Motion (SfM) and multiple software implementations of these concepts exist. For this case, the IGN'S open source photogrammetric suite Apero-MicMac was used. We took more than one hundred photos of each statue, moving the shooting points in order to cover the whole surface with a good overlap and a suitable detail of the Tx and Rx targets. The processing workflow of the acquired images consisted in automated tie point extraction, bundle adjustment for camera parameters derivation, dense image matching for surface reconstruction and orthoimages generation. The resultant point clouds were imported in CloudCompare for visualization, scaling, mesh generation and distance measurements. The final results also allowed the 3-D imaging of ultrasonic velocities, directly inside the statues.

Tomographic Analysis

The tomographic analysis of the acquired data was performed using GeoTomCG (Fig. 3, a and b), software which allows both processing and visualization of seismic data in a three-dimensional space, with sources and receivers located in any configuration within a 3-D grid. Starting from the dataset of coordinates obtained from the photogrammetric reconstruction (x, y, z) of each couple Tx-Rx and the related travel time, we built an initial model with cubic cells (dx=dy=dz=5 cm) and homogeneous velocity (the mean obtained from each whole dataset: 3300 m/s for Hator and 4100 m/s for Uahka II). GeoTomCG performs the tomographic inversion with the Simultaneous Iterative Reconstruction Technique, or SIRT (Lytle *et al*., 1978; Peterson *et al*., 1985). The algorithm modifies the initial velocity model by repeated cycles of three steps: forward computation of model travel times, calculation of residuals and application of velocity corrections. We rejected all the cells of the final model having no ray coverage and visualized only the ones really crossed by one or more Tx-Rx travel-paths. The remaining velocity nodes were plotted inside the photogrammetric point cloud in order to point out the weakest zones with low velocity values.

A further tomographic analysis was computed using the "staggered grid" method (Böhm and Vesnaver, 1999), a procedure implemented in another tomographic package (Cat3d). This method uses a single grid, called base grid, on which different shifts in space are applied along X, Y and Z directions. A tomographic inversion is carried out using all these new grids; then, a unique final high-resolution grid is obtained by averaging all tomographic results achieved from the different shifted grids. The advantage of using this method is to obtain a high resolution tomographic image not affected by high null space. In fact, the final high resolution grids keeps the same low null space values, corresponding to high reliability, of the base grid, which has been chosen to be well conditioned with respect of the tomographic system. In the first case (Hator, Fig. 3c), we obtained a 3D model with 30x24x90 pixels (dx=dy=dz=1.66 cm), starting with a base grid of 10x8x30 pixels (dx=dy=dz=5 cm). In the second case (Uahka II, Fig. 3d), the final model has 27x30x39 pixels (dx=dy=dz=1.66 cm), starting with a base grid of 9x10x13 pixels (dx=dy=dz=5 cm).

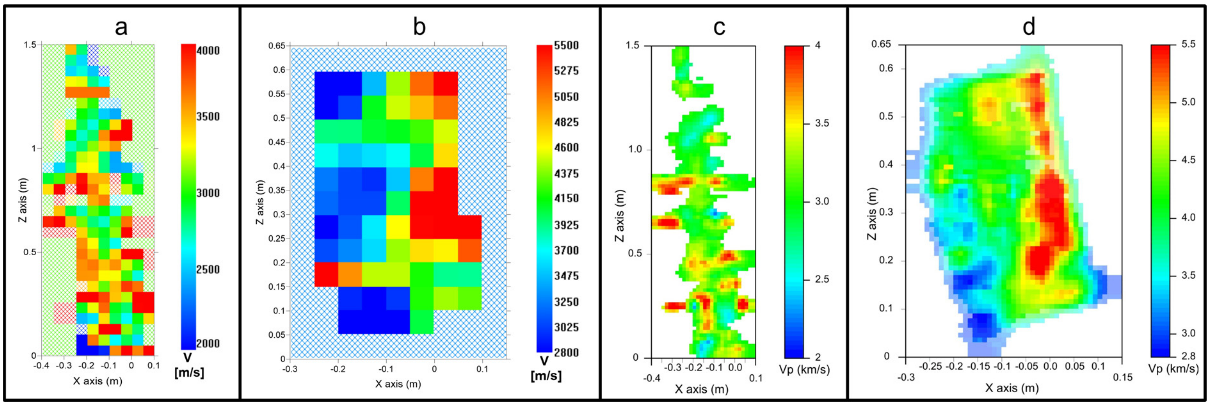

Figure 2 *Comparison of the tomographic inversion using classical (a, b) and staggered grids (c, d), starting from a model with cubic cells (dx=dy=dz=5 cm). All the results refer to vertical sections (XZ plane) at the middle of Y dimension of the 3D models obtained from the tomographic inversion (Hator: a and c; Uahka II: b and d).*

Results

The results of classical and staggered tomography showed a good agreement in locating the low velocity zones, even if, starting from the same initial model, staggered grids circumscribed them with a finer resolution, as it is clear from Figure 2.

A statistical analysis of the obtained ultrasonic propagation velocities gave a mean of 4100 m/s for Uahka II and 3300 m/s for Hator, with standard deviations of 680 m/s and 460 m/s. These are rather distant values for being recorded on objects of the same material. The comparison of the velocities on rays crossing portions of intact material returned comparable values on the two statues, supporting the thesis of a structural difference between them.

For the statue of Uahka II, all the results showed that the surface fracture do not affect in depth the volume of the statue, except for a relevant open fracture on the back left side (Fig. 3b), highlighted from both volumetric analysis of the mean velocities and classical and staggered tomographies.

While Uahka II can be considered as an intact volume with circumscribed and shallow criticalities, the results on Hator showed widespread problems, with no high-velocity rays crossing the whole statue. The tomographic results emphasized the main weaknesses in the neck, head and back base of the statue (Fig. 3a).

Conclusions

The work showed a fruitful combination of geophysics and photogrammetry for the analysis of the integrity of a couple of Egyptian statues and revealed a valuable tool to guide the procedures for their mobilization, transport and restoration.

Compared with the simple analysis of the mean ray velocities, the processing of data with tomographic inversion allowed to better circumscribe the low velocity zones (Fig. 3). The use of staggered grids led to a more detailed final resolution of the investigated volumes.

Recent development in photogrammetric processing revealed fundamental not only for the correct measurement of the transmitter and receiver coordinates of the ultrasonic survey on small-volume and complex-shape objects, but also for the visualization and interpretation of the final results.

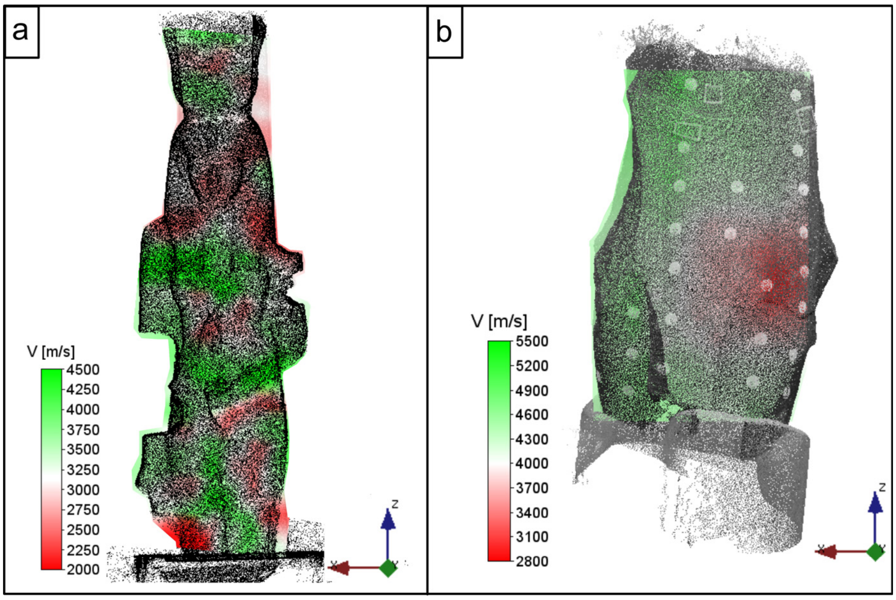

Figure 3 *Tomographic results superimposed to the simplified photogrammetric point clouds of the statue of Hator (a) and Uahka II (b).*

Acknowledgements

The authors are grateful to *Fondazione Museo delle Antichità Egizie di Torino* and to *Fondazione centro conservazione e restauro dei beni culturali "La Venaria Reale"* for the permission to work on the statues and publish the results. Thanks are also due for Diego Franco, for his fundamental help in the data acquisition.

References

Böhm, G. and Vesnaver, A. [1999] In quest of the grid. *Geophysics*, **64**, 1116-1125.

Capizzi, P., Cosentino, P.L. and Schiavone, S. [2013] Some tests of 3D ultrasonic traveltime tomography on the Eleonora d'Aragona statue (F. Laurana, 1468). *J. Appl. Geophys.,* **91**, 14-20.

Lytle, R.J, Dines, K.A., Laine, E.F. and Lager, D.L. [1978] Electromagnetic Cross-Borehole Survey of a Site Proposed for an Urban Transit Station. *UCRL-52484*, Lawrence Livermore Laboratory, University of California, 19.

Martinho, E. and Dionísio, A. [2014] Main geophysical techniques used for non-destructive evaluation in cultural built heritage: a review. *J. Geophys. Eng.*, **11**, 053001, 15.

Peterson, J.E., Paulson, B.N.P. and McEvilly, T.V. [1985] Applications of Algebraic Reconstruction Techniques to Crosshole Seismic Data. *Geophysics*, **50**, 1566-1580.

Sambuelli, L., Böhm, G., Capizzi, P., Cardarelli, E. and Cosentino P. [2011] Comparison between GPR measurements and ultrasonic tomography with different inversion algorithms: an application tothe base of an ancient Egyptian sculpture. *J. Geophys. Eng.*, **8**, S106-S116.