DOCUMENTATION AND MONITORING OF UNDERWATER ARCHAEOLOGICAL SITES USING 3D IMAGING TECHNIQUES: THE CASE STUDY OF THE "NYMPHAEUM OF PUNTA EPITAFFIO" (BAIAE, NAPLES).

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ABSTRACT:
The preservation status of an underwater cultural site can be determined as the combination of two primary factors, namely the site physical integrity, which results from the past and present interaction of the site itself with the biological/chemical agents located in the surrounding environment, and the exposure of the site to human-related threats. Methods to survey underwater archaeological sites have evolved considerably in the last years in order to face the challenges and problems in archaeological prospection, documentation, monitoring, and data collection.
This paper presents a case-study of an archaeological documentation campaign addressed to study and monitor the preservation status of an underwater archaeological site by combining the quantitative measurements coming from optical and acoustic surveys with the study of biological colonization and bioerosion phenomena affecting ancient artefacts. In particular, we present the first results obtained in the survey and documentation campaign carried out during the spring – summer 2018 in the "Nymphaeum of Punta Epitaffio" located in the Marine Protected Area - Underwater Park of Baiae (Naples).

1. INTRODUCTION

The coastal and maritime areas represent an outstanding environment pervaded by a huge diversity of cultural richness. This cultural heritage represents an important source of information for understanding the development of human civilization and it is nowadays threatened by multiple anthropic and natural risks. Several countries have already elaborated legislative frameworks for the preservation of on land cultural heritage (Vallega, 2003). On the other side, Underwater Cultural Heritage (UCH) still suffers from a lack of specific norms that clarify how the UCH has to be preserved and make accessible to the tourists.
The monitoring of the conservation state of underwater archaeological sites and the subsequent planning of the preservation activities is an important issue that, until nowadays, has been managed following several different approaches and, often, without the support of specific tools. The state-of-the-art shows just few studies that deal with single specific problems (Bruno et al., 2015; Bruno et al., 2016).
On the contrary, UCH requires the application of a holistic approach based on the collaboration among experts in archaeometry, archaeology, restoration, geology and biology. Furthermore, innovative methodologies have to be developed for improving the resolution of the surveys and to analyze materials and biological colonization of the underwater remains. All these data allow conservators to characterize the state of preservation, to plan the restoration and conservation activities and to define a strategy for the mitigation of the natural risks.
This work presents the results obtained during an archaeological documentation campaign addressed to study and monitor the preservation status of an underwater site by combining the quantitative measurements coming from optical and acoustic surveys.
The use of 3D acquisition techniques before and after dredging operations, in addition to the standard video and photographic documentation, allows scientists to acquire quantitative measurements about the volume of the sand removed during the operations and the biological growth after a certain period, to map flora and fauna colonizing the archaeological remains.

2. ARCHAEOLOGICAL CONTEST

2.1 Baiae underwater archaeological park

Baiae was a famous coastal settlement in the volcanic Phlegraean Fields, much appreciates by the Roman aristocracy since the Late Republic (II-I century BC). The thermal waters and the climate favoured the development of a monumental and residential architecture which was improved by the Emperors during the following centuries (I-IV AD). At the end of the fourth century, beginning of the fifth century AD, several ground movements (bradyseism) caused the sinking of a portion of the city below the sea level. Many luxurious villas

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built in Baiae and a large part of the town, became Emperor's property under Augustus and his successors (such as Julius Caesar, Augustus, Pompeius the Great, Marcus Antonius, Caligula, Nero, Hadrian, Septimius Severus and the list goes on).

Nowadays, most of the buildings of the city lie on the bottom of the sea covering an area of about 177 hectares that since 2002 has been declared a Marine Protected Area. The scuba divers can visit several underwater paths: 1) the Nymphaeum of Claudius lying off Punta Epitaffio with the copies of the original statues, now exposed in the Phlegraean Fields Museum; 2) the remains of the Villa dei Pisoni, with the spectacular architectural changes due to emperor Hadrian; 3) the remains of houses and storehouses of Portus Iulius; 4) the "Villa con ingresso a protiro – (Villa with Vestibule)", that is the subject of this paper, siding a road along which there were thermae, tabernae, and other buildings (Davidde, 2002; Davidde et al., 2010).

2.2 Nymphaeum of Punta Epitaffio

The Nymphaeum *(Figure 1)* was part of the imperial palace and its structure dates to the Julio-Claudian era. Its decoration finds parallels in the nymphaeum of Tiberius' villa at Sperlonga, this also decorated with scenes from the Odyssean cycle. The stratigraphic excavation identified and revealed the various phases of existence that the monument had lived through. Marble statues depicting the episode of Ulysses in the lair of Polyphemus (Ulysses offering the cup and his companion with a full wineskin), recovered by chance in 1969, are situated in the apse of the hall. In the niches of the longer sides there were statues of some members of the Emperor Claudius 'family: Antonia Augusta, his mother in the guise of Venus Genitrix; an armoured torso variously identified; a statue of a child – according to Zevi – one of Claudius' daughters who died at a tender age; two statues of Dionysus (recovered during the underwater excavation campaigns of 1981 and 1982). The new wall decoration of white marble slabs fluted with Corinthianesque calyx capitals can be dated to the end of the 3rd century AD; shortly after, at the beginning of the 4th century AD, as a result of bradyseism, the palace began to be invaded by the sea and therefore the entrances to the Nymphaeum were barred and the majority of the wall decorations as well as the lead conduits were recovered (Bernard et al., 1983, Gianfrotta, 1983). The statue of Polyphemus, not discovered during the excavation works, was evidently recovered in antiquity since its place had been taken in the 5th century AD by a child buried in an African amphora. Subsequently, before the area became permanently submerged by the waters, other tombs occupied the apse; a gold coin bearing the head of Justinian (527-565 AD) was found in one of these.

Figure 1. One of the replicas of the statues located in the Nymphaeum of Punta Epitaffio

3. METHODOLOGIC WORKFLOW

The survey and documentation of the Nymphaeum of Punta Epitaffio, one of the most important sites of the Underwater Baiae archeological park, have been carried out by a multidisciplinary teamwork coordinated by the ISCR and composed by DIMEG and 3DResearch staff.

The teamwork was composed by engineers, biologists, conservators and restorers in order to introduce the application of new technologies in the traditional methodology thus making the process of survey and documentation more efficient and accurate. With the use of acoustic systems and photo-cameras, it has been possible to obtain a very precise geo-referenced map or 2D geo-referenced reconstruction of large areas of the seabed, instead of daily sketches. The aim of this activity was to produce an accurate three-dimensional model of the archaeological site. It exploits the high-resolution data obtained from photogrammetric tools and the latest techniques for the construction of acoustic micro bathymetric maps to build 3D representations that combine the resolution of optical sensors with the precision of acoustic bathymetric surveying techniques. The method allows to obtain a complete representation of the underwater scene and to geo-localize the optical 3D model using the acoustic bathymetric map as a reference.

Such maps, obtained by optical, acoustical and position data correlation are important because they are not dependent from divers' memories; they also can be inserted in GIS tools with a daily frequency and, later, with appropriate filtering, in 3D virtual reconstructions of the site.

The use of optical 3D recording techniques before and after dredging operations, in addition to the standard video and photographic documentation, was aimed to acquire quantitative measurements about the volume of the sediment removed during the operations and to map the biological growth on the archaeological remains in order to detect areas with greater colonization. On the other side, acoustic bathymetry of the site allowed us to obtain a detailed description of the morphology of the seafloor hosting the archaeological remains.

Modifying the classical way to proceed, directly using the gathered data in order to automatically and daily improve the output maps have brought to a sort of self-assessed work cycle, where the operation planning is performed directly on the electronic format of the site visualization. Maps allow

understanding if some data have not been documented yet and if some areas require further investigations. In this way, the teamwork can dynamically change the plans during the campaign, optimizing costs and time.
The main steps of the documentation campaign are: 1) a preliminary opto-acoustic survey of the site; 2) the identification of all the archaeological structures present in the site; 3) the planning of the dredging and documentation activities; 4) the execution of dredging operations; 5) the sampling of materials and other documentation activities; 6) the detailed 3D acquisition of the area; 7) the analysis of the data about material composition and biological colonization.
The data gathered using these technologies have been used by different figures (biologists, archaeologists, engineers) in order to extrapolate different types of information such as dimensions, volume estimation, visual census of the biological species.

3.1 Planning of Dredging and documentation activities

Planning a dredging operation can be a hard task considering the amount and the kind of sediment on the sea-floor, the meteorological conditions and the sea-currents, capable of bring back the sand moved during the working days. 3D technologies can help to plan and monitor the excavation by estimating the amount of sand to be removed.
A preliminary optical survey gives a 3D model that can be useful to calculate the perimeter of the area of interest. During the survey some metric scale bar can be introduced in the sediment in order to have raw reference about the height of the sand. Those values can be used to perform a raw volume estimation and plan how many working days are needed to perform the dredging operations, based on the airlift power.
After the dredging, when the site is clean, a new 3D model of the site can be recorded to be used in future as a reference to estimate the amount of sand accumulated in a certain period.

4. GEOMORPHOLOGICAL SURVEY AND 3D RECONSTRUCTION

The survey and documentation campaigns have been carried out at the same time of a dredging operation performed to remove the sand and the sediment that was accumulated in the last years over the Nymphaeum. As it is clear from *Figure 1*, the level of the accumulated sediment was so high that the architectural and artistic peculiarities of the site were partially indistinguishable. Indeed, the topography of the submerged structures, similar to a receptacle, inexorably involves its cover-up. It is a sort of natural cage that, due to the currents, the wave motion, the prevailing winds and the sedimentological and granulometric characteristics of the seabed, tends to cover continuously itself.
The purpose of the dredging activity has been twofold: 1) make it fully accessible to the diving tourists; 2) gather the necessary diagnostic observations of the archaeological structures in order to plan the conservation interventions.
The dredging operations have been performed during the April month for 25 days. The operators, supported by 2 boats of 7 and 10 meters, removed the sand, with the use of an airlift, and big stones on the sea-floor, with weight lift bags. At the end of the work almost 80 vertical centimetres of sand have been removed from the site *(Figure 2).*

Figure 2 (a). The “Nymphaeum of Punta Epitaffio” before the dredging operations.

Figure 2 (b). The “Nymphaeum of Punta Epitaffio” after the dredging operations.

4.1 Acoustic Survey

An acoustic bathymetry of the site has been used in order to have a detailed description of the morphology of the seafloor in which the archaeological remains are located, to geo-localize the optical 3D models using the acoustic bathymetric map as a reference, and to planning the field work.
Survey operations have been conducted by using the autonomous surface vehicle (ASV) PlaDyBath (Mišković et al., 2015) equipped with a Norbit WBMS multibeam sonar, a 256 beam array with a variable swath coverage from 5° to 210°, and a pulse frequency of 400 KHz. During the acquisition, the use of an RTK GNSS-INS Applanix POS MV SurfMaster with differential correction has ensured a sub-metric precision on positioning.
The survey mission has been planned with a 90°-120° field of view angle, covering the whole area with a complete overlap between any two adjacent along-track survey lines, and also having across-track survey lines in order to maximize as much as possible the amount and quality of the bathymetry data, and to avoid holes in the bathymetric map. In particular, data have been acquired with a high percentage of along-track overlap among sonar swaths (a distance of 30m between survey lines with a swath angle of view of 120°), as well as among across-track overlap, acquiring also additional perpendicular strips.

The area covered by acoustic data extends about 45.000 m^2 in the -0.5 m / -5.6 m below sea level (bsl). The average footprint has been 0.1 m, which can be considered the smaller grid cell size in order to build the final Digital Terrain Model (DTM) *(Figure 3).*
The merging of optical and acoustic data has been done by following a consolidated approach that has been already tested in Baia (Bruno et al., 2015). It consists in the alignment of the two 3D datasets by manual selecting a set of corresponding points in both representations.

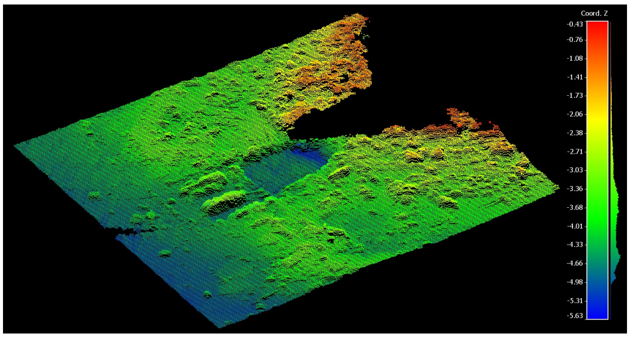

Figure 3. Digital Terrain Model (DTM) of the underwater archaeological site and the surrounding area (grid at 0.1 m)

4.2 Optical Survey

The two optical 3D models, before and after the dredging operations, was obtained using standard photogrammetric techniques undertaken with the adoption of optical cameras. In particular, the photogrammetric acquisition process has been performed according to standard aerial photography layouts that consist of overlapping straight lines and also cross lines with oblique poses to minimize the occluded areas. A Sony A7II mirrorless camera with a CMOS (Complementary Metal-Oxide Semiconductor) sensor size of 36 x 24 mm and a resolution of 6000 × 4000 pixels (24 effective megapixels), equipped with a Sony Zeiss 16-35mm f/4 lens used at 16mms was used for both photogrammetric surveys. The camera was mounted in an underwater housing manufactured by Easydive, equipped with a spherical 125 Ø port. No artificial source-lights have been used considering the low depth of the archeological site.
The camera network planned to survey the site consisted in open loop strips taken at a mean distance of 2 m above the sea bottom, ensuring a mean Ground Sample Distance (GSD) of 0.075 (cm/pixel). The camera was in downward-looking position and was moved horizontally right–left and left–right on overlapping strips along straight lines, ensuring a 70-80% forward overlap and 50% side overlap. A dataset of 780 images has been created for both models.
Considering the level of detail required to properly evaluate the biological colonization, all the images have been acquired in RAW file format (.arw files format with Sony cameras) and image enhancement techniques (Mangeruga et al., 2018a; Mangeruga et al., 2018b) have been applied to recover details lost due to the poor visibility in the water, as shown in *Figure 4.*

Figure 4 (a). Raw picture before image enhancement.

Figure 4 (b). Picture enhanced with algorithms described in (Mangeruga et al., 2018).

A Structure-from-motion (SfM) 3D reconstruction was performed using the commercial software Agisoft PhotoScan Pro. A local metric coordinate system based on a network of Ground Control Points (GCPs) was set in the software to scale the sparse 3D reconstruction. In particular, 20 natural features were used as GCPs whereas their Euclidian coordinates were retrieved through a simple trilateration algorithm based on in situ measurements. A non-linear optimization strategy, in which both camera pose and interior orientation parameters were adjusted, was applied to minimize error at GCP coordinates. The average root mean-square error (RMSE) achieved at this step was 0.022 m for ground coordinates. The GCP RMSE encompasses both errors in the GCP measures and intrinsic accuracy of the sparse SfM reconstruction. Finally, a Multi-View Stereo (MVS) algorithm was used by PhotoScan to produce a dense 3D point cloud from the refined intrinsic orientation and ground-referenced camera exterior orientation.
After the meshing and the texturing process a complete model is obtained *(Figure 5).*

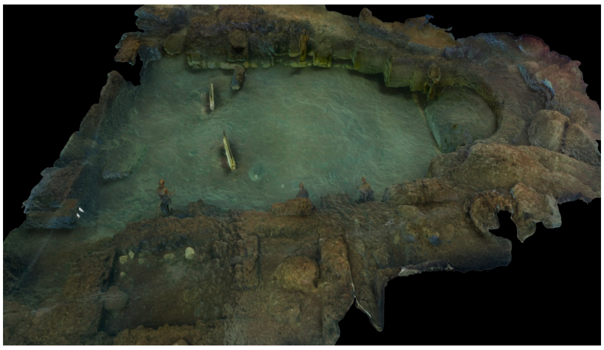

Figure 5. Textured 3D model of the "Nymphaeum of Punta Epitaffio" after the dredging operations (19 million polygons).

5. DATA POST-PROCESSING FOR DOCUMENTATION AND CONSERVATION

5.1 Biological Degradation and 3D Mapping

The monitoring of biological colonization on archaeological artefacts in marine environment is a fundamental phase in the field of conservation works. In fact, underwater archaeological artefacts are particularly subjected to recolonization phenomena after restoration or dredging interventions because of their susceptibility to marine biodeterioration. Previous studies have highlighted how biodegradation phenomena represent a destructive force against submerged archaeological artefacts, sometimes leading to total destruction of them. Significant case studies are the Roman submerged mosaics in the Underwater Archaeological Park of Baiae, Naples (Italy) and the statues now displayed in the Archaeological Museum of Campi Flegrei in Baiae (Davidde et al., 2010; Antonelli et al., 2015; Ricci et al. 2009, 2016). Other research on archaeological artefacts recovered from Capri showed the bioerosive role of micro and macroorganisms (Sacco Perasso et al., 2015). In this frame, monitoring operations require periodic inspections to detect change in an underwater site's condition. Preliminary studies have illustrated the use of 3D imaging techniques to study bioerosion phenomena of Underwater Cultural Heritage (Ricci et al., 2015), but the field of biological monitoring with the abovementioned techniques has not yet been investigated in detail. For this reason, the development of a new methodology providing useful information to document the biological colonization (in particular before and after restoration or dredging interventions) by 3D imaging techniques was performed. This method can be carried out easily on selected volumes that have to be controlled and can therefore provide useful information on the growth rate of the organisms, on their distribution on the surface and the related influence of environmental factors such as the hydrodynamism (on different exposures, at different heights, on different lithotypes etc.). The 3D images associated with the photographic documentation permit to reach a greater level of detail leading to an identification of the main groups of colonizers. The advantages of this method are above all in the possibility of observing the archaeological structure in its entirety and simultaneously assessing the biodeterioration level and any damage suffered by the artefact/structure in relation to its exposure in a specific microhabitat. The rapidity and multiplicity of the results obtained with the 3D imaging techniques make this method very useful both in the periodic monitoring procedures and in the planning of maintenance and restoration works.
The 3D mapping of the biological attacks has been made using Blender open-source modeling 3D software. The method adopted in this study is based on the creation of 3D surfaces by selecting over the existing 3D model areas colonized by the various group of organisms. The 3D mapping can be carried out using the high detailed images acquired in the photogrammetry as reference, so that the biologist can refer to the high-definition image to recognize the groups of organisms colonizing the areas affected by biodeterioration. Using a laze selection, the scientist can circumscribe the region of interest and then he/she duplicates it creating a new object. A very small offset, in the millimeters scale, has to be applied to the new mesh in order to visualize it over the original model. Every small surface has been grouped, in what Blender calls "collection", and has been colored according to the biological group to which it belongs. This method permits to turn on and off the visualization of every kind of degradation class to better visualize the information needed and to set a transparency level in order to simultaneously display multiples class of degradations *(Figure 6).*
Considering that every part of deterioration is represented by a mesh it is possible to calculate their surface. Blender has a specific 3D tool that perfectly suits this need. In this way, making multiples monitoring surveys during the time, it is possible to estimate the superficial growth of the biological colonizers after a certain time.

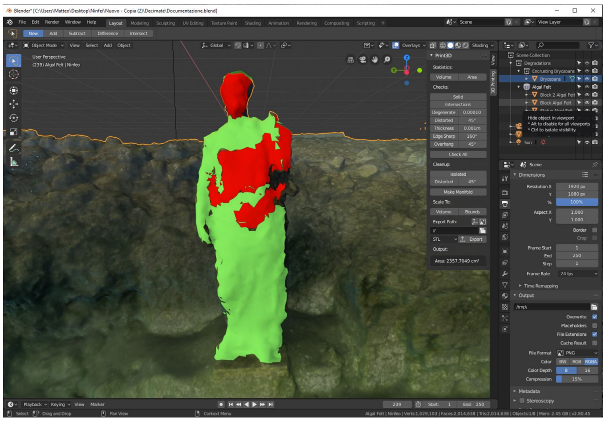

Figure 6. An example of 3D Mapping on the 3D model of Nymphaeum of Punta Epitaffio. Each colour is associated to a specific group of biological colonizers.

5.2 Volume Estimation

Once the survey activities ended, the final optical model and acoustic data have been merged by means of a target–based registration approach based on the detection of homologous geometrical entities in both 3D representations. An affine transformation between the two representations has been used to define a quantitative error metric. In particular, the mean distance has been used as accuracy parameter. An average error of about 8 cm has been obtained.

The opportunity to acquire two 3D models, representing the site before and after the dredging operations, gave the possibility to estimate the quantity of sand removed from the sea-floor. Volume *(Figure 7)* and position *(Figure 8)* of the removed sand provide very useful information for biologist and archaeologist to understand which parts of the artefacts become exposed to the sea water and consequently, to future biological colonization. This method allows the periodic monitoring of the area during the seasons, to better understand the sand movements and consequently provide useful data to evaluate a conservation strategy.
In the workflow, firstly, the two models have been aligned based on well-known natural common points like statues heads and walls. The final alignment has been refined using the ICP algorithm, integrated in the software, with 20 iterations. After, the models have been cut of the surrounding archaeological areas using the same shape cutting mask, in order to have a comparable area to process. The outcoming meshes cannot be used to calculate 2.5D volume so those have been transformed in point clouds with 2 million of points, assuring a comparable density in the entire area of the models. At the end of this process the 2.5D volume calculation have been performed. From the analysis 234 m^3 of sand have been removed from the sea-floor, making, for example, the lower parts of the statues visible.
Since the archaeological site is very exposed to the sea currents, the area will be probably covered by sand in a close future. In this case the amount of sand covering the area could be calculated by comparing the 3D model of the current state with the model acquired after the dredging work, that represents the reference model of the structure perfectly cleaned. In addition, it will be easy to estimate how many days of work technical underwater operators will need to dredge the site based on the airlift power.
Those examples explain how those kinds of data are useful in planning conservation activities in the archaeological sites.

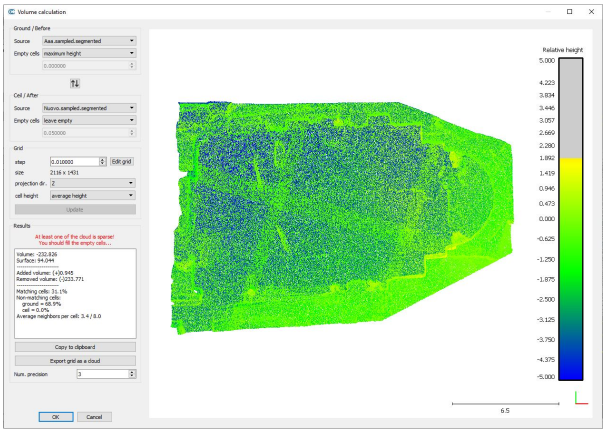

Figure 7. 2.5D volume estimation using CloudCompare software on the Nymphaeum of Punta Epitaffio.

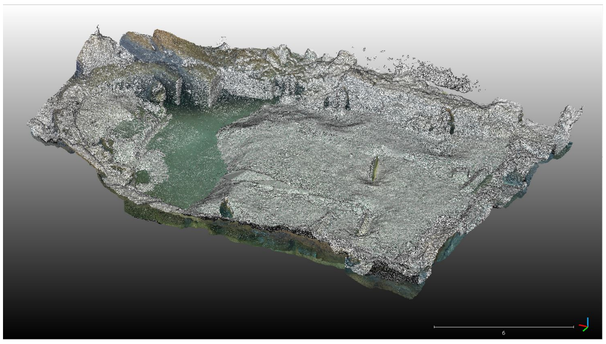

Figure 8. Overlapped 3D models of the site before and after dredging: in white the sand that covered the archaeological site.

CONCLUSIONS

The use of 3D acquisition techniques before and after dredging operations, in addition to the standard video and photographic documentation, has allowed acquiring quantitative measurements about the volume of the removed sediment during the operations, document the biological colonization of the archaeological remains in order to detect areas with different biological growths, whereas acoustic bathymetry of the site allowed us to have a detailed description of the morphology of the seafloor in which the archaeological remains are located.

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