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Coastal and shallow marine geophysical investigations in the Roman site of Baia in Naples, Italy

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***Abstract* – The Roman site of Baia (Naples, Italy) belongs to the Campi Flegrei volcanic field, which is affected by vertical ground movement called "Bradyseism", that strongly influenced the morphology of the coast. As a consequence, a number of architectural remains are now below the sea water surface, and partly or totally buried within the marine sediments. This work presents the results of the coastal and ultra-shallow marine geophysical survey aimed to investigate and reconstruct the onshore-offshore hidden built environment in the specific site. The geophysical approach included Ground Penetrating Radar (GPR) to check the continuation of structural remains on the coast, static 3-D Electrical Resistivity Tomography (ERT) to reconstruct the architectural relics in the shallow part and 2-D dynamic ERT to examine the layers below the the seabed in the deeper sections of the bay. The outcomes of this work contributed to the better understanding understanding of the submerged cultural landscape of Baia expanding the archaeological knowledge towards the shallow part and the coast.**

I. INTRODUCTION

The study and documentation of the hidden Cultural Heritage is rapidly developing as technology advances, allowing for detailed spatial investigation and interpretation of both under ground and under water archaeological features. Nowadays, it is possible to "look" beneath the soil and produce images of buried structures to assist and complement archaeological research in a timely and costly efficient manner. In marine environment, the classification of visible submerged archaeological objects and the mapping of the morphology of the sea bottom using multibeam bathymetry and acoustic backscatter imagery have substantially contributed to the management of submerged archaeological remains [1, 2]. To this direction seismic imaging techniques proved to be effective tools for obtaining detailed descriptions of the shallow subseafloor [3]. However, the land-sea-boundary often remains a blank spot, due to the difficulty to match land-based and marine geophysical data. Moreover, acquiring detailed image of the subsurface structures in very shallow water is still a changeling issue due to disadvantages associated with linear acoustics used by conventional sub-bottom profiler systems, and the highly conductive nature of the seawater in comparison with the resistive sediments when the electrical resistivity method (ERT) is employed [4].

In recent years, innovative geophysical investigations have been carried out in littoral and shallow off-shore marine environments using ERT methods [5]. A combination of submerged static and moving survey modes were used to document potential buried and submerged structures. The new approach incorporates precise knowledge for the conductivity of the saline water and the shallow bathymetry in the modelling and inversion procedure to counterbalance the inherent limitation of employing ERT in a conductive environment. Resistivity surveying based on the above mentioned methodology has been tested in different coastal archaeological sites proving its efficiency in mapping buried archaeological and stratigraphic features in extremely shallow water environment [6].

II. ARCHAEOLOGICAL BACKGROUND

The Roman site of Baia (Naples, Italy – Fig.1) belongs to the Campi Flegrei volcanic field, which is affected by vertical ground movement called "Bradyseism" that strongly influenced the morphology of the coast over the last 2 Ka. As a consequence, a number of architectural remains including villae maritimae and landing ports are now below the sea water surface, and partly or totally buried within the marine sediments.

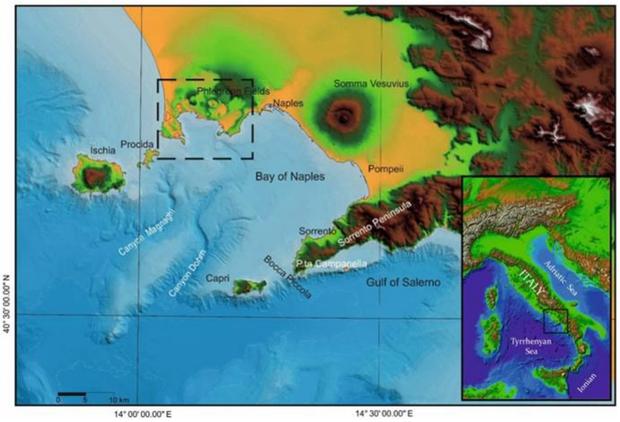

Fig. 1. Location of the study area

The entire archeological area from the ancient Puteoli (the currrent Pozzuoli) harbour to the Baianus Lacus (Baia) was mapped under the framework of multiannual underwater archaeological surveys and, more recently, with relatively deeper marine geophysical investigations. The Puteoli remains are mainly related to the presence of Portus Iulius, which was initially a military complex, later converted to commercial. On the other hand, the Baianus Lacus was essentially made from Villas and luxury buildings and was the site of several thermal complexes (Fig. 2). Geophysical prospections included high resolution bathymetry, which enabled to map the three-dimensional shape of submerged objects and ultra-high resolution parametric (non-linear) echo sounder (PES) surveys to search for structures and paleo-topographies that are hidden below the seafloor [7].

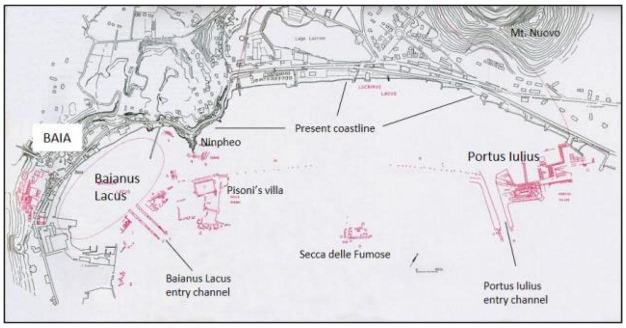

Fig. 2. General archaeological map of the archaeological area.

III. METHODOLOGY

The geophysical campaign on the coastal and shallow marine area in the bay of Baia has been performed as a demonstration study to indicate the effectiveness of the Ground Penetrating Radar (GPR), static and dynamic electrical resistivity tomography (ERT) to fill the gap of data in the very shallow water and onshore environment of the very shallow water archaeological settings. The survey was carried out in the period of 6-12 November 2022 and it was focused on the coast, the shallow and the relatively deeper sections of the bay up to 4 m depth.

The bathymetric survey covered more than 19,000 square meters and it was conducted by combining two different methods depending on the depth of the sea water. The coastal area and the shallower part of the bay was mapped using a GNSS unit mounded on a pole which was in constant connection to a base station for differential corrections. For the deeper parts of the bay the SonarMite BTX single beam sonar was used.

The GPR survey was completed using a 250 MHz antenna. The measurements were concentrated along the coast covering an area of 1,250 square meters next to the sea shore and on the beach of the site (Fig. 3). The inter-line distance of the transects was 0.5m and the sampling interval along each line 0.05m within the different deployed grids. Afterwards the signal of the individual GPR transects was enhanced with the employment of standard processing routines (trace reposition, time zero correction, dewow filter background subtraction, spreading & exponential compensation gain). The velocity of the electromagnetic signal was calculated through the fitting of a hyperbola in respective reflections appeared in the radargramms. Then a Hilbert Transform was applied to calculate the instantaneous amplitude and extract depth slices based on the calculated velocity.

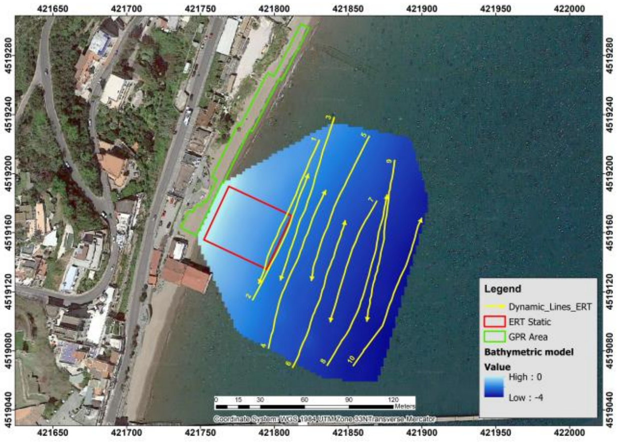

Fig. 3. Layout of the GPR and static ERT grids long with the dynamic 2D ERT lines on a Google Earth satellite image.

The static 3D ERT covered a grid with dimensions 40m by 47m (Fig. 3) with multiple parallel 2-D lines where the inter-line and inter-electrode distance was equal to 1m. The marine multimode cable with 48 stainless steel electrodes was attached on the sea bottom along the predefined survey transects and the resistivity instrument was placed on the coast. A dipole-dipole electrode configuration combining was chosen for the collection of the tomographic apparent resistivity data where multiple combinations of N separations (distance between the current electrode and the potential dipole) and unit electrode spacing was utilized to increase the signal to noise ratio and map the deeper stratigraphy.

The dynamic measuring mode was used to map the sub bottom electrical properties in the deeper part of the bay along 10 lines (Fig. 3). The marine cable composed of 13 graphite electrodes with 1m separation was sunk in the sea and the multichannel resisitivity instrumentation was placed on a being able to log ten dipole-dipole apparent resistivity readings from different layers with a single current injection, facilitating the field application of the dynamic mode. The one end of the underwater cable, the GNSS sensor and the sonar device was connected to the resistivity instrument, which in turn was synchronized to a toughpad running a special managing software to log the resistivity and bathymetry measurements at the same time. The boat was navigated along predefined transects with relatively small speed (~1-2m/sec) trying to keep a constant distance between the individual lines.

The processing of the individual static and dynamic 2-D ERT lines followed a specific flowchart described in [6] (outlier removal, correction for bathymetry and sea water resistivity measured with a high precision conductivity meter) to evaluate their resolving capabilities in imaging the vertical stratigraphy and outlining potential submerged archaeological structures. For the static grid 3D processing and inversion approaches was used to compile depth slices at increasing depth below the sea bed.

IV. RESULTS

The GPR depth slices show a strong attenuation of the electromagnetic signal in the depths larger than 40-50cm, especially in the section that is closer to the coastline. Furthermore, the superficial slices outline some strong reflections along the western boundary of the GPR grid. The nature of these high reflectivity areas is twofold, originating from the increased moisture due to the flow of water along small streams and the accumulation of surface stones/pebbles. Thus, the existence of these external factors obscured any electromagnetic signal that could be attributed to potential subsurface archaeological features (Fig. 4).

Fig. 4. GPR depth slice of 0.3m below the ground.

Sonar bathymetry in combination with GNSS receivers mapped the shallow and the deeper part of the bay. The resulted bathymetric model shows a smooth increase of the sea floor depth from the coast towards the eastern section of the bay with the respective depth ranging from 0m to less than 4m and an average depth of 2.65m (Fig. 3).

The 3D resistivity inversion model of the static ERT grid exhibited relatively low RMS error (8.2%) showing the good quality of the collected data. The submerged subsurface was divided in ten layers of progressively increasing thickness reaching up to the depth of 5.6 meters below the sea-bottom. The entire range of the respective depth slices outline a linear conductive feature with resistivity values less than 0.05 Ohm-m that is characteristic to a metallic object. It has an average thickness of 3.5m and an almost north-south orientation. Its visible length is more than 27m that seems to extend further to the south and outside the limits of the grid. The in situ visible observation of a metallic object on the seabed during the measurements and the information from the locals, it is reasonable to assume that this conductive linear feature is attributed to a collapsed funnel related to a shipwreck (Fig. 5).

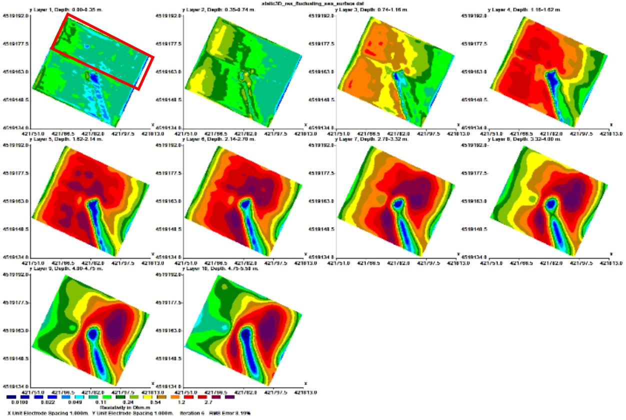

Fig.5. Resistivity depth slices extracted from the three dimensional inversion model of the static ERT grid.

Unfortunately, the existence of the above conductive object below the seabed can potentially affect the respective resistivity measurements in the entire surface of the static ERT grid. Thus, an extra effort was made to enhance the resolving capabilities of the resistivity depth slices by processing only the ERT lines covering the northern half of the grid, excluding the southern lines crossing the metallic object. The respective 3D inversion model has even smaller RMS (3.76%) in relation to the respective model of the entire grid. In addition to this, the horizontal slices up to a depth of about 1.5m below the seabed managed to illuminate resistive features most probably related to structural remains belonging to a wider building complex.

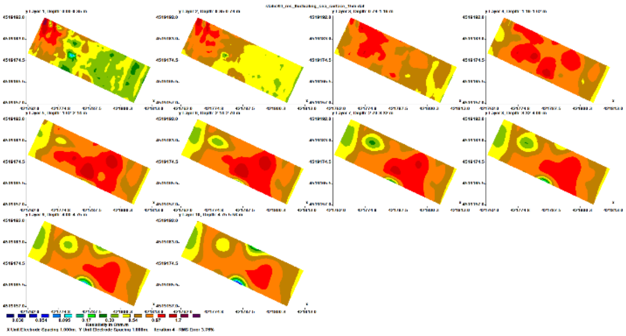

Fig. 6. 3D resistivity inversion model of the the red rectangle that outlines the northern part of the area extracted from the static ERT grid and re-preocessed in order to avoid the influence of the long, diagonal conductive feature.

The field strategy of the dynamic ERT survey resulted in a relatively coarse spatial distribution of the respective ten lines having a larger interline distance (>4-10m) in relation to the basic electrode distance (~1m) along the lines. This actually prohibited the simultaneous 3D processing of all the tomographic data. So inevitably, the lines were inverted individually within a 2D context using similar processing parameters in order to extract the vertical resistivity distribution along the specific sections. The 2D inversion models outline the vertical stratigraphy formed by submerged soil materials with different resistivity properties up to a depth of about 3m below the seabed (Fig. 7). All lines reconstructed a resistive coarser layer in depths more than 2-2.5m below the seabed having undulating upper surface and resistivity value more than 0.8 Ohm-m. The overlain layer with resistivity values in the range of 0.3-0.8 Ohm-m corresponds to finer soil deposits. Within this resistivity background of soil material, possible structural archaeological features have been indicated as point resistive anomalies in a depth of less than one meters below the sea bottom up (Fig. 7). The rectification of these point features along each dynamic line shows a relatively dense distribution of possible cultural material hidden below the seabed (Fig. 8). The combined interpretation of the point and polygon resistivity anomalies indicate the continuation of the submerged Roman site of Baia in the shallower marine part towards the coast.

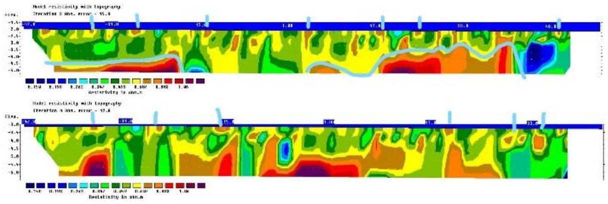

Fig. 7. 2D vertical resistivity section along two representative dynamic lines. Vertical cyan lines highlight the resistive anomalies buried up to 1m below the sea bed.

V. CONCLUSIONS

It is generally accepted that the land-sea-boundary often remains a blank spot, due to the difficulty to match land-based and marine geophysical data. Moreover, acquiring detailed image of the subsurface structures in very shallow water is still a changeling issue due to disadvantages associated with linear acoustics used by conventional sub-bottom profiler systems, and the highly conductive nature of the seawater in comparison with the relative more resistive sediments. In order to overcome these problems an integrated implementation of complementary geophysical methods is often needed to provide optimal information on structural remains submerged in the ultra shallow water context.

Overall,this work accomplished its basic objective aiming at a better understanding of the submerged cultural landscape of Baia through the implementation of geophysical methods appropriately modified to fit in the ultra-shallow marine environment. The results expanded the archaeological knowledge towards the shallow part and the coast, completing the archaeological evidence in the deeper marine sections (Fig. 8).

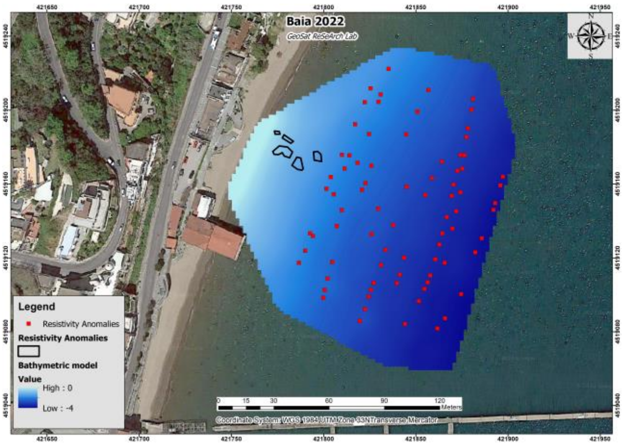

Fig. 8. Point and polygon resistivity anomalies indicating the location of possible archaeological remains in the marine area that was surveyed in the bay of Baia.

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