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COMPLEX GEODETIC AND GEOPHYSICAL WORKS SUPPORTING CONSERVATION AND ARCHITECTURAL RESTORATION OF THE HISTORICAL MONUMENTS. VALUING THE VESTIGES OF TRAJAN'S BRIDGE HISTORICAL MONUMENT

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ABSTRACT:

This scientific work aims to present the complex topo-geodetic and geophysical works carried out as part of the project history files, highlighting the vestiges of the historical monument "Trajan's bridge", built between 103-105 by the architect Apollodorus from Damascus. The focus of the research was on combining in-situ studies of the natural terrain, using topographic, geodetic, and photogrammetric methods, with the analysis of lithology and buried structures, as well as applying geophysical methods like magnetometry and electrometry, to better understand the lithology and provide new insights into historical monuments.

1. INTRODUCTION

Trajan's Bridge over the Danube River was made by the great Greek architect Apollodorus of Damascus at the request of the Roman Emperor Trajan, it was built between the years 103 and 105. A ruin of this bridge still exists today. This bridge is a Romanian historical monument, classified by the Ministry of Culture under the code MH-I-m-A-10047.04.

In the 19th century, when the water level of the Danube River was still low, the twenty supporting pillars could be observed. Subsequently, for navigational reasons, some of these pillars were dismantled. Currently, only one of the pillars is visible on the Romanian side of the Danube. In 2023, Mehedinți County, through the Mehedinți County Council, launched a project to showcase the historical monument of Trajan's Bridge, along with a second project titled "Pages of History – Restoration, Conservation and Enhancement of the Roman Amphitheatre".

The archaeological research of Trajan's Bridge was carried out in the past by P. Polonic, J. Fakler, N. M. Ștefănescu, and O. Richter during the years 1896–1898, under the archaeological supervision of Gr. G. Tocilescu. The excavations that aimed at consolidating the ruins of Trajan's Bridge were conducted between 1961 and 1962, focusing on the portal-type pier and the abutment-type pier. In 1984, the project titled "Reconstruction and Protection of Historical Monuments in the Reservoir Area" was carried out as part of the development of the "Iron Gates II Hydropower and avigation System", under the supervision of architect Aurel Teodorescu. Between 2020 and 2021, restoration and conservation operations were performed on Trajan's Bridge (Marc Arvinte, 2010), as illustrated in Figure 1.

Figure 1. Image of the reconstruction of Trajan's Bridge, according to the Iron Gates Region Museum, based on Edgar Duperrex, 1906

At present, the Mehedinți County Council has launched a project to enhance this historical monument, including the execution of topographic, geophysical, geotechnical, architectural, and structural studies at the site. The lithology and stability of the site are affected by water infiltrations occurring in the basin area that safeguards the remains of Trajan's pier.

2. Mainbody

2.1. Geodetic and Photogrammetric Survey

Between 2023 and 2024 we carried out comprehensive topographic, geodetic, geotechnical, and geophysical surveys as part of an interdisciplinary team, focusing on the historical monument of Trajan's Bridge. The outputs of the in-situ research consisted of: a Topographic Site Plan at a 1:500 scale, to support architectural enhancement efforts; a digital orthophoto map mosaic; and a digital terrain model of the studied area, from which contour lines corresponding to the natural terrain topography were digitally extracted. Photogrammetric methods can be also used for the preparation of cadastral documentation, approved by OCPI Mehedinți, or any cadastral operation required for the inventory of public property (Manu C-S et. al. 2023). The studied site is part of the public domain of Mehedinți County, managed by the Iron Gates Region Museum.

Comprehensive geophysical and geotechnical investigations were conducted, including dry drilling, percussive drilling, dynamic penetration testing, direct current geo-electrical measurements, utilizing the electrical resistivity tomography method and geomagnetic surveys aimed at identifying buried structures and assessing existing water infiltrations in the vicinity of the ruins of Trajan's Bridge.

The geodetic works involved performing topographic measurements using a Stonex S10 Plus GNSS receiver for establishing a detailed topographic survey network and a Stonex R2W Plus Total Station (1-second angular accuracy, RL1000 m range) for setting out characteristic points. We also utilized photogrammetric technology based on the use of low-altitude UAVs, previously successfully integrated into architectural conservation-rehabilitation projects and archaeological research of heritage monuments (Nache R, Păunescu C, Manu C-S, Cucăilă S, Tivig D-F, 2019); specifically, a DJI Phantom 4 RTK system was used to produce a digital orthophoto map mosaic with a resolution of 5.00 cm and a digital surface model, with an absolute accuracy of 10.00 cm. These outputs are valuable for volume calculations, generating cross-sections, and disseminating spatial altimetric data across large areas. Image processing was conducted using Agisoft Metashape and Global Mapper software, operated on advanced graphic workstations, as illustrated in Figure 2.

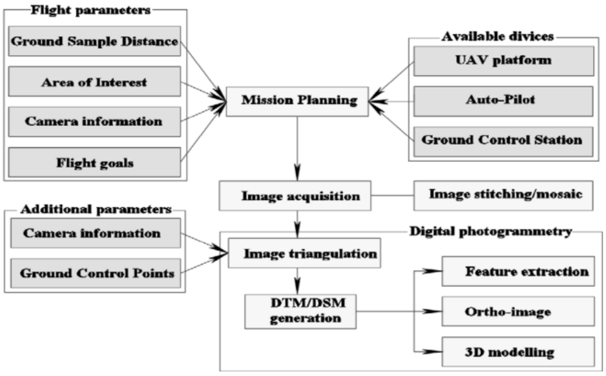

Figure 2. Workflow used in photogrammetric processing

Figure 3. Trajan's Bridge Pier Area, DTM (upper side of the figure) and Orthophoto map (down side of the figure) obtained using U.A.V. technology

2.2. Geoelectrical works

Field data acquisition involved the execution of six electrical resistivity tomography (ERT) profiles, designed to provide detailed information on the resistivity variations within the geological formations of the studied area.

The geo-electric investigations were conducted using an IRIS resistivity meter, produced by IRIS Instruments, equipped with 48 electrodes.

The field data acquisition procedure involved placing metallic electrodes along the predefined alignments, ensuring proper soil contact. Subsequently, the cables were deployed, and each electrode was securely connected to its designated cable connector using clamp connectors, ensuring the correct sequence was maintained. Once the cables were connected to the instrument, the acquisition parameters were configured to mitigate various types of noise that could compromise data quality, aiming to improve the signal-to-noise ratio. Among the potential sources of noise are electrode polarization, telluric currents, and electrical power networks. For the receiver, after selecting resistivity as the measurement mode, an error limit of 0.2% was established. This error limit corresponds to the standard deviation of repeated measurements, relative to the mean value. Considering the distance between the electrodes, each measurement was repeated between 1 and 4 times, but only if the error limit was not reached. The delay time, defined as the interval between switching to current transmission and the signal integration for initiating the resistivity measurement, was set to 300ms to ensure proper soil charging. The acquisition time, which is the duration needed to integrate the signal for each measurement cycle, was set to 500ms. It was also possible to set the frequency of the high-voltage lines to 50-60 Hz to ensure parameter adjustments for filtering noise from the power lines and grounding systems. For the transmitter, the minimum current was set to 0.1mA, the maximum current to 500mA, and the maximum power to 150 W; the maximum output voltage was set to 500V. The acceptable threshold for electrode/soil contact resistance was set at 50KΩ, while a resistance above 300KΩ was considered to indicate a weak electrode/soil coupling. The maximum current used for electrode testing was 100mA. To ensure quality control of the recordings, an electrode/soil contact test was conducted, along with a verification of the instrument's current source charge level. The geo-electrical data processing was carried out using Res2DINV software. The final objective was to generate a section depicting the variation of real resistivity with depth. Various filtering techniques were applied to each profile to enhance the signal-to-noise ratio and reduce measurement errors caused by contact conditions or geological factors.

From a geophysical perspective, the geo-electrical surveys conducted on the upper terrace, within the courtyard of the Iron Gates Museum in Drobeta Turnu Severin, revealed a structure with significant lateral variations. By correlating these findings with historical data, an interpretation was made to provide valuable insights for two primary objectives: identifying the original natural topography and the condition of the subsequent fill deposits in the area, and detecting potential water sources causing infiltrations in the Trajan Bridge ruins area.

The geo-electrical profiles revealed the boundary between the fill material and the natural geological substrate. In situ fill layers were identified with thicknesses ranging from 5.00 to 10.00 meters. Considering the paleo-topography of the area, it is estimated that the fill thickness reaches a maximum of over 15.00 meters near the retaining wall beside the existing railway line within the studied site. The lithology of the natural environment beneath the former valley, which was filled with deposits, is predominantly argillaceous. This suggests the existence of an impermeable layer that could serve as the base for an aquifer system within the fill material. Water infiltration most likely accumulates along the paleo-topography of the old valley. The current flow is heavily influenced by the morphology of the fill and human-made structures, with the retaining wall and railway embankment functioning as a dam, allowing water to accumulate up to a certain level, as illustrated in Figure 4 and 5.

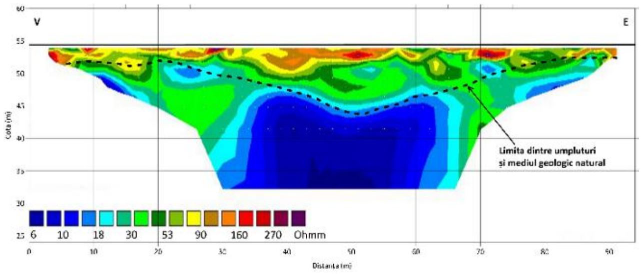

Figure 4. E3 profile: real resistivity section

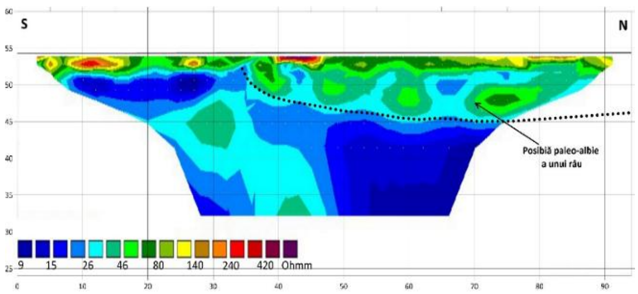

Figure 5. E1 profile: real resistivity section

The increase in resistivity values in the northern part of the profile has been interpreted as a depositional channel of alluvial sediments. This theory is further supported by data obtained from geotechnical boreholes carried out in the area of the Roman amphitheater. This channel represents a former river valley that flowed in a NE-SW direction into the Danube River. This porous-permeable geological structure is most likely the primary route through which groundwater circulates, directing it towards the fill material layer, then beneath the support wall and railway embankment towards the concrete basin (where the historical monument, represented by the remains of Trajan's Bridge, is currently situated).

To assess the groundwater level in the fill material layer, it is essential to carry out a borehole investigation and piezometric monitoring in the terrace area of the museum courtyard, close to the railway support wall. Understanding the functioning of this hydro geological system will facilitate the design of a drainage solution to prevent flooding of the basin where the historical monument, the remains of Trajan's Bridge, is located, as illustrated in Figure 6.

Figure 6. Geophysical data collection with the GSM-19 magnetometer in the work area (in the right side of the figure)

The geo-electric profiles E5 and E6 were executed on the lower terrace located on the Danube River bank, near the base of Trajan's Bridge. Profile E5 was able to reveal the presence of a bored pile, which is part of a diaphragm wall constructed for the protection of the monument's basin during the 1984 works. Profile E6, through correlation with data obtained from geotechnical boreholes, allowed for lithological interpretation also resulting in geo-electrical profiles that reveal the upper soil lithology as illustrated in Figure 7; another way of revealing the subsoil stratum is the use of techniques specific to mining topography (Cucăilă, S, Cucăilă, M, 2021) methods and technologies successfully used in archaeology (Palmer L.S., 2014, Schmidt, A., 2009, Daria, H. et al., 2011).

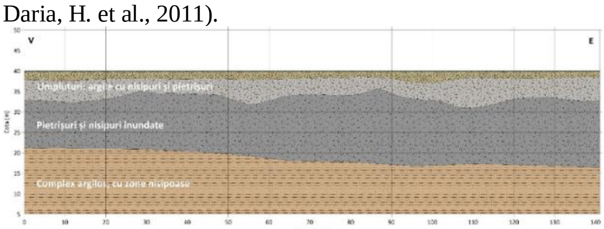

Figure 7. Geo-electric profile E6 - lithological interpretation

2.3. Geo-magnetic surveys

A geomagnetic survey was carried out in the area of the Trajan's Bridge pier ruins to detect buried structures. The perimeter of the survey area was irregular, as the equipment used for recording magnetic field values provided great flexibility, allowing for access to the entire area free of dense vegetation. Field measurements were taken using a GemSys

GSM-19W Overhouser Magnetometer (Smekalova T.N. et al., 2008), with the data being processed using custom software and visualized using Surfer 23 software. The purpose of the magnetometric survey was to measure variations in the Earth's magnetic field, as illustrated in Figure 8.

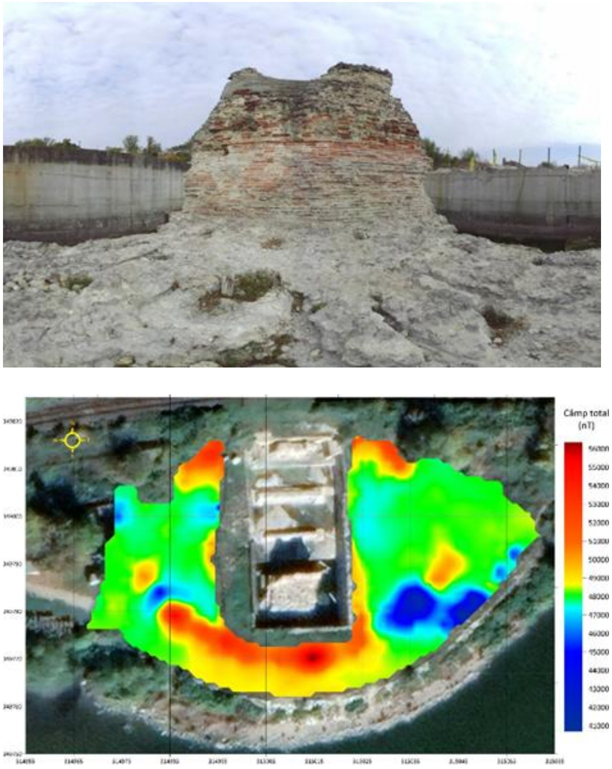

Figure 8. Foot of Trajan's Bridge Area – Total Magnetic Field Map

The geomagnetic investigations revealed several anomalies in the southern part of the pier's basin. This anomalous distribution was interpreted as a diaphragm wall constructed from bored piles with embedded steel reinforcement.

Another sheet pile wall was identified in the northern area, with its edges detected within the geomagnetic survey zone. In sections where investigations were not possible, parts of the wall were visible at the surface, as illustrated in Figure 9 (a, b).

Figure 9. a) Dynamic penetration test (SPT) execution (at the upper side of the figure), b) Geophysical data collection with the GSM-19 magnetometer (down side of the figure)

Figure 9. a) Dynamic penetration test (SPT) execution (at the upper side of the figure), b) Geophysical data collection with the GSM-19 magnetometer (down side of the figure)

An analysis using a modified colour scale highlighted a local anomaly with a longitudinal shape, exhibiting a much lower intensity compared to the drilled piles. Based on surface observations in the area, this anomaly was interpreted as the path of a stormwater drainage pipe from a section of the city of Drobeta Turnu Severin, as illustrated in Figure 10.

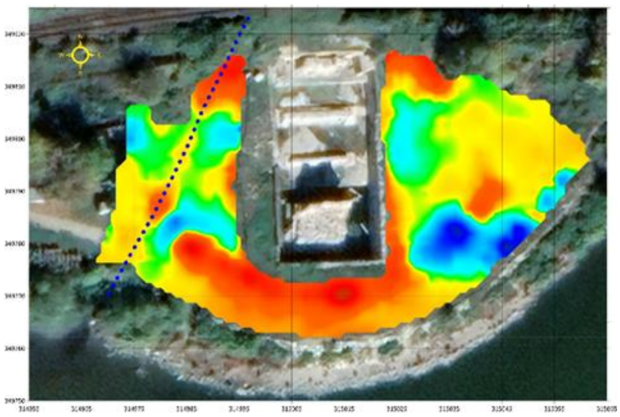

Figure 10. The total magnetic field map – stormwater drainage pipe (blue dotted line)

3. CONCLUSIONS

The archaeological research and architectural restoration of historical monuments rely on interdisciplinary collaboration between experts in geosciences, archaeology, architecture, and structural engineering (Melinte, M., 2007, Milo, P., Murin, I., Vágner, M.,2022). Techniques and methods from surveying and photogrammetry, such as 3D laser scanning, successfully used in conservation and monitoring projects (Herbei, R.C., Cucăilă, S., Cucăilă, M; David, F, 2024). Digital orthophoto mosaic, make the transition from the concept of coordinates of a point to the point cloud, improving the quality of research and reducing the amount of fieldwork required. The focus of the research was on combining in-situ studies of the natural terrain, using topographic, geodetic, and photogrammetric methods, with the analysis of lithology and buried structures, as well as applying geophysical methods like magnetometry and electrometry, to better understand the lithology and provide new insights into historical monuments.

Geodetic and photogrammetric methods were used to map the current topography of the area for the Trajan Bridge monument preservation project.

The photogrammetric product obtained was the digital orthophotoplane mosaic with a pixel resolution of 5.00 cm and digital surface model, with an absolute accuracy of 10.00 cm, for a studied area of approximately 20,000 square meters, with the use of six photogrammetric reference points determined by GNSS tehnology.

The mechanical characteristics of the upper substrates are strongly influenced by the presence of water, saturation level and water freezing, producing significant reductions in resistance to breakage, as well as cohesion, as is the case with andesite rocks (Danciu, C, Marchiș, D, Cucăilă S 2021).

Electrometric methods were used to determine the area's historical topography, the fill zone, and the characteristics of the upper layers of the soil, as illustrated in Figure 11.

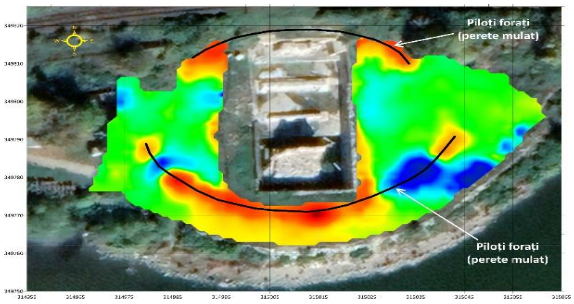

Figure 11. Total Magnetic Field Map – Interpretive Elements

Magnemometry has been successfully used in architecture and archeology projects (Jörg W E Fassbinder, 2017,). This allowed the determination of the buried route of the stormwater discharge channel from a section of Drobeta Turnu Severin municipality into the Danube River, thus eliminating the need for trenching, a costly and time-consuming procedure; Additionally, it enabled the precise identification of the locations of two diaphragm walls, constructed from drilled piles, which were installed during the 1984 works. Additionally, the position of two sheet pile walls, constructed from bored piles and installed at the site during the 1984 works, was identified, as illustrated in Figure 12.


Figure 12. Digital orthophotoplan created

The orthophotoplane mosaic, as well as other photogrammetric products, supports classic measurements for accurately revealing the topography of the land, useful in hard-to-reach areas, with a risk of collapse or in isolated areas, as illustrated in Figure 13.


Figure 13. Water infiltrations present in the monument area

In recent years, affordable solutions in terms of cost and technology have emerged in the field of topographic measurements historical and cultural heritage (Verma, Mukesh & Yadav, Manohar, 2023), graphic stations computers combined with photogrammetry mapping software such as Pix4D, Agisoft Metashape, making the processing of images intuitive, easy to use (Zeballos, Carlos & Quiroz, Carlos & Bustinza, Daniel & Pacheco, Edwin, 2020). Also, laser scanning faithfully relating the facades, glazed spaces and architectural elements of buildings and monuments, as illustrated in Table 1 and Table 2.

Software	Affordability	Quality	Ease of use
Agisoft MetaShape Profesional 1.5	Medium	Medium	High
Pix 4D	Low	High	High

Table 1. Photogrammetric processing software solutions

Method	Output format	Accuracy	Quality	Ease of use	Affordability
Traditional	Vectorial	Low	Low	High	High
Camera Photogrammetry	Cloud point	High	High	High	High
Camera 360	Cloud point	High	High	High	High
Aerial photogrammetry	Cloud point	High	High	Medium	Medium
Laser scanner	Cloud point	Very High	Very High	Medium	Very Low

Table 2. Major characteristics of different types of surveying historical monuments

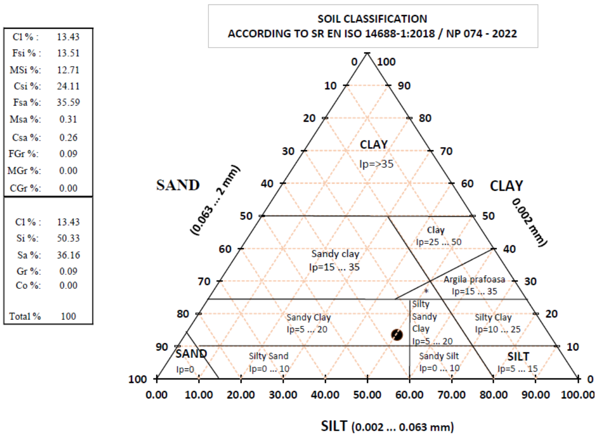

Figure 14. The main type of soil intercepted in the upper lithology

Further research directions will be the study of piezometric level, the in-depth research of the causes that produce water infiltration in the area of the Trajan's Bridge historical monument, given the fact that the soil in the studied area is of alluvial origin, sandy clay (SaCl), as shown in Figure 14.

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