Multidisciplinary Documentation Using Non-destructive Testing Techniques for the Diagnostic Study of an Ancient Temple

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Abstract. In this work, an approach regarding the representation of a monument in combination with building material documentation information (deriving from non-destructive techniques) is presented. Through this approach, data incorporating architectural, surveying and building material documentation information are aggregated with the 3D documentation model, leading to valuable information regarding the preservation state of a monument. The illustration of the Pythian Apollo ancient temple, located in the Ancient Acropolis of Rhodes, Greece, aims to highlight the manner in which the fusion of multilayered information can contribute to the diagnostic study of a monument, ultimately leading to its sustainable protection through time. Information deriving from the three dimensional documentation of the monument is enriched with information deriving from non-destructive techniques (Ground Penetrating Radar, Infrared Thermography, Digital Microscopy) in combination with historical and architectural data and in-situ visual inspection observations. In addition, information regarding quantitative data can be acquired, facilitating future conservation interventions.

Keywords: Ancient temple · Geometric documentation · NDT applications · Diagnostic study · Multidisciplinary approach

1 Introduction

During the last decade, a rising interest is observed among the scientific community for interdisciplinary documentation in regards to the preservation of Cultural Heritage assets of great historical, architectural and structural value. Especially, in the case of Ancient Temples, a thorough multidisciplinary documentation is a prerequisite, since in

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most cases ancient temples have endured natural weathering and they are in a bad state of preservation and, additionally, due to their longevity they have undergone repeated restoration interventions.

Overall, integrated documentation of cultural heritage assets includes the acquisition of all available data regarding the monument, contributing thus to its safeguarding in the future. Available data usually includes historical, archaeological and architectural information, photos, etc. Geometric information can, also, contribute to the location, volume and form of an asset in relation to its alterations through time. It contributes to the assessment of the current state of preservation of a monument in terms of deformations and deviations from past form and size. In addition, geometric documentation products can be used as a base for material prospection studies on monuments. Geometric documentation techniques, such as photogrammetry and laser scanning, can provide 3D geometry with millimeter accuracy [1–3]. However, both of these techniques, non-contact and non-invasive, can only record measurements on the surface of the application area and nothing beyond that [4].

Moreover, diagnostic study using Non-Destructive Testing (NDT) techniques for the assessment of the preservation state of an asset, and more specifically for monuments, where in most cases, sampling is limited and in sometimes even prohibited, is growing as common practice. For the sustainable protection of a monument, damage assessment is a process aiming to provide accurate information about structural condition and is generally used to plan maintenance and structural updating activities as well as monitor safety [5]. There are several documentation studies in this area of interest, which in most cases, combine surface documentation techniques for the assessment of the preservation state of a monument [6–8]. In most cases, a combination of infrared thermography with geophysical methods was performed in order to detect defects and alterations in the historic structures [9, 10].

For the assessment of a preservation state of a monument, geometric documentation provides various data, nevertheless additional studies are necessary. Non-destructive techniques are broadly utilized as a tool for the assessment of the current state of preservation of a monument [11–15]. The coupling of geometric data with NDT results can further optimize the diagnostic process. In this study, a multidisciplinary documentation is performed, incorporating geometric documentation information and products with historical, architectural and building material data, in order to retrieve valuable information regarding the current state of preservation of an ancient temple.

In general, ancient temples undergo through major alterations through time, and thus, are in need of restoration. The structure ages, due to its longevity in environmental factors alterations and, also, because of man-made factors, such as destructions, bandalisms and improper restoration attempts with the use of incompatible restoration materials, which eventually worsens the state of preservation of the Temples. Deformation of the structure, building material loss, cracks and deviations in the columns of a temple are some of the most common damages that can be observed considering a monuments preservation state.

The monument under study is the Pythian Apollo Temple, in Rhodes Island, Greece. The monument constitutes a characteristic example of a Doric Temple; it is dated to the 3rd century BC and was built with a local porous limestone. It is located in the south part of the ancient Acropolis of Rhodes. Its foundation is established on an artificially shaped natural rock. The orientation of the Temple is to the east [16]. The Ancient Temple, 20.05 m × 37.37 m length, consisted of 6 columns in the East and West and 11 columns in the North and South (Fig. 1). The historical building material was a fossiliferrous biocalcarenite stone.

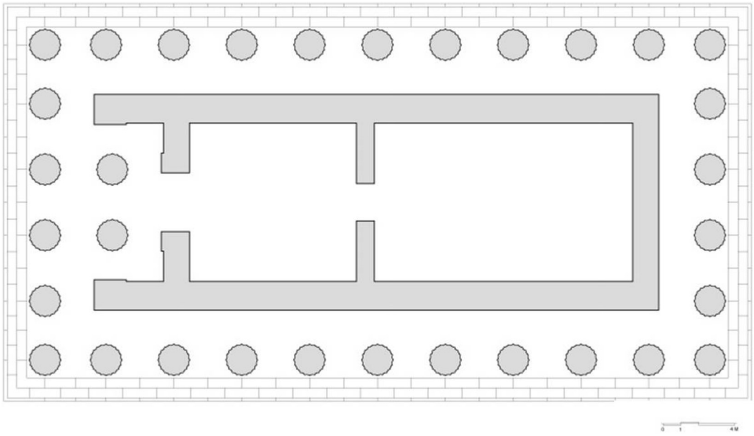

Fig. 1. Plan of the Pythian Apollo Ancient Temple, Acropolis of Rhodes, Greece [17].

Over the years the Temple has undergone many interventions; in the millennia since its construction, damages have been inflicted on the monument leading to its collapse. In the period of 1912–1936 several parts of the monument were excavated from the surrounding area. An important restoration project was implemented in 1938 by the Italian Archaeological Services, with Paolini as a leader of the team, which combined historical and contemporary building materials in the restored structure. The excavation that started earlier, brought to light a part of the temple and a section of the eastern pedestal. In total four columns and part of the entablature were restored [18]. During the restoration process, a new type of stone of unknown origin (rehabilitation stone) was used; cement based mortars and concretes were applied to connect the shafts and the columns respectively and metal connectors were employed to reinforce the stone built structure. During the 60s and 70s, additional restoration interventions were performed. Currently, metal scaffolding has been installed by the Hellenic Ministry of Culture for the protection of the monument (Fig. 2).

In this study, geometric documentation was employed at the Temple of Pythian Apollo to obtain the geometrical characteristics of the monument, while non-destructive testing was applied in situ in order to evaluate the extent of the building materials' decay and state of preservation [19]. The non-destructive techniques used were Digital Microscopy (DM), in order to examine the surface morphology of the materials and study their decay; Schmidt hammer test to estimate the mechanical characteristics in certain areas; infrared thermography (IRT) in order to obtain information regarding the presence of different materials, deterioration, incompatibility issues and environmental loads; and Ground Penetrating Radar (GPR) in order to examine the structure in depth [20].

Fig. 2. Top view of a column of the Temple (top left); Image of the Pythian Apollo Temple from the drone(lower left); West Façade of the Pythian Apollo Temple (right).

2 Materials and Methods

2.1 Geometric Documentation

For the documentation of the Apollo Temple, a combination of field surveying measurements, photogrammetric and laser scanning techniques was performed. The geometry of the Temple is complex, and data acquisition was performed from different positions in order to acquire all the necessary information for the 3D documentation. The measurements had to be acquired from a close range, surrounding the Temple, since the scaffolding posed an obstacle for the 3D documentation. In some cases, the scaffolds were located in contact with the monument resulting in concealments, which needed to be resolved in order to ensure the complete geometric documentation and visualization of all entities.

The field survey measurements were accomplished with the Topcon 3003LN geodetic total station. The Temple was scanned using the Leica ScanStation2 terrestrial laser scanner. It is a pulse-based laser scanner and has the ability to collect up to fifty thousand points per second, with an accuracy of 5–9 mm in its position, depending on the distance of the scanning range. It records 360° around the horizontal axis and 310° around the vertical. The scanner was employed as a 3D data source for the documentation of the Temple. In total 4 scans were obtained for the documentation of the Temple, in preselected positions to enclose the monument under study.

Digital photos for the multiple image coverage of all surfaces of the Temple were acquired using the professional Canon Eos 5D Mark III full frame CMOS digital camera, with 22.3 MP resolution (5760 × 3840 pixels) with a 24 mm fixed lens. Additionally, aerial images of the Temple, the entablature, the pediment and the bedrock and the remaining walls surrounding the monument, were acquired with a DJI Phantom 4 drone (Fig. 3).

A vast number of digital images were taken for the documentation, depending on each part of the monument that should be documented and the difficulties that arose in each case. The scaffolding, nearly in contact and enclosing the columns, added difficulties in the data gathering process. Digital images were taken from different angles and distances, at a very close distance (in many cases less than 1 m) though, since the scaffolding was too close to the columns of the Temple. In the case of the higher part of the Temple, the documentation was very difficult; the scaffolding did not cover the entablature and the pediment and as a result there was no access to this part. The images were taken using the UAV. A total number of approximately 1600 terrestrial images were taken. In addition, approximately 1800 images were taken from the UAV for the Temple including the upper part of the columns. For the creation of an accurate 3D textured model of the Temple a combination of the documenting techniques were used. Furthermore, in the developed model of the Pythian Apollo Temple, all the exterior details incorporating texture, surface variation, material differentiation and alterations were also obtained.

Fig. 3. Geometric Documentation of the Pythian Apollo Temple – Field work process.

2.2 Non-destructive Testing Techniques

In the current study Infrared Thermography, Ground Penetrating Radar and Digital Microscopy were applied. Schmidt hammer test was also applied, in order to estimate the buildings materials compressive strength. Results from the application of NDT methods were used to provide information regarding the Temples' current state of preservation and to reveal information regarding the restoration materials used and differentiate them from the original historic building materials.

The NTUA multidisciplinary team carried out field measurements at the Temple of Pythian Apollo between 14–16 June 2018. During the measurements light cloud cover (<50%) and low intensity winds prevailed, while the average temperature was 28.4 °C, with relative humidity at 64% during the IRT measurements. In order to avoid confusion and combine the measured data with the relevant geometric information, the exact location of each measurement was carefully documented on a detailed sketch of the monument.

Schmidt hammer test was used for an estimation of uniaxial compressive strength of the monument stones. Measurements were conducted in accordance to EN 12-504-2: 2012 "Concrete Construction Testing - Non-destructive Impact Resistance Testing".

Concerning the IRT measurements, a FLIRB200 thermo camera was employed. This thermo camera was equipped with the 25° lens for close-up shots and the 15° detachable telephoto lens for long-range operation. For data analysis, the FLIR Quick Report 1.2 SP2 software was used. In addition, Temperature and Humidity measurements, with the thermo-hygrometer FLIR MR77 was applied in order to calibrate the FLIRB200 thermo camera temperature data and to measure the temperature and moisture content of the structure's materials.

A Moritex - i-scope was used in this survey. This digital microscope is equipped with several magnifying lenses (x30, x50, x120).

The Ground Penetrating Radar system used in this survey was a MALÅ Geoscience ProEx system with 1.6 GHz and 2.3 GHz antennae. The MALÅ Geoscience Groundvision 2 software was used for data acquisition. Ground Penetrating Radar (GPR), is an established non-destructive technique [21] with which, through the use of radar pulses, sub-surfaces can be examined. It exploits the wave character of electromagnetic fields and through the propagation and further analysis of electromagnetic radiation an examined structure is depicted. In cultural heritage protection projects, GPR is utilized for the assessment of the preservation state of historic structures. Through the use of GPR, discontinuities such as voids and inclusions of materials can be obtained. Moreover, past repair interventions can be evaluated and the geometry of the structure sections can be revealed indicating the layers of stone and other types of material structure [22, 23].

3 Results

3.1 Geometric Products

The NTUA multidisciplinary team performed 3D documentation measurements at the Pythian Apollo Temple. All the diverse data were elaborated in the Laboratory of Photogrammetry in the NTUA premises. The creation of the 3D model deriving from these diverse data is a procedure that requires large computational effort. The laser scanning products were elaborated within Cyclone by Leica Geosystems for the target to target registration of the four scans.

The digital images (terrestrial and aerial) were processed using multi-image photogrammetric techniques including Structure-from-Motion (SfM) and dense image matching (DIM). These methods were used for the orientation of the orientation of the images and the 3D point cloud extraction. The processing was realized with the Agisoft PhotoScan software. Each façade of the Temple, including the columns, was elaborated as a different project in PhotoScan using masks in the areas of occlusions. This process was very demanding since the areas excluding the scaffolding illustrated in the images were limited and the resulting orthophotos required a very detailed development.

In addition, the processing of the point clouds was realized with the Geomagic Studio software. For the elaboration several algorithms were applied for the creation of a uniform point cloud. In addition the processed dense point cloud was wrapped into mesh in the same software.

For the georeferencing of the model, coded targets as GCPs (i.e. ground control points) were mounted in specific areas of the monuments and were measured with a total station. The registered point clouds of the Temple were also referenced to a common system. The accuracy obtained after the elaboration of the point cloud was within millimeters.

A high resolution three dimensional model of the Temple was produced, including all the voids, cracks and discontinuities that were encountered throughout the process of the 3D modeling (Fig. 4).

Fig. 4. 3D Photorealistic Model of the Pythian Apollo Temple; East Façade.

The next step was the elaboration of the orthoimages of each façade with a pixel (groundel) size of 1 mm, for the digitization of the selected facades. The resulting orthoimages illustrate all the information regarding the current state of preservation of the Temple including cracks, variation of building materials, etc. (Figs. 5, 6, 7).

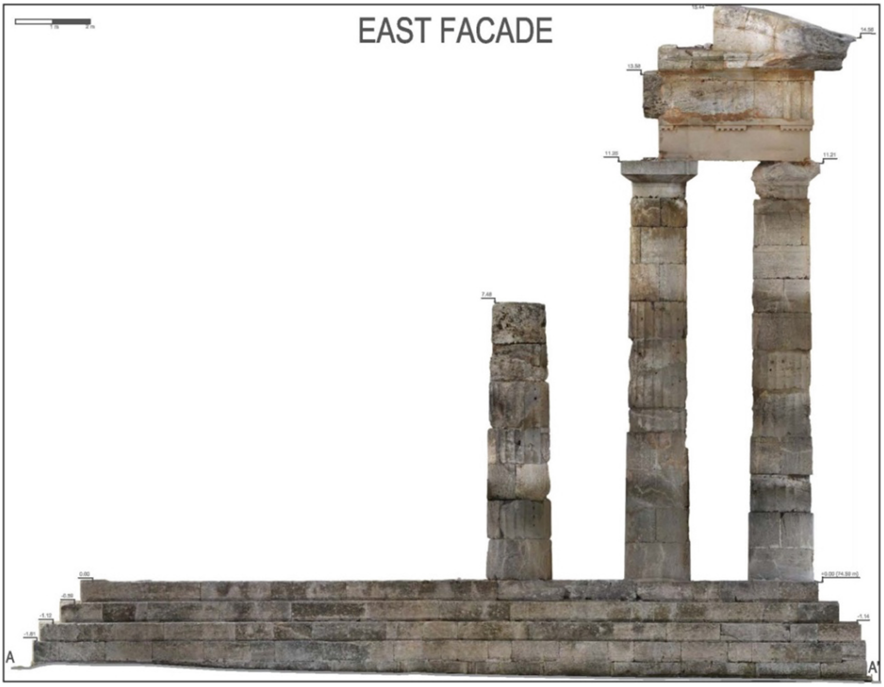

Fig. 5 Orthophoto of the East Façade of the Pythian Apollo Temple.

In the case of the Pythian Apollo Temple, it was very important to obtain a high quality textured products, in order to assess the state of preservation of the restored columns. The variation of the building materials is documented. Cracks and deformations are obtained and can be digitized since the orthoimage can be utilized as a blueprint for further elaboration. The various segments which comprise the Temple can be analyzed, measured in terms of their dimensions with millimeters accuracy. In addition the Temple can be monitored, should structural alterations occur in the future.

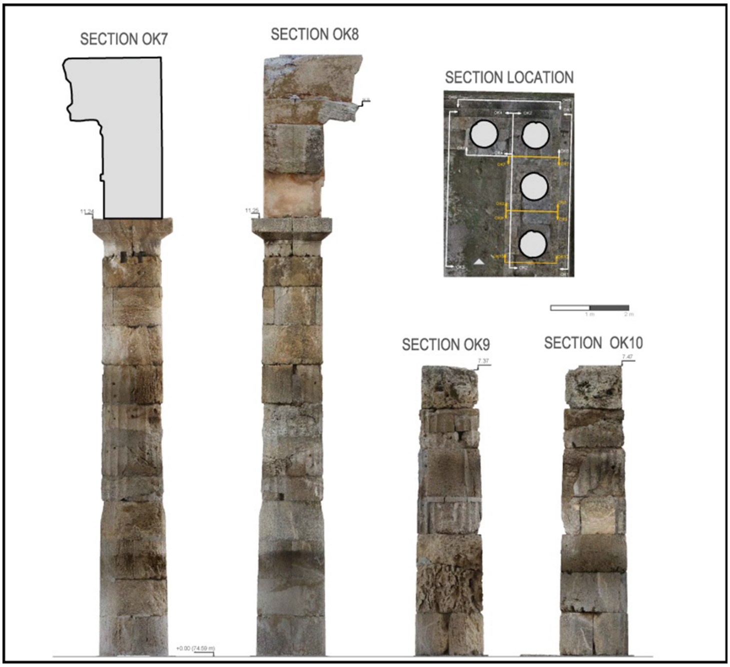

Fig. 6. Sections of the Columns of the Pythian Apollo Temple, north and south facades.

3.2 NDT Results – Fusion with Geometric Documentation

As mentioned above, in order for all the diverse data to be integrated, the location of each NDT prospection needs to be documented according to each column. For this reason, the columns were documented in terms of their position, leading to a sketch where the column located in the west was designated as K1 column; the column located in the corner of the temple in the north façade as K2 column, etc. (Fig. 8). The monument under study consists of these 4 columns, including building materials that are considered as the historic stones and the rehabilitation stones used in the restoration project in 1938. Since, additional building materials are included within the structure of the columns, due to other performed restoration interventions, it is considered that the rehabilitation stone from the Italian restoration project is regarded as a historic stone as well. Nevertheless, in this study, the historic stone as a building material will herein be addressed as “ancient stone”, whereas the rehabilitation stone from the Italian Restoration Project will be termed as “restoration stone”.

The Schmidt hammer test was employed on the K4 column (Fig. 8) of the Pythian Apollo temple. The surfaces under-study consisted of the historic and the restoration stones, bound together through cement mortars. Measurements were performed per orientation (East, North, West, and South) and per shaft, initially in a 30 cm x 30 cm

Fig. 7. Orthophoto of the North Façade of the Pythian Apollo Temple.

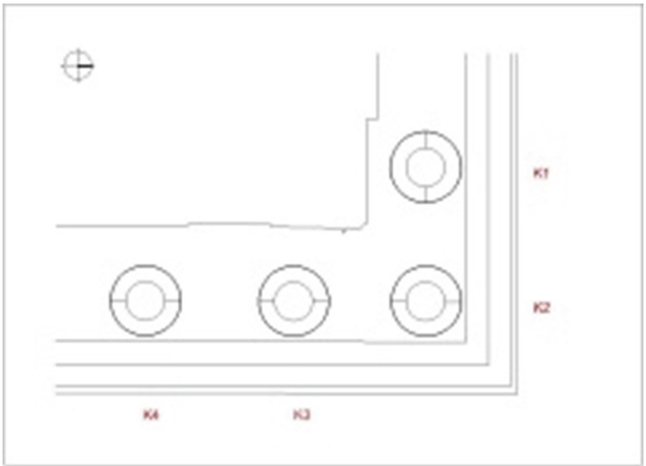

Fig. 8. Sketch of the Columns including their designation.

square area and continuously per 10 cm high on every shaft. The areas were selected based on surface smoothness, as irregular surfaces can lead to misleading rebound results. Table 1 shows the mean uniaxial compressive strength in a 30 cm x 30 cm square area, as well as the average of the uniaxial compressive strength in height according to its position.

Table 1. Table of the Average uniaxial compressive strength (MPa) of stone surface measurements in K4 column.

Shaft/ Orientation		Type of stone	Measurements of uniaxial compressive strength (MPa) in height	Measurements of uniaxial compressive strength (MPa) in height	Type of stone
1	S	Restoration stone	8,12	7,89	Restoration stone
2	S	Restoration stone	7,53	7,21	Restoration stone
3	S	Restoration stone	6,98	7,06	Restoration stone
4	S	Restoration stone	8,24	10,26	Restoration stone
5	S	Historic stone	10,09	16,16	
6	S	Historic stone	11,38	Not applicable	
7	S	Historic stone	18,00	Not applicable	
1	W	Restoration stone	7,40	7,21	Restoration stone
2	W	Restoration stone	7,23	7,31	Restoration stone
3	W	Restoration stone	6,78	6,78	Restoration stone
4	W	Restoration stone	7,19	11,47	Restoration stone
5	W	Restoration stone	14,09	14,96	Restoration stone
6	W	Historic stone	12,61	Not applicable	
7	W	Historic stone	18,71	Not applicable	
1	N	Restoration stone	6,98	7,45	Restoration stone
2	N	Restoration stone	7,18	7,05	Restoration stone
3	N	Restoration stone	8,47	6,99	Restoration stone
4	N	Restoration stone	7,02	11,11	Restoration stone
5	N	Not applicable		15,31	Historic stone
6	N	Historic stone	8,76	Not applicable	
7	N	Historic stone	16,16	Not applicable	
1	E	Restoration stone	7,84	8,68	Restoration Stone
2	E	Historic stone	11,24	7,89	Historic stone
3	E	Restoration Stone	8,76	7,68	Restoration Stone
4	E	Historic stone	7,45	10,67	Historic stone
5	E	Not applicable		14,64	Historic stone
6	E	Historic stone	12,28	Not applicable	
7	E	Historic stone	16,98	Not applicable	

Stone blocks with the presence of cement grouts presented increased compressive strength values. However, this is perhaps misleading, as the presence of salts within the materials may lead to higher surface hardness. Especially in cases where stone blocks are in high proximity to the sea, sea salt spray tends to be one of the major material decay factors. The presence of incompatible materials, such as cement mortars or grouts, aggravates the decay mechanism affecting the more porous stone. In some cases the test could not be applicable, due to surface decay.

Very low average values of compressive strength are observed on the restoration stones, presented values within the range of 6.8 MPa to 8.8 MPa. The historic stones exhibited a compressive strength range from 7.5 MPa to 18.8 MPa. Overall, the measurement reliability was affected by the fact that the surfaces were rough and the building materials of the monument consist of large pores, thus, Schmidt hammer test results are only indicative of actual compressive strength.

The lowest average values of compressive strength were measured at the north side of column K4, while the highest average values were measured on the south side. This differentiation due to the orientation of each façade, leads to the conclusion that the compressive strength is directly dependent on micro-environmental conditions.

Relative humidity and temperature measurements were conducted on the K4 column of the monument. The selected surfaces consist of both ancient and restoration

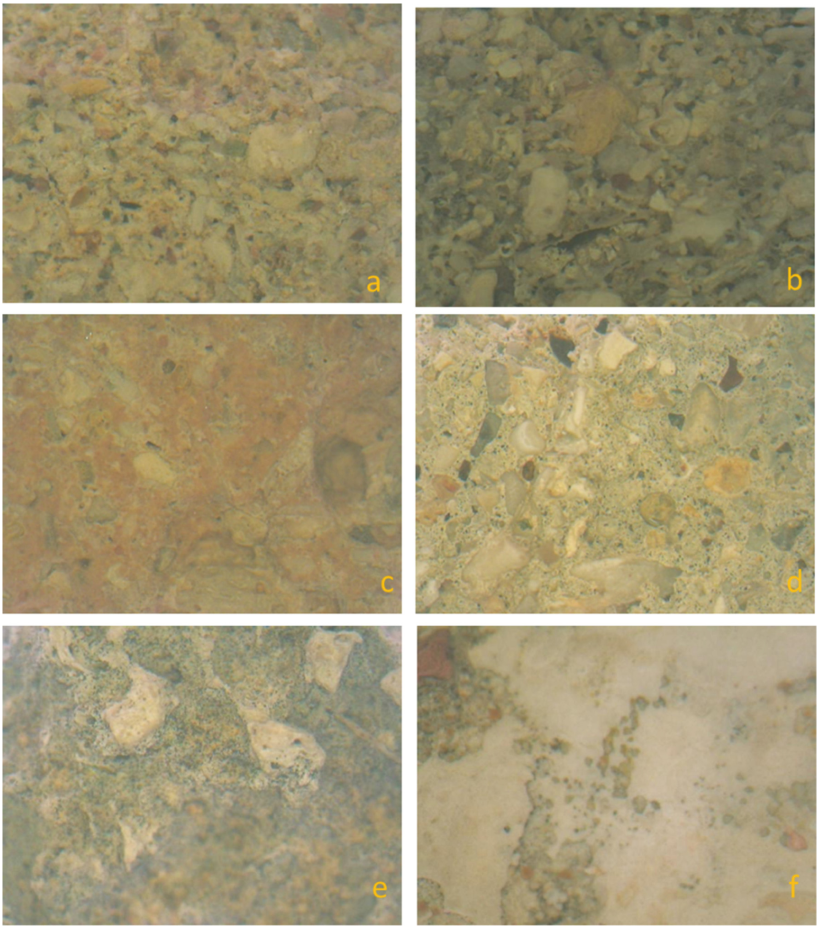

Fig. 9. Digital Microscopy images: (a) ancient stone (x30); (b) stone granular disintegration (x30); (c) plaster (x30); binding material (cement) (x30); dark grey area presenting biodeterioration (x30); white lichen decay (x30).

stone. The measurements were applied per column and per every 10 cm vertically. The most coherent surface of the shaft was selected for this investigation. During measurements the average ambient temperature was 26.3 °C, while the relative humidity was 58.3%. No specific conclusions could be drawn from the flow of moisture in the column body due to a great anisotropy resulting from the use of incompatible materials during the restoration process of the monument and the major and in-depth decay of its materials (Fig. 9).

Digital microscopy, using several magnifying lenses (x30, x50, x120) and providing information regarding the building material type and decay pattern, was assisted in the inspection of the decay patterns of the building materials. Digital microscopy results provided information about the texture, the cohesiveness, the aggregates, the formation of grains and possible residual foreign bodies, the bio corrosion and coloring of stone due to soluble salts and other factors. In various characteristic areas of the Temple, digital microscopy was applied in order to obtain information regarding the building material of the Temple such as the historic ancient stone of the monument and various decay patterns affecting the structure.

Through the fusion of multidisciplinary data, with the contribution of geometric documentation to the NDTs results, the geolocation and orientation of a building material in regards to the monument, significant information can derive from the inspected areas. In Fig. 10, DM images, from K4 column with the same orientation (east) of the restoration stone and the ancient stone provided valuable information

Fig. 10. Geolocation of the DM measurements; Up – Ancient dark orange color stone (30x); Down - Dark brown orange decay on biocalcarenite restoration stone (120x).

regarding their state of preservation. More specifically, concerning the ancient stone, the sample presented no consistency since it was disintegrated and fragile. Micro fissures and holes were observed. Green biodegradation prevailed in the sample. There were quite a few aggregates of different colors, shapes and sizes and agglomerated shells were observed on the body of the stone. As far as the restoration stone, located in the same area with the same orientation, presented different characteristics than the ancient stone. More specifically, the sample was compact and coherent. Externally showed a darker shade and black biodegradation prevailed. Malignances and holes were observed. From the resulting images of the DM technique, additional information regarding the restoration building materials and their state of preservation can be obtained. In Fig. 11, DM images from the K3 column, located in the west façade of the monument, presented restoration cement mortar, which was coherent and compact. The same applies for the plaster located in the same area, which presented coherence and decay patterns were not evident.

Infrared thermography was applied for the investigation of the current state of preservation of the Temple. IRT was employed, in order to inspect the thermal differences between the ancient stone, the restoration stone and the cement products, and to detect high moisture areas. Surfaces were selected based on the possible occurrence of temperature variations. Thermal maps of the monument were created. Initially, the thermal incompatibility between the ancient and the restoration building materials was

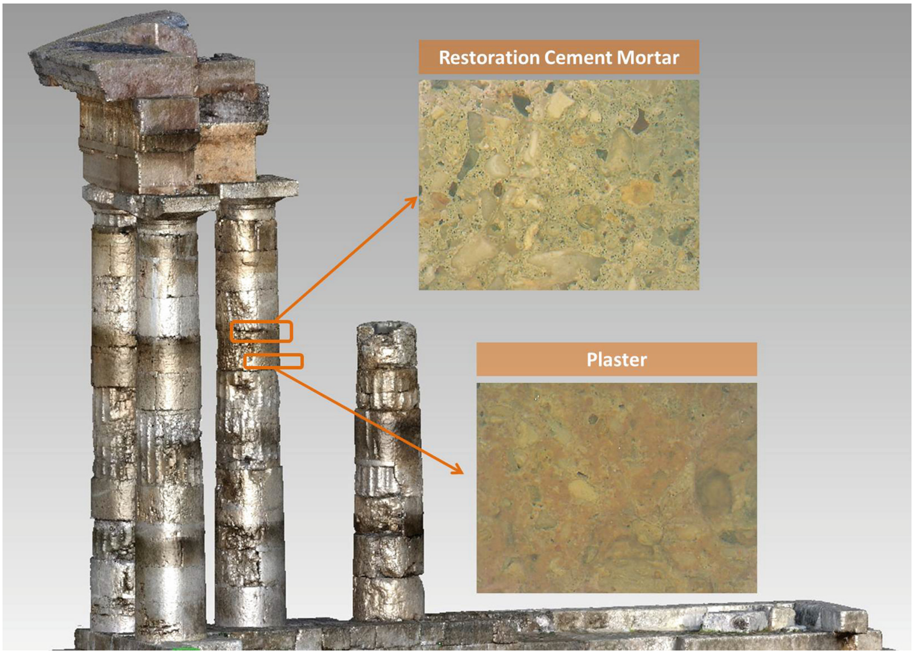

Fig. 11. Geolocation of the DM measurements in the K3 column. Up: Restoration Cement Mortar (30x); Down: Plaster (30x).

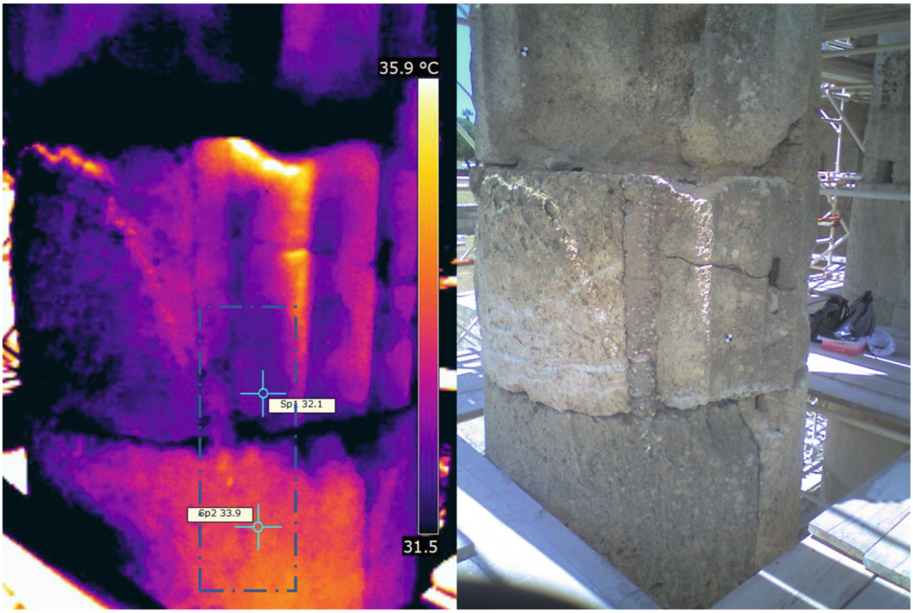

Fig. 12. Lower temperatures are indicative of the ancient stone.

evident. Specifically, the ancient stone presented lower values of temperature than the restoration stone, located in the same level of the column and having the same orientation in regards to other external environmental conditions (Fig. 12).

The breaches of the stones are noted with lower temperature at the thermal maps (Figs. 12 and 13) by contrast the edges of the shaft were noted to present higher surface temperatures than the rest of the round area of the shaft in the thermographs (Fig. 14).

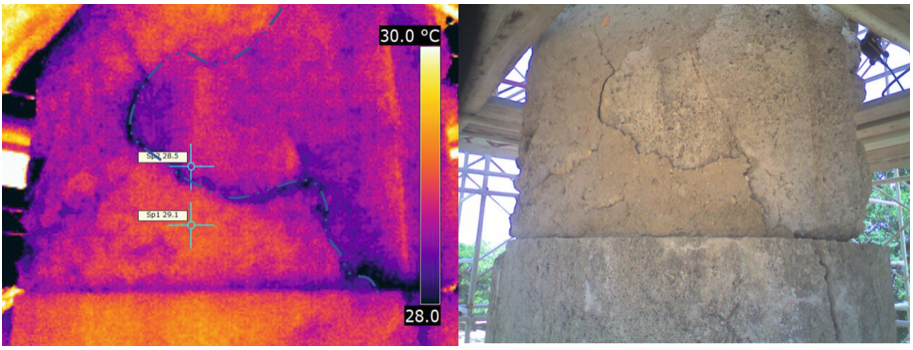

Fig. 13. Incompatibility due to different temperatures observed between restoration cement mortar and ancient stone.

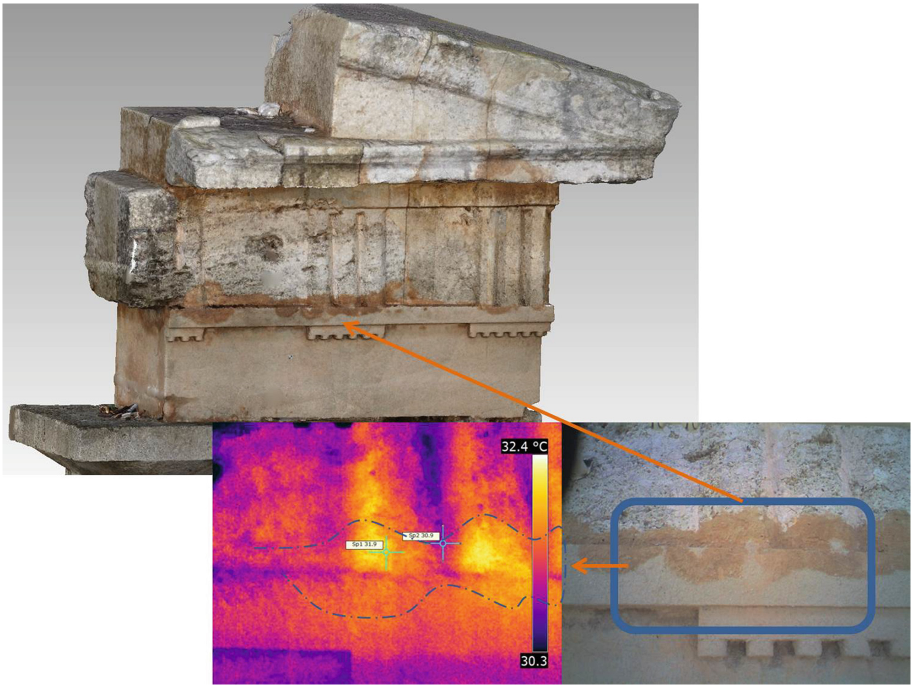

Fig. 14. Thermal incompatibility between restoration cement mortar and ancient plaster.

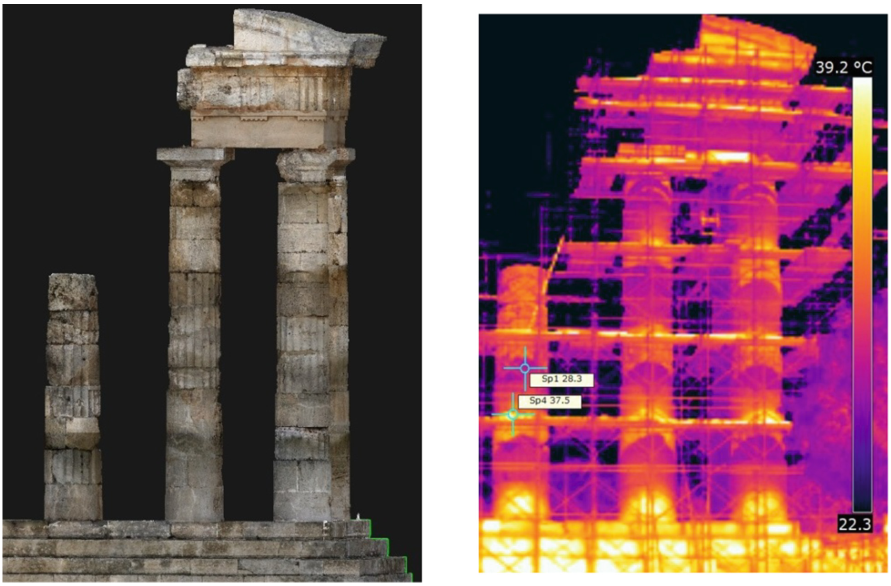

Fig. 15. Anisotropic heating is created by the scaffolding surrounding the monument.

Anisotropic heating is caused by the scaffolding surrounding the monument (Fig. 15) in addition to the physical and chemical incompatibility of the materials. In conclusion, a non-uniform mechanical stress distribution was created from the anisotropic heating and thermal allocations resulting in failure of the construction materials.

In addition, for all the columns, inspection of the structural formation of the Temple was performed through the use of the Ground Penetrating Radar. For column K4, the results deriving from the GPR interpretation, indicate that there is a mean depth for all the shafts, of the ancient/authentic stone of 0.32 cm. In total, seven vertical scans are deployed in the four columns and the outcome of the GPR interpretation indicates that the mean depth of all building materials that correspond as the exterior layer of the columns is 0.32 m (Fig. 16). This information from the scans was correlated with information from historical and architectural documentation and the results provide validation to the historical documentation regarding the restoration project by the Italian Archaeological Services. It is evident that, for the restoration project, the ancient stones were carved, so that a cement core could be embedded to the external stone structure.

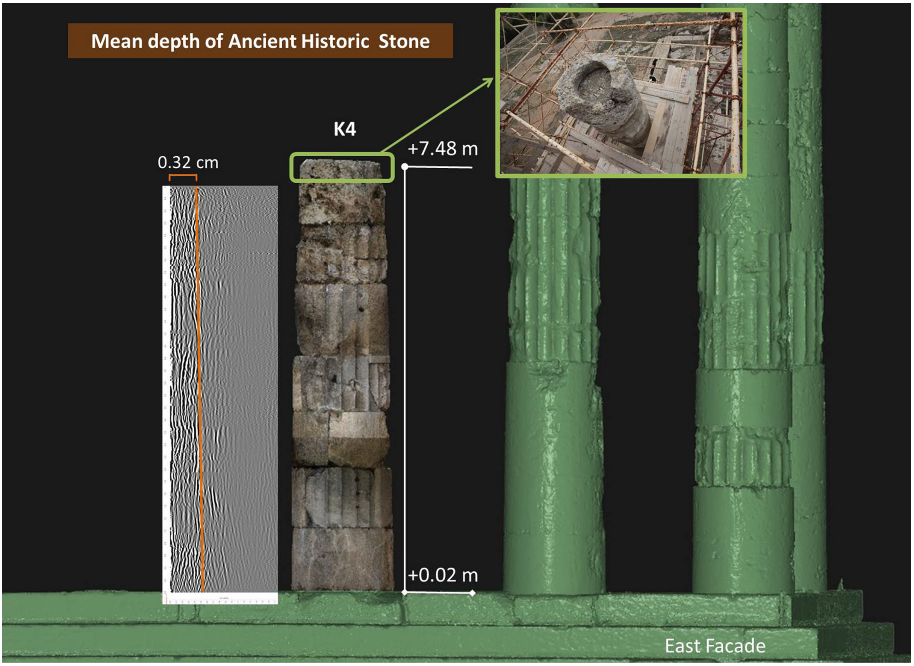

Fig. 16. GPR scan of the column K4, indicating the depth of the Ancient Material as illustrated for all the shafts of the column.

4 Conclusions

Through the combination of NDT techniques regarding building materials and decay patterns classification with geometric documentation, various information of great importance, that would have been otherwise overlooked, is revealed. A combination of high-resolution digital images and terrestrial laser scanning techniques was implemented for the creation of a high-resolution 3D textured model and other geometric documentation products.

Past restoration interventions are confirmed, documented and further assessed in relation to the deterioration they might provoke to the monument and its building materials. Building materials susceptibility to various environmental factors and other geolocation factors are examined in terms of geolocation and their deterioration. In the case of digital microscopy, the fusion of these results with the geometric documentation revealed the patterns of decay prevailing in the columns and the areas that had not been affected by external factors, such as winds directions, causing salt spray due to the proximity to the sea.

In addition, building materials can be assessed and correlated within an information system since the geometric documentation provides the necessary data that can quantify information regarding the location, the environmental loads and the interrelation between building materials and decay factors. The documentation of the Temple facilitated also in highlighting the damaged areas from the Italian restoration and obtaining information regarding its structural analysis. The fusion of the geometric documentation with the GPR scans, provided information of the interior of the carved historic stones through all the columns. This information can be utilized in future restoration works. The fusion of the infrared images with the geometric documentation validates the incompatibility of the restoration interventions from the Italian restoration project. It displays, also, the need for prompt restoration works in the Temple due to the anisotropic heating that the scaffolding is causing. Finally, the structure of the monument as a whole can be assessed and examined, and, this initial approach, especially in cases where historical information is difficult to gather, can act as the first input for a three dimensional reconstruction of the monument in the case of a new restoration project.

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