Application of Non-destructive Techniques for the Investigation of Old Masonry Structures

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Abstract. This study aims at the acquisition of a reliable image of the non-visible parts of historical masonry buildings in Greece by in-situ application of non-destructive techniques (NDTs). To serve the purpose of obtaining overall conclusions on the documentation of the monuments' internal condition, the deriving results are examined and combined together with the in-situ observations. The structures under investigation are the Katholikon of Osios Loucas Monastery (Boeteia), the Monastery of Kaisariani (Attica), the Agia Paraskevi Church (Chalkida) and the Nativity of Christ's Church (Athens). The main investigation method applied on all monuments was that of the Ground Penetrating Radar. Additionally, the methods of Boroscopy and Schmidt Hammer Testing were also used when further investigation was required. The techniques were applied on targeted areas, representative for the entire examined structure. Thanks to the assessment of the results, it was possible to identify data relevant to the dimensions and the type of stones used in the piers and the three-leaf masonries, the thickness and the condition of the mortar and the infill, the coexistence of different construction types in a structure, as well as the approximate compressive strength of stones.

Keywords: Monuments · Historical buildings · Non-destructive testing · Structural documentation

1 Introduction

All four examined structures (Fig. 1) are Christian historical buildings, listed by the Ministry of Culture for their historical, architectural and artistic value. Although they are constructed in different areas of Greece, during different historical periods, they exhibit similarities in terms of construction types and materials. Furthermore, they either continue to serve the purpose of their construction (Fig. 1a, c, d) or are monuments with open access to the public (Fig. 1a, b). At the same time, they are prone to ageing, to earthquakes and environmental risks, and have suffered severe damages during their lifetime. Their preservation and maintenance, essential for their structural safety and functional performance, depend on the alleviation of potential risks. Towards this direction, the

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identification of the structural system and the mechanical behavior of the monument is crucial.

To effectively interpret the behavior of existing structures and, hence, to design appropriate intervention techniques for their repair or strengthening, the most important step is the investigation of their current condition, which is the purpose of the present study. Thanks to the evaluation and the combination of the results deriving from in-situ non-destructive techniques (NDT), it was possible to identify data relevant to: (a) the thickness of stones used for the construction of piers, as well as the exterior leaves in perimeter masonry walls; thus, the thickness of the internal filling material for the case of three-leaf stone masonry could be estimated, (b) the coexistence of different construction types in a structure, (c) the mortar's condition and the existence of voids and discontinuities between adjoining stones could be identified, as well as (d) the strength of the stones, in one of the examined cases, with an approximate estimation.

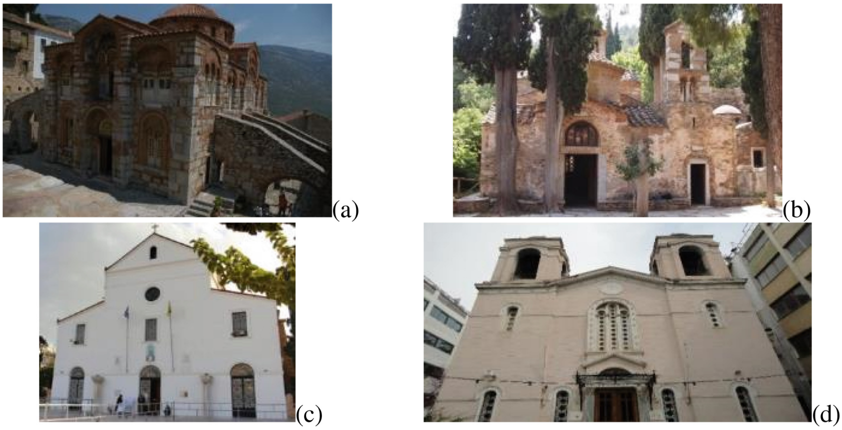

Fig. 1. The investigated monuments: (a) the Katholikon of Osios Loucas Monastery (Boeteia), (b) the Monastery of Kaisariani (Attica), (c) the Agia Paraskevi Church (Chalkida) and (d) the Nativity of Christ's Church (Athens).

2 Non-destructive Techniques Used

The acquisition of a reliable image of the non-visible parts of the structures was performed by applying three NDTs, namely the Ground Penetrating Radar (GPR), Boroscopy and Schmidt hammer testing (briefly described in the respective section). The equipment of the NTUA Laboratory of Reinforced Concrete was used, Ground Penetrating Radar being the main method that was applied. Since no single technique can sufficiently provide the required reliability, and taking into account the limitations of each method, the two other techniques were used in those cases where the need for further investigation was apparent and safe access was feasible.

2.1 Ground Penetrating Radar

The non-destructive technique of GPR, which is based on the transmission of electromagnetic waves, was applied on various areas of all the examined monuments. The system consists of an antenna, serving as the transmitter and the receiver of the pulse, and a control unit (Daniels 1996; Utsi 2017). When the pulse reaches an interface of materials with a different dielectric constant, a part of it returns to the transmitter, furnishing the system with this information, whereas its remaining part continues to penetrate the material in greater depth while attenuated (GSSI 2009). The final radar image is a section of the examined area. Given the scope of these applications, where the thickness of the masonry is relatively small (up to 100 cm approximately), a rather high frequency antenna (1600 MHz) was selected, offering the twofold advantage of the high image quality and the small size, which subsequently facilitates scanning on areas with limited dimensions.

To use the GPR results on a quantitative basis, rather than a qualitative one only, the calibration of the device is a prerequisite. In the examined monuments, the calibration was carried out in locations where the dimensions of single stones or the entire width of a pier or a masonry wall was already known or could be easily measured. The dielectric constant that results in correct depth evaluations is adopted and, hence, the vertical axis of the radar files presented herein expresses the depth (in [m]), whereas the horizontal axis indicates the length of the path (also in [m]).

2.2 Boroscopy

In some of the cases, following the radar method, and to verify the reliability of the images taken, the slightly destructive method of boroscopy was applied. In this method, the borescope is inserted into a (pre-existing or drilled on purpose) hole of sufficient diameter (12 mm–25 mm, depending on the width of the mortar joint in which boroscopy is applied) and length (usually up to 500 mm), allowing for direct visual observation of the masonry's interior and for videos or pictures to be taken at various depths, offering the ability to detect stone surfaces, discontinuities, gaps and timber or metal elements, as well as their position inside the masonry (Palieraki et al. 2007; Palieraki et al. 2013). In the present study, boroscopy was applied with the aim to confirm the findings of the GPR technique and to acquire also qualitative information about the in-depth condition of each examined area.

2.3 Schmidt Hammer Testing

For the estimation of the mechanical properties of rock material, the Schmidt hammer non-destructive method provides a quick measure of surface hardness (Aydin and Basu 2005). A metal mass hits the tested surface and, based on its average rebound value, the compressive strength is estimated by means of calibration diagrams, depending on the material of the tested element. To enhance the reliability of the results, at least ten measurements per application site were conducted, the repeated application of the method at close points and near the edges of the stones were avoided, whereas the plaster was carefully removed and the stone surface was of acceptable roughness.

Since the acquisition of stones from the monuments is -in general- not preferred or even not permitted, the calibration of the hammer through in-laboratory testing of stone specimens under compression is usually not possible. Therefore, in this study, the strength assessment was based on calibration curves available at bibliography. It is emphasized that the deriving strengths are approximate, indicative estimations.

3 Application of the Techniques and Test Results

The suitable NDT or a combination of NDTs is selected on the basis of the specific features of each monument and the scope of its investigation. To obtain accurate and -as much as possible- conclusive results, both horizontal and vertical radar scans were performed in the examined areas, in all cases. The results of NDTs were combined together and decisively contributed towards drawing conclusions on the construction type of masonry. Hereafter, the concise presentation and the commentary of the most significant results offered by the applied techniques is given for every structure.

3.1 Katholikon of Osios Loucas Monastery in Boeteia

The Katholikon of Osios Loucas, dating back to the 11th–12th centuries AD, consists of two storeys and is one of the most efficiently preserved Middle-Byzantine Churches in Greece. Due to its dominant significance, many researchers have devoted efforts towards understanding the monument from the structural perspective, encountering, however, the lack of adequate relative written sources. This fact renders the need for in-situ investigation of monument's targeted areas even greater. In the recent years, several investigation campaigns of the structure have taken place, with the most recent one conducted during 2016–2017 within the context of an NTUA Research Programme, where the authors participated. In this programme, 93 radar scans and observation with the boroscope at 15 positions were performed in total.

The main goal of the recent investigation campaign was the correlation of the gathered results with those that derived from previous investigations (Vintzileou 2007; Vintzileou et al. 2008). The scope of the investigation was fulfilled, as the observations reported in the aforementioned papers were confirmed; more specifically, the fact that the piers in the Yperoon demonstrate a solid construction, with extensive use of large stones and joints of limited volume was verified. Also, the findings of both the present and the previous investigation campaigns on the examination of the perimeter walls in the ground floor revealed the existence of three-leaf masonry, with the external leaves being constructed with cut stones of significant dimensions.

The most important findings of one typical pier of the gallery (Yperoon-second storey of the monument) are reported in the present study. The fact that the entire surface of the sides was covered with plaster was the main problem faced. To allow for a reliable calibration of the technique, and for an assessment of the plaster's effect on the suitable value of the dielectric constant, the plaster of two sides was removed up to a specific height of the pier (80 cm approximately, measured from the floor) (Fig. 2a). Thanks to the plaster removal, the exact position of the structural units placed at the lowest part of the pier was locally revealed. The value of the dielectric constant both for the covered and

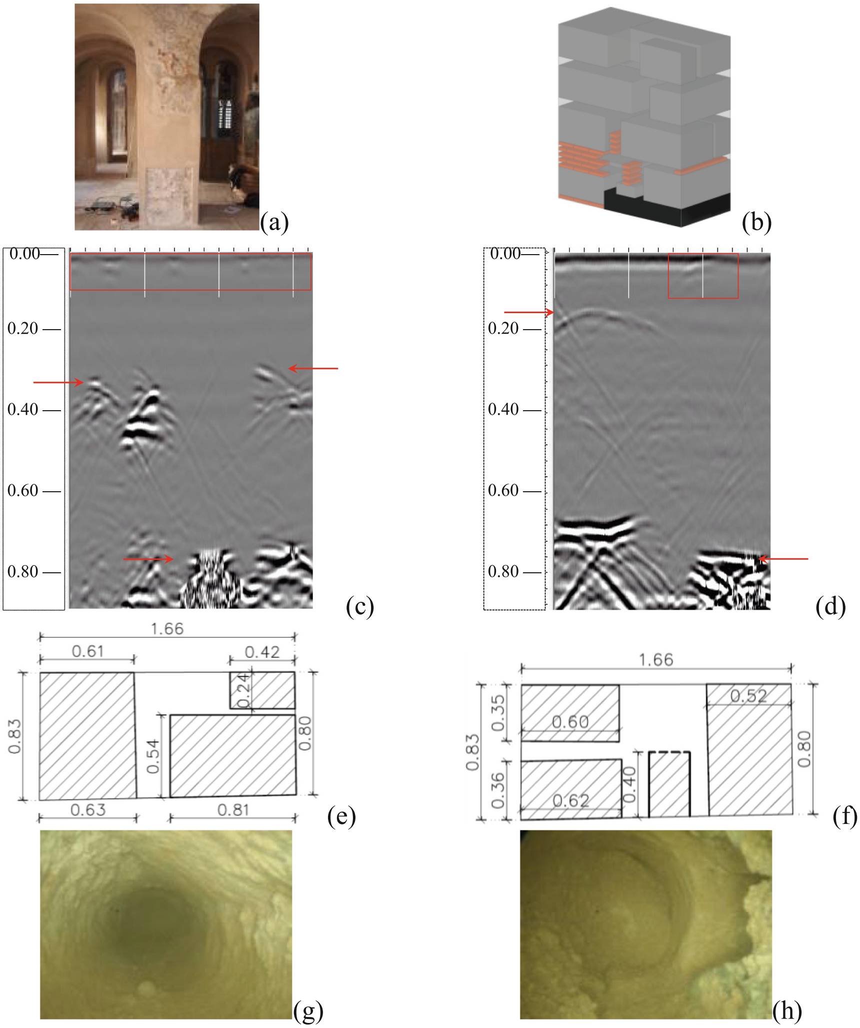

Fig. 2. (a) Pier Y25 of the Yperoon, (b) Three-dimensional drawing of the pier, depicting the overall findings of the visual inspection and the applied NDTs, (c) Radar profiles of vertical and (d) horizontal path along the pier: the arrows indicate the thickness of the identified distinct stones, whereas the frame denotes reflections created due to the presence of bricks, (e)– f) Horizontal sections at two levels (0.30 m and 0.80 m respectively), measured from the floor level, as derived from the GPR findings and the visual confirmations (where possible). Only the stones, and not the bricks, are depicted in the sections. (g),(h) Images taken at various depths (45 cm and 49 cm, respectively) of the borescope's path along the hole drilled in mortar area, between stones placed up and down.

the uncovered parts remained the same. This is attributed to the insignificant thickness of the plaster compared to that of the entire pier, and the nature of the plaster's material, as well. As all four sides of the pier were available for scanning without obstacles, a more detailed investigation was feasible.

As observed in Fig. 2(c) and (d), the reflections corresponding to the adjacent stones are strong and very clear. Thanks to the penetrating capacity of the antenna, the entire thickness of the pier could also be identified, in some cases. By combining the scans of the grid, the horizontal sections in two different levels are drawn (Fig. 2e, f), revealing a solid construction, with large-size cut stones, interconnected along the vertical axis of the pier. As visually noticed, also bricks were used at specific areas of the pier at its lowest part, depicted only in the three-dimensional drawing (Fig. 2b). The findings correlate well with those reported in Vintzileou et al. 2008, where similar observations yielded regarding pier Y32 of the gallery.

As for the nature and the quality of the mortar, its investigation was attempted via boroscopy. It seems to be rather stable and uniform along the hole, as illustrated in Fig. 2 (g) and (h). The perimeter of the hole provides the observer with information relative to a stone surface (up and right- Fig. 2g). The stone is visible until a depth that is lower than its thickness, as estimated with the radar. This could indicate that the stone is semi-cut, so its surface does not follow the axis of the horizontal hole, and therefore, its entire dimension cannot be identified with the borescope. Also, the existence of some voids of insignificant magnitude (right- Fig. 2 h) can be identified.

3.2 Monastery of Kaisariani in Attica

The in-situ measurements in the Kaisariani Monastery have been executed in the framework of the Research Programme "Thales-NTUA: Antiseismic Protection of Monuments and Historical Structures" (Vintzileou et al. 2015). The Kaisariani Monastery is situated in the area of Imittos, in Attica. The Katholikon (main Church) of the Monastery has been constructed in the 11^{th} century and it has been subjected to various interventions and modifications during its lifetime. The masonry of the Katholikon follows a construction type typical for Byzantine Churches: Masonry is constructed with stones of rather small dimensions, while solid bricks are used both within the horizontal and several vertical mortar joints. The Narthex, as well as the small church of Saint Antonios in the south part of the Katholikon, have been added during the 17^{th} century. The initial paintings of the interior of the Church have been lost. The older painting still existing in the Katholikon dates back in the 14^{th} century.

The aim of the in-situ investigations was the documentation and the assessment of the current state of the Katholikon and the Saint Antonios Church. The radar technique, as well as the boroscopy, have been used in order to identify the masonry construction type, without disturbing the masonry materials. Almost 60 radar scans over more than 120 m of masonry and observation with the boroscope at three positions were performed. The paths for the application of the radar technique have been selected according to the information to be obtained and the ease of safe access. Scans have been performed along the perimeter masonry, along the piers and the marble columns of the interior, as well as along the pavement of the Church.

It is noted that in some areas the obtained radar images are not reliable: The stones are of small dimensions, leading to the acquisition of multiple reflections, the humidity in the lower part of the masonry may be high, decreasing the accuracy of the obtained image, while, on the other hand, the radar images differ between parts of the masonry constructed in different phases (Fig. 3a). Nevertheless, the systematic radar measurements together with the application of the boroscopy gave the possibility of measuring the width of the exterior masonry leaf in most of the areas of the monument (Fig. 3b), and drawing conclusions about the construction type of the piers (Fig. 3c).

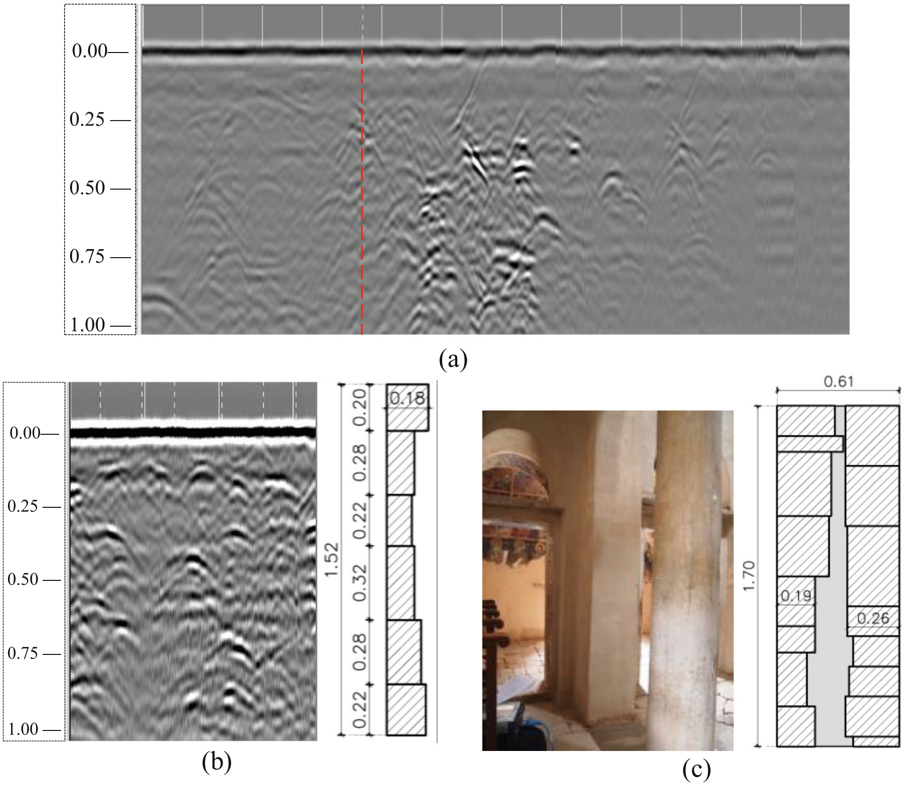

Fig. 3. (a) Radar profile of horizontal scan at the exterior (Northern façade). The red line stands for the limit between the two different construction phases, (b) Radar profile of vertical scan at the east façade of the Katholikon and the respective masonry section, (c) The scanned masonry pier and the vertical section deriving from the radar measurements. Only indicative dimensions are provided in the sections.

3.3 Agia Paraskevi Church in Chalkida

The Agia Paraskevi Church is a dominant monument of the Frankish occupation period (13^{th} century). Parts of the church were constructed again during the 14^{th} or the 15^{th}

century, whereas the west façade had to be reconstructed after the 1853 major earthquake. The historical building is considered to be one of the most important ones of its era (Bertolini Cestari et al. 2007). NDTs were applied on both the interior and the exterior of the monument, in selected areas. In total, 139 radar scans and observation with the boroscope at four positions were performed.

As different construction phases of the monument throughout the years have been reported, the present research intended to identify areas of different construction types. The goal was accomplished, since the historical data concerning the reconstructed parts of the monument guided the in-situ investigation strategy and, the combined findings deriving from the visual inspection and the GPR and boroscopy application led to the conclusion that the different construction types of distinct areas can be indeed recognized.

The most important findings from representative areas of the west and south perimeter walls are presented herein. Since the same number, level and direction of scans was kept for the interior and the exterior leaf of the three-leaf masonries, the direct combination of the findings became feasible. Regarding the west examined area of the monument, the façade is covered with plaster, whereas the interior is not, allowing thus for the positions of the stones and bricks to be known. Despite the presence of plaster at the façade, the obtained image has great clarity, with strong reflections indicating the thickness of the stones comprising the exterior leaf (Fig. 4a). The image of the interior is also clear, and the vertical short dotted lines of the file (Fig. 4 b) denote the joints between adjacent stones. Local horizontal sections depicting the geometry of the three-leaf masonry can be reproduced and, as observed in Fig. 4 (c), the average thickness of the infill is not negligible; a fact that demonstrates that further investigation is required.

This is valid for the south examined area (Fig. 4f) as well, where the thickness of the infill is estimated to be slightly smaller. The radar image exhibited less clarity (Fig. 4d), as the existence of numerous interfaces made the accurate interpretation of the files rather questionable, especially at areas constructed extensively with bricks. As structural units with various characteristics (cut-stones, rubble stone, oblong stones, bricks) have been used at the examined areas and different construction phases coexist in the structure, the acquired images significantly vary from region to region. For an overall survey of the south masonry, two interior positions were also examined with the borescope: the captures of Fig. 4(e). The first image corresponds to hole positioned right by gothic stone of the interior south wall, in proximity to the Sanctuary. The surface of the stone can be clearly identified at the left side of the hole's perimeter, as well as the drilled mortar of reddish shade. In a short distance within the same area, another hole is drilled (Fig. 4e-second image) right over a horizontally placed long timber element, at area where a buttress exists at the exterior. The images taken from this position are significantly different compared to the previous one: the light-colored mortar is unstable, powdered due to drilling, and several voids can be identified. In addition, near the end of the hole, a rectangular cross-section can be clearly observed together with a dark-colored fragment, which could be an indication of timber element position.

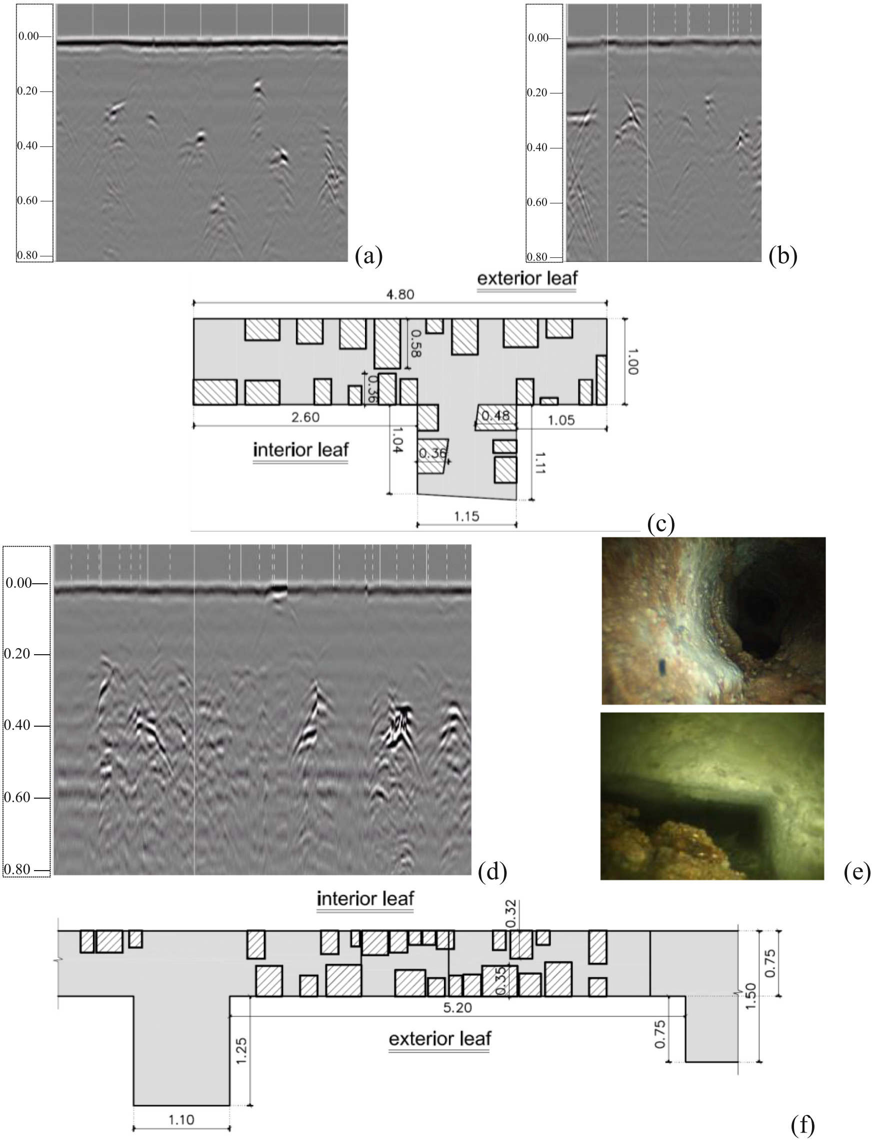

Fig. 4. (a) Radar profiles of horizontal scan at the exterior and (b) respective horizontal scan at the interior of the examined west area: the clear reflections correspond to the thickness of the identified distinct stones, (c) Horizontal section of the west wall, at the level of +2.0 m measured from the ground floor, as derived from the GPR and the visual findings, (d) Radar profile of horizontal scan at the exterior of the examined south area, (e) Images taken at various depths (24 cm and 95 cm respectively) of the borescope's path along two different holes in the examined south area, (f) Horizontal section of the south wall, at the level of + 1.70 m measured from the ground, as derived from the GPR and boroscopy findings. Only indicative dimensions are provided in the sections.

3.4 Nativity of Christ's Church in Athens

The position of the Nativity of Christ's Church, alternatively known as "Christocopidis Church," was occupied by a temple owed by the Copidis Athenian family, who gave the name to the monument. The monument at its current scheme was constructed with cut-stones in 1860 or 1880 and has experienced two main earthquake incidents in 1981 and 1999, which caused major structural damages that can easily be observed nowadays. The GPR technique was applied on both the interior and the exterior of the monument and, in total, 100 radar scans were performed. Schmidt hammer testing was applied on twelve stones of the south perimeter masonry wall, in limited area with removed plaster.

The investigation campaign for this monument was conducted as the first prerequisite step in the context of an extensive study on the assessment of the monument's existing condition, ultimately aiming at the design of suitable structural interventions. Towards this direction, the sound simulation of the structure is required and, hence, the collection of adequate and accurate data related to the construction type of distinct parts of the monument (perimeter walls and piers). In addition, for the complete modelling of the structure, sufficient estimation about the strength of the materials used (stones, mortar) was also required. Thanks to the application of the described NDTs, the goals were achieved, decisively assisting the structural design towards the definition of the needed interventions. The most important findings from representative areas are reported herein.

The great effect of the frescoes on the radar image is depicted in Fig. 5(b): when the antenna crosses the area where gold color has been used in the frescoes (Fig. 5a), the signal propagation is totally obstructed and no information can be acquired by the image. When the antenna is moved in other areas of the same side of the pier, a very clear profile is obtained, as observed in the vertical scan of Fig. 5(c), where the thickness of the adjoining stones is depicted with clarity, revealing the consistent interconnection between them. Thanks to the existence of adequate surfaces without frescoes, the geometry of the pier can be represented in indicative horizontal sections (Fig. 5d).

The results obtained from Schmidt hammer testing (Fig. 6) indicate the existence of stones that can be distinguished in two categories based on their strength: (a) stones of relatively low strength, varying between 8 MPa and 17 MPa (i.e. average rebound values between 18 and 30), and (b) stones of higher strength, ranging from 33 MPa to 41 MPa (i.e. average rebound values between 39 and 42). The estimated values reported correspond to the average of the strengths resulting from two calibration curves available at bibliography (Tassios and Mamillan 1985; Aliabdo and Elmoaty 2012). The findings from the macroscopic observation of the stones correlate well with the estimated strength values. In particular, stones of lower strength are friable and porous. On the contrary, stones of higher strength do not exhibit the aforementioned characteristics, while being slightly different in color and having reddish veins. As anticipated, stones of high strength are concentrated in the lower zone of the examined area.

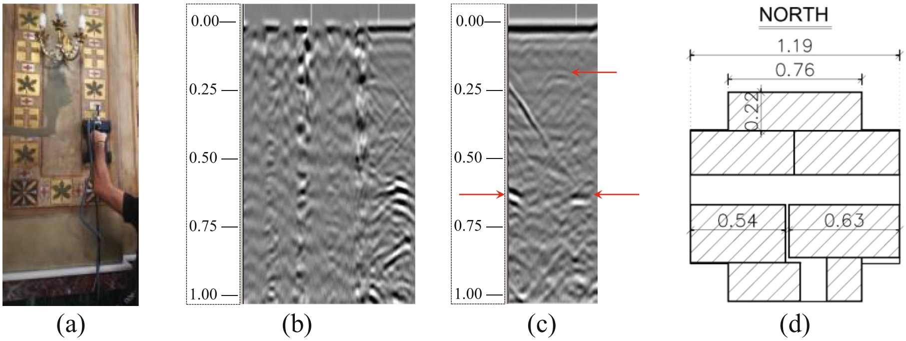

Fig. 5. (a) Scanning on the frescoes of the pier, (b) Radar profile of vertical path along the pier: the gold color of the frescoes does not allow for the propagation of the signal, (c) Radar profile of vertical scan along the pier, path without frescoes: the arrows indicate the thickness of the identified stones. (d) Horizontal section, as derived from the GPR findings: only indicative dimensions are provided.

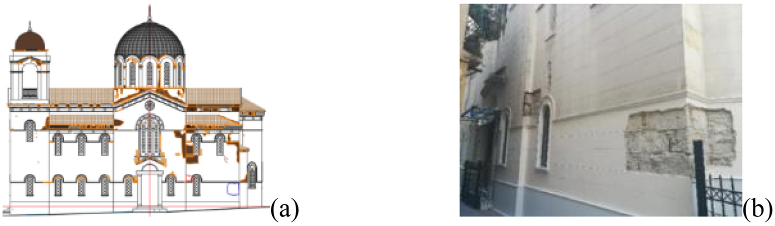

Fig. 6. (a) Side view of the church (drawing provided by E. Tavouktsi, Civil Engineer, Designer of the interventions): the blue frame indicates the presented examined area, (b) Photo of the examined area: the plaster was removed and the stone surfaces were revealed.

4 Conclusions

Based on the material presented, it is concluded that the application of non-destructive techniques in gingerly selected areas, organized in specific steps and preceded by careful inspection, can yield reliable and in-detail results regarding the structure of the monuments. Thanks to the combination of the information emerging from each method, the outcome is enhanced and the final results provide sufficient data for the visible and non-visible parts of the examined structures.

The evaluation of the mechanical properties of the materials and the comprehension of the geometry of the structure are the prerequisite for a sound analysis, which is strictly linked to the decision-making process on formulating proposals towards efficient interventions in monumental structures of high historical and cultural value. All the methods presented herein are applicable in the field of monument investigation, on condition that constrains arising by the characteristics of each unique structure are considered.

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