

Article

Enhanced Documentation and Evaluation of Grouting Process, through the Fusion of Non-Destructive Testing and Evaluation Information—The Case Study of the Katholikon of the Monastery of Panagia Varnakova

Stergios Roumeliotis, Kyriakos Lampropoulos ^{*}, Ekaterini Delegou , Elisavet Tsilimantou ,
Vasileios Keramidas, Asterios Bakolas  and Antonia Moropoulou 

School of Chemical Engineering, National Technical University of Athens, Iroon Polytechniou 9, 15780 Zografou, Greece; stergios.roum7@gmail.com (S.R.); edelegou@central.ntua.gr (E.D.); elisatop@gmail.com (E.T.); bkeramidas@hotmail.gr (V.K.); abakolas@mail.ntua.gr (A.B.); amoropul@central.ntua.gr (A.M.)

* Correspondence: klabrop@central.ntua.gr; Tel.: +30-210-7723103

Abstract: The restoration of historic buildings and structures involves a wide range of scientific and technical fields. The grouting process is among an array of rehabilitation and preservation interventions and aims to homogenize the structure after the implementation of strengthening measures. The process can provide important information regarding the state of preservation of the examined structure and correlate the progress of the process with the pathology of the monument. To achieve this, the analysis of typical raw grouting data is progressively fused with additional information from the diagnostic studies, non-destructive testing, geospatial information, and from the calculation and analysis of grouting indices. The restoration project of the Katholikon of the Monastery of Panagia Varnakova in Fokida, Greece was selected as the case study, due to its large scale and the severe earthquake damage it has sustained, which has necessitated comprehensive strengthening interventions and extensive grouting. The implementation of an integrated methodological approach validated the enhanced level of co-analysis, revealing information that is not readily deduced from a typical approach. Selected sub-areas of the Katholikon are presented, demonstrating how the observed pathology can be correlated with the results of the grouting process, while incorporating 3D data, and findings from structural and non-destructive analyses.

Keywords: grouting; geospatial data; ground penetrating radar; infra-red thermography; laser scanning; photogrammetry; structural analysis; Monastery of Panagia Varnakova



Citation: Roumeliotis, S.; Lampropoulos, K.; Delegou, E.; Tsilimantou, E.; Keramidas, V.; Bakolas, A.; Moropoulou, A. Enhanced Documentation and Evaluation of Grouting Process, through the Fusion of Non-Destructive Testing and Evaluation Information—The Case Study of the Katholikon of the Monastery of Panagia Varnakova. *Buildings* **2024**, *14*, 814. <https://doi.org/10.3390/buildings14030814>

Academic Editor: Marco Di Ludovico

Received: 26 February 2024

Revised: 9 March 2024

Accepted: 14 March 2024

Published: 16 March 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The preservation of built Cultural Heritage (CH) is an interdisciplinary scientific and technical field that attracts significant interest due to the importance of CH to our society. Past experience and recent technological advancements have demonstrated the effectiveness of a holistic approach for the assessment, restoration, management, and safeguarding of CH [1–3]. Such a holistic approach is based on (a) a systematic spatial and temporal documentation of CH assets utilizing state-of-the-art techniques and three-dimensional management and analysis of data [4–16]; (b) multi-modal assessment of the state of preservation of the CH assets [2,17–20]; (c) diagnosis of the environmental and human-induced decay/damage phenomena and analysis of risks and hazards [2,21–26]; (d) systematic design of effective and compatible interventions utilizing innovative materials and techniques, based on scientific findings and analyses [1,2,27]; (e) application of compatible materials and implementation of designed interventions in conjunction with in situ, real-time assessment [2] to evaluate their effectiveness [28,29] and adjust the works as required; and (f) monitoring of critical parameters of the CH asset to ensure its sustainability and preservation of its values [26,30].

This approach regards a wide range of activities, among which those addressing the structural integrity, stability, and performance of the CH asset are the most common and important. Major restoration projects typically focus on reinstating or improving the structural integrity of the involved monument or historic building, so that the asset can sustain environmental and dynamic (earthquake) loadings. Due to the sensitive nature of CH assets, such projects are not considered as conventional civil engineering applications; the requirements for compatibility, reversibility, minimal intervention, sustainability, and preservation of values pose challenging and often contradictory requirements and limitations.

Grouting is an established procedure utilized as part of comprehensive structural interventions on CH assets [31–33]. During this procedure, a low viscosity mortar composition (grout) is injected into the masonry from specific openings, with the aim—upon the hardening of the grout—to result in a masonry structure that is devoid of internal cracks and voids, without, however, compromising the stability of weaker elements of the structure. Grouts can contribute to the increase in compressive and tensile strength of the masonry. Grouting is a non-reversible intervention, in the sense that once the grout is solidified within the masonry internal void network, it is impossible to remove it without disassembling the masonry. Hence, significant research for historic structures is being conducted regarding the composition [34–39], the physicochemical [39,40] and rheological characteristics of the grouts [41–43], their impact on the mechanical behavior of the grouted masonry [44–47], the criteria for the compatibility of the grouts with historic materials and the issues of sustainability [48–51], as well as the grouting procedure. The assessment of the efficacy of grouting is largely based on laboratory testing of the grout prior to grouting, in conjunction with in situ mainly destructive testing post-grouting [31,33]. In situ post-grouting assessment with non-destructive testing has demonstrated rather limited success and difficulties in the interpretation of NDT results and correlation with the masonry characteristics [52], or thus far has been limited to laboratory testing [53,54].

Generally, the grouting procedure comprises three interrelated stages. The first stage regards the design and installation of an appropriate matrix of injection tubes, based on the results and findings from the diagnostic study; the location of each injection tube is carefully documented. The second stage regards the recording of the amounts of grout injected at each injection tube, during the various grouting phases, as well as the recording of the exit tubes. The third stage regards the analysis of detailed grouting data per grouting area/zone and per grout injection tube and the analysis of tube interconnectivity, with the aim to assess and justify the spatial variations of grout consumptions.

In a recent study [55], this analysis has been expanded through the correlation of geospatial and grouting data by considering the three-dimensional documentation aspects of grouting data and the development and application of grouting indices. These indices enabled—at a pilot scale—the merging of grouting data, geospatial data, and non-destructive testing (ground-penetrating radar prospections) to reveal the internal structure and assess the state of preservation of the Holy Aedicule of the Holy Sepulchre. However, the case study of the Holy Aedicule is a structure of rather limited dimensions, approximately 6×8.5 m. In addition, it exhibits a number of specific characteristics: a rather complicated architecture and geometry (relative to its size) with a diverse variation of masonry thickness as well as dimensions and morphology of its internal spaces; intense spatial variations of structural layers (historic masonries from various periods, Holy Rock, restoration masonry); very limited grouting from the interior surfaces due to the requirement to retain internal marble claddings for sensitivity issues. These characteristics considerably influence the analysis of the developed indices, as described in [55]. Even so, the previous study served well as the starting point upon which a more systematic and methodological assessment and correlation could be achieved; a more “typical” case study was thus required, in the form of a large building of a more “conventional” geometry and with reduced variations in the masonry structural layering.

From this previous research, the objective of the current work was to develop and test a methodological approach for improved documentation and evaluation of the grouting

process, through the fusion of non-destructive information. The restoration project of the Katholikon of the Monastery of Panagia Varnakova in Fokida, Greece was selected as the case study, due to its large scale, its rather “conventional” form (a rectangular church with two internal rooms), and the severe earthquake damage it has sustained. In comparison, the Katholikon has approximately 7.5 times the volume of the Holy Aedicule and offers masonry surfaces for grouting with an area approximately 25 times those of the Holy Aedicule. In addition, it presents a three-leaf type masonry of very consistent thickness, as compared to the multitude of structural layers in the previous case study. Therefore, in principle, the analysis of the grouting indices and the application of the proposed methodology are less dependent on the “peculiarities” of the examined structure, which was the case of the previous work. As will be discussed below, this was indeed accomplished.

The interdisciplinary diagnostic study implemented by the National Technical University of Athens (NTUA) prior to the restoration works offered invaluable information about the state of preservation of the Katholikon’s structural systems, which in conjunction with detailed monitoring of the grouting activities and the application of non-destructive testing offers a realistic framework for the fusion of multi-modal information at large and severe scales and for the capacity of the developed grouting indices to adequately correlate with the observed pathology.

2. Materials and Methods

2.1. The Use Case of the Katholikon of the Monastery of Panagia Varnakova

The Monastery of Panagia Varnakova is a historic byzantine monastery located at the Efpalio municipality east of Nafpaktos, in Fokida prefecture, Greece. It is dedicated to the Assumption of Virgin Mary (Panagia). The monastery complex was built in 1077 by Monk Arsenios [56,57]. The name Varnakova refers to the Slavic toponym where the monastery is located, typical of many toponyms in the region [56]. During the byzantine period, the monastery prospered significantly from the Komnenoi emperors. The religious importance of the monastery is highlighted by the fact that many emperors from the Komnenian dynasty were buried within the Katholikon of the Monastery. During the Turkish occupation, the monastery’s power decreased, without, however, losing its significance as spiritual center of the region. During the Greek revolution, and specifically in 1826, the monastery was partially destroyed by a fire (explosion) set by the army of Ibrahim Pasha. The Katholikon was rebuilt in 1831, following almost exactly the plan of the original basilica, with financial aid from I. Kapodistrias, first Governor of Greece. The Katholikon sustained significant damage from the Aigio earthquake in 1995 and remains closed for safety since 2010. The Katholikon was fortunately not destroyed during two recent fires that erupted in the monastery complex. A 2017 fire destroyed the monastic cells and the archives of the Monastery. Another fire erupted on 14 June 2020 and destroyed the new temporary church building that was constructed within the monastery complex after the damaged Katholikon was closed; unfortunately, this fire destroyed the historic miraculous icon of Panagia Varnakova as well as other religious relics.

Between 2018 and 2020, NTUA implemented an interdisciplinary diagnostic study of the Katholikon of the Monastery of Panagia Varnakova, to assess its state of preservation, to document its pathology, to identify areas of the monument in need of structural strengthening, and to design and propose restoration interventions [58]. In 2020, the Hellenic Ministry of Culture approved the proposed architectural and static restoration studies, and the first phase of the works commenced on July 2021, under the scientific supervision of NTUA. The restoration project is expected to be completed in 2024, and among the various strengthening measures implemented, it includes extensive and systematic grouting of the masonries and the dome structure of the monument, which is the subject of the current work.

The Katholikon is a suitable case study for the development and evaluation of a methodology for an enhanced documentation and evaluation of grouting process, due to the combination of its architecture and the sustained damage. The original church (1077) was an elongated domed basilica divided into a nave and two aisles through two rows of

parallel columns. The presence of a small step elevation at the west segments of the current nave and aisles has been interpreted by A. Orlandos [56] as remnants of an eso-narthex constructed and decorated in 1151. In 1229 or 1230, an exo-narthex was constructed at the west part of the church. According to historic sources [57] and architectural analysis [58], when the Turks exploded the Katholikon in 1826, the exo-narthex largely remained intact and was retained and integrated into the newer construction; thus, the exo-narthex dates to 1229 or 1230, whereas the main church dates to 1831. This was actually verified during the restoration project of the Katholikon, when during the removal of the interior plasters from east (interior) wall of the exo-narthex, a byzantine masonry system (cloisonné style) was revealed [59]. This masonry corresponds to the west façade of the church prior to the construction of the exo-narthex (note: as part of the restoration project, this masonry will be conserved and remain visible and will not be plastered).

The new church followed the same foundation plans, visible at that time after the aforementioned destruction, although the architectural analysis [56] suggests that only the interior width (7.70 m) of the original church was retained. The rebuilt apse of the basilica may have shifted eastwards as compared to its original location at the first building, increasing the total length accordingly. These features present an appealing case study, since the current Katholikon (Figure 1) includes parts dating to the 13th century (exo-narthex), an interface of these parts with the newer 19th century structure, a nave that contains parts of a foregone modification (12th century eso-narthex), and a rebuilt apse that potentially does not coincide with the configuration and location of the original one.

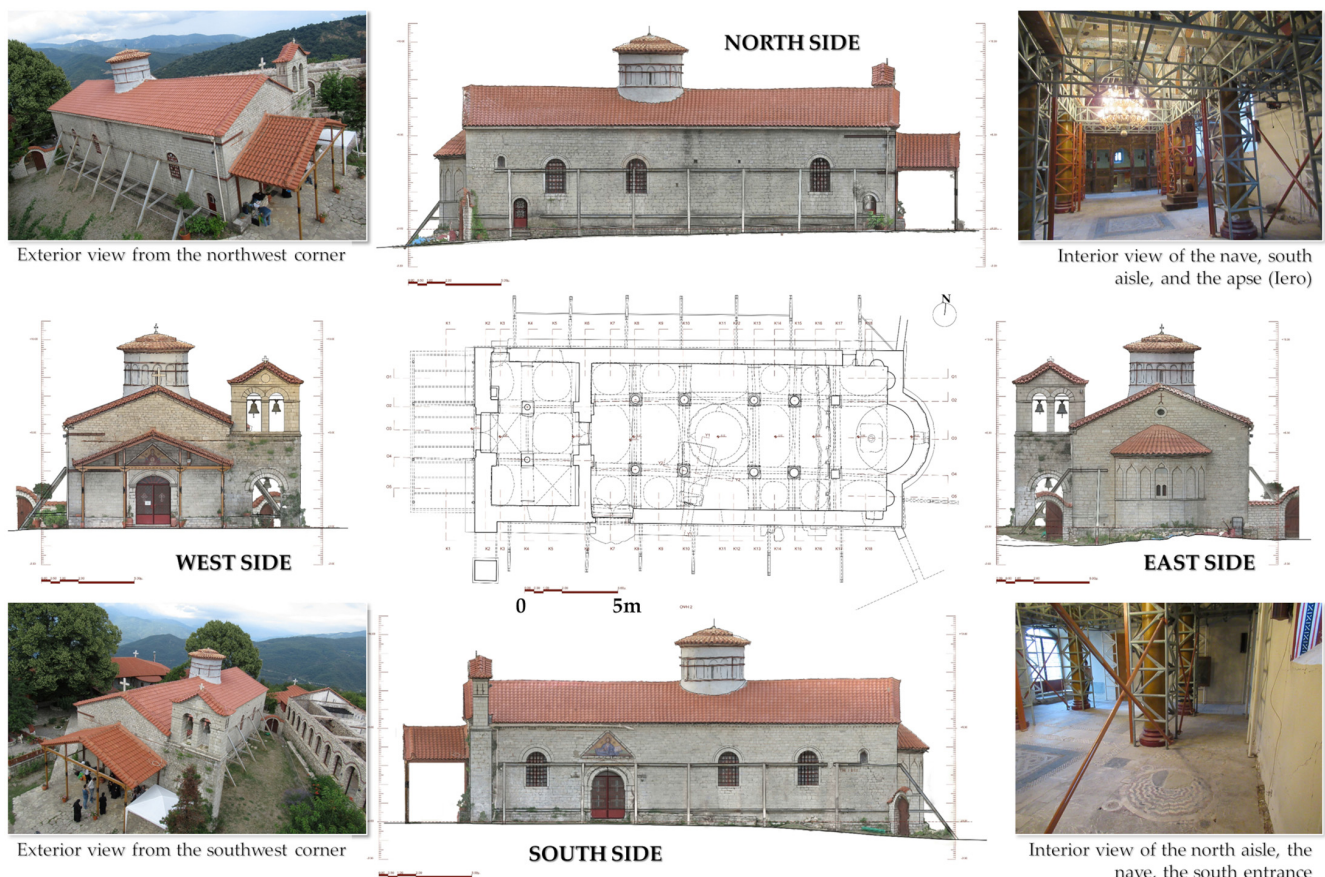


Figure 1. The Katholikon of the Monastery of Panagia Varnakova (adapted from [58]).

As mentioned above, the Katholikon has sustained extensive structural damage due to recent earthquakes, as evidenced macroscopically by exterior and interior cracks and failures. The pathology is described in detail in [58], whereas its non-destructive evaluation with ground-penetrating radar is presented in [60]. Figure 2 presents typical cracks and

failures prior to the initiation of the restoration works. Figure 2A indicates an exterior structural crack observed on the north side of the Katholikon, which corresponds to the pair of structural cracks created by the northward thrust of the main dome during the earthquakes (mode along the N–S direction) as validated by the finite element modeling and assessment of the dynamic behavior of the Katholikon under simulated earthquakes [58,60]. Figure 2B indicates the crack located at the north side at the junction of the exo-narthex and the main church. Figure 2C indicates the cluster of structural cracks created at the east end of the south side of the Katholikon, as the result of the dynamic loading during the earthquakes along the E–W direction [58,60]. Figure 2D indicates a typical cluster of cracks created in the west side and the bell tower. Figure 2E indicates typical horizontal cracks observed at the interior of the main church (south aisle in this case), whereas Figure 2F,G indicate typical failures of the arches supporting the domes. Figure 2G, in particular, corresponds to the south arch supporting the main dome, and it is interesting to note that no pair of exterior structural cracks is observed in the corresponding positions on the south side of the Katholikon, as compared to Figure 2A. This indicates that the failure at the south arch relieved much of the earthquake loadings and did not influence the south wall accordingly, during the movement of the main dome along the N–S direction. In addition, many other cracks originate at the openings (doors and windows) of the Katholikon.

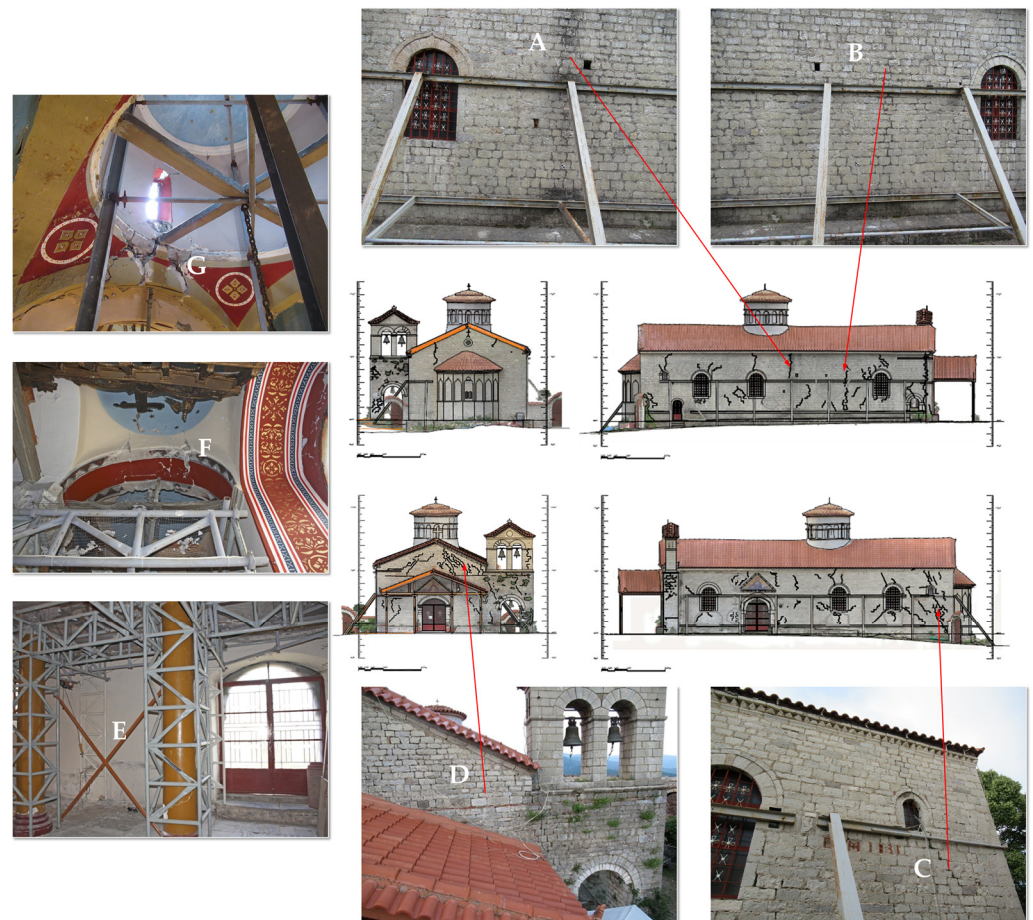


Figure 2. The pathology of the Katholikon (adapted from [58]). Typical damage/cracks (A–G); see description in main text.

The restoration project of the Katholikon of the Monastery of Panagia Varnakova aims to address risks and findings as revealed in the interdisciplinary diagnostic study [58]. The project regards restoration and strengthening measures as proposed in [58], as described in the relevant architectural and static studies, and as approved by the Hellenic Ministry of

Culture. The progress of the project is described in more detail in [59]. Briefly, and within the scopes of this work, and in order to put the grouting process within the appropriate analysis perspective, the project includes (a) the opening of the roof and removal of 300 tons of filler stone material; (b) optimization of the architectural and static studies to take into account the removed load from the roof; (c) removal of mortars from all joints in the stone structure at the interior, exterior, roof, and dome; (d) application of restoration joint mortars; (e) grouting of the structure, in two phases; (f) repositioning of the sixteen arches in which their keystones were dislocated; (g) addition of stainless steel rods to support damaged arches; (h) installation of stainless steel struts–ties at the base of the arches, in both directions, in the interior of the Katholikon; (i) strengthening of the transverse roof pediments with steel rebars; (j) reconstruction of the wooden roof; (k) installation of stainless steel hoops along the height of the columns; (l) construction of concrete tie beams at column foundation; and (m) application of new compatible restoration plaster and motif decorations on the interior surfaces, wherever this is planned according to the approved architectural study.

The current work focuses only on the grouting process and its correlation with non-destructive testing.

2.2. Grouting Material

The selection of the grout material was based on the following criteria: (i) it fully complied with compatibility requirements, (ii) it achieved the specified performance specifications, and (iii) it addressed technical issues posed by the grouting procedure and construction site limitations.

A comprehensive characterization of the historical materials—masonry stones, joint mortars and interior plasters—was implemented as part of the diagnostic study [58]. It included the following: optical microscopy for the petrographic analysis of the stone samples; digital microscopy to examine the morphology and texture of the stones, mortars, and plasters; X-ray diffraction for the mineralogical analysis of the stones, mortars, and plasters; simultaneous differential thermal and thermogravimetric analysis for the determination of the stone, mortar, and plaster compositions; total immersion tests of stones, mortars, and plasters to evaluate their open porosity accessible to water, their water absorption behavior, and their apparent density; determination of total soluble salts (TSS%) of stones, mortars, and plasters; mechanical tests; Schmidt hammer rebound in situ tests on several areas of the Katholikon masonries to evaluate the surface hardness of the various lithotypes; infra-red thermography to evaluate the state of preservation of the masonries and identify areas of different thermal and thermohygric behavior, indicating macroscopic variations of decay and damages. Based on the findings of the above analyses [58] and following an established design and selection procedure [39,45,48–50], a lime–metakaolin-based restoration mortar was proposed, containing no cement, to ensure compatibility with the historical building materials and be resilient to the prevailing environmental factors. Consequently, and in order to be of the same type and compatible with the aforementioned restoration mortar, a lime–metakaolin-based restoration grout was selected, in order to enhance the homogeneity of the restored structure after the various strengthening interventions.

Regarding the performance requirements, these were specified through a dynamic structural analysis based on the finite element model of the Katholikon [58]. This analysis required the selection of a restoration lime–metakaolin-based grout with a minimum compressive strength of 10 MPa, in order to achieve adequate mechanical reinforcement of the rehabilitated structure and ensure structural integrity under static and dynamic loads [58,60].

The worksite posed some restrictions, since the presence of visitors and pilgrims to the Monastery did not allow for the operation of a facility for manufacturing ad-hoc grout compositions. Consequently, this necessitated the selection of a commercial ready-mix material to decrease preparation time and ensure reproducibility of the grout.

Based on the above, a commercial lime–metakaolin grout, MasterInject 222 from Master Builders Solutions, was used in the restoration of the Katholikon. It is a cement-free, lime–pozzolan (metakaolin) grout with a very fine particle size ($<12\ \mu\text{m}$), high flowability, and excellent sustainment of its workability. The presence of the metakaolin—a highly reactive pozzolan—in the composition of both the restoration mortar and the grout material, ensures a fast consumption of the free calcium hydroxide of the lime, while, in parallel, allows for an early attainment of the grout’s mechanical strength [40,51]. The grout expands in the plastic phase; thus, it can fill even the smallest voids within the reinforced structure. Furthermore, it does not release water-soluble salts, it does not induce the development of efflorescence, and it presents excellent resistance to sulphates. This is important, because the results of the diagnostic study revealed the presence of soluble salts ($>3\%$ TSS) at the highly porous stones of the upper structure (arches), as well as at the mortar samples at the floor levels, where the presence of Cl^- and SO_4^{2-} is favored due to rising damp. The selected commercial grout develops a compressive strength $>10\ \text{MPa}$ and may therefore be classified as an M10 type according to EN 998-2:2016. The dry grout was added to the appropriate amount of water, according to the manufacturer’s directions (1 kg dry grout plus 0.3 kg of water) and mixed in the grouting vessel (Figure 3).



Figure 3. (Left) The mixing tank and pump with pressure manometers, where the grout was mixed with the appropriate amount of water. The mixture is filtered to remove coagulated particles. (Right) Grouting at the eastern masonry at an exterior tube position and monitoring of pressure on the manometer of the gun.

2.3. Grouting Procedure

The injection of grouts is an important stage of the restoration project at the Katholikon. Initially, all joint mortars from the exterior surfaces and plasters and joint mortars from the interior surfaces were removed and a compatible restoration joint mortar was applied at the masonry [59]. During the application of the joint mortars, plastic tubes (10 mm diameter) for the injection of grout were installed at approximately 6500 positions throughout the whole monument. The tubes were installed with a horizontal spacing of approximately 40 cm and with a vertical spacing of approximately 10–30 cm corresponding to the heights of the stone rows. The tubes were inserted at a depth of approximately 50 cm. According to [60], the masonry is of the three-leaf type; the exterior and interior stone layers have a thickness of approximately 25 cm, and the filler layer occupies the remaining central layer of the ~80 cm thick masonry. Therefore, the insertion of the injection tubes at a depth closer to the opposite stone layer from where the grout is injected aims to ensure that as much of the filler layer and the internal voids within the examined masonry section are filled with grout, instead of only the internal zone close to the injection point.

The tubes were coded as follows: the first letter of the code corresponded to the façade (North, South, East, West) on which the corresponding masonry area is located; the index “e” or “i” corresponded to exterior or interior injection positions; the three-digit number indicated the sequential numbering over the specific façade area. An exception to the

coding method regarded the tubes located in the aforementioned historical byzantine wall separating the nave from the exo-narthex, which were coded with the letter H. In addition, the north and south interior surfaces of the exo-narthex (Pronaos in Greek) were coded PN and PS, respectively, whereas its west interior surface was typically coded as Wi. The bell tower tubes were sequentially coded as TB. Due to the vast number of tubes installed, and in order to expedite the analysis of the results, the masonry areas were divided into sub-areas (Figure 4), defined by the location of the windows. Sub-areas NB, ND, NF, SB, SE, and SG regard masonry areas right above and below the respective windows. Sub-area SC includes the masonry area above the south entrance. Sub-area WB regards the masonry above the main (west) entrance. Sub-area EB regards the semicircular apse at the east side of the building. Sub-area ED is located above EB and corresponds to the upper flat central part of the east façade, whereas EB regards the semicircular apse.

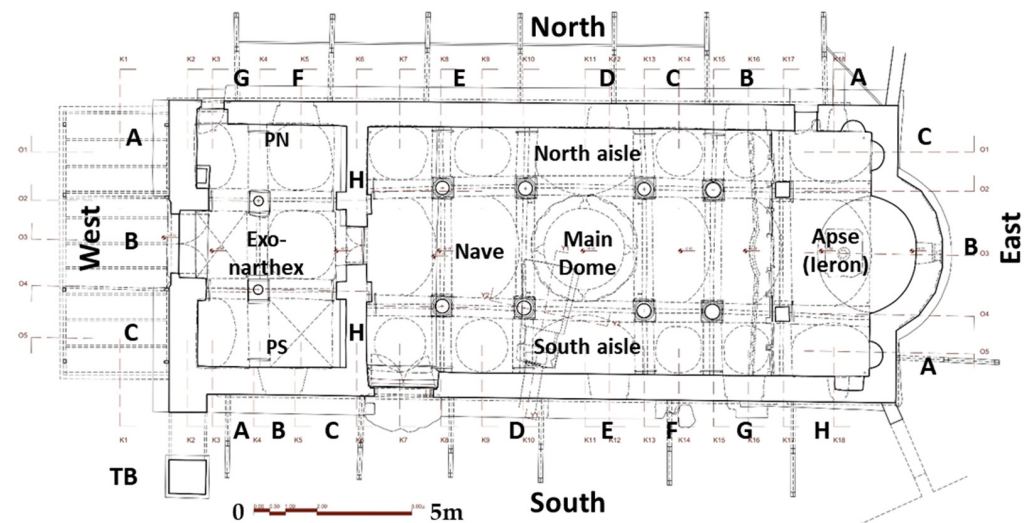


Figure 4. Plan of the Katholikon with indication of the grouting sub-areas and the main features of the church (adapted from [58]).

The grouting process was completed in one initial and three main phases. The initial pilot phase (May 2022) regarded the lower parts of the exo-narthex from injection tubes at its exterior and interior surfaces, as well as the lower parts of the bell tower. The first main phase (October 2022) regarded the lower parts of the Katholikon, approximately up to the level of the windows. The second main phase (May 2023) regarded mainly the mid-height parts of the building, whereas the last main phase (July 2023) regarded mostly the upper parts of the building and interior grout injection points. In general, the grouting sequence initiated at the sub-area (panel SA) of the south façade adjacent to the bell tower and ended to the west façade, along an overall south–east–north–west façade sequence, although adapted in situ with small variations according to the observed grouting behavior.

The implementation of the grouting process in discrete phases ensured that the masonry was not loaded with a large amount of fluid grout, encountering problems with its hygric behavior during the solidification of the grout. The considerable interval between the grouting phases ensured that the grout had dried and solidified before continuing the process to higher levels. Thus, the enhancement of the strength of the masonry was obtained gradually and height-wise.

Grout was pumped from the mixing tank, through the pipes, until it reached the gun which was attached to the active tube, from where it was injected under low pressure into the masonry. Care was taken to keep the pressure at the position of the grout gun at a low value (1 bar) to avoid affecting the stability of weaker elements of the structure. Thus, the pump pressure was adjusted as required to cope with the total dynamic head (height difference between the pump and gun) and the different “resistance” encountered at various injection points. The desired flow characteristics of the liquid grout were ensured

by a careful mixing process (accurate grout-to-water ratio) and filtering to remove potential coagulated particles.

Once injected through the entry tube, the grout gradually filled all the internal cracks and voids that were interconnected with this entry point, as evidenced by the variation of the gun pressure and volumetric consumption. Whenever grout overflowed from another grouting tube or an exit point, the exit tube was sealed in order to stop grout overflow. Grouting was continued from the entry tube, until all cracks or internal voids interconnected with the active entry tube were filled with grout material and the pressure remained at a constant value, usually equal to 1 bar, indicating that the tube did not carry any more grout out to the masonry (as verified by monitoring of the volumetric consumption). Upon completion of the grouting from this specific grout entry tube, it was sealed-off, the time was recorded, and the total volume of grout consumed through this entry tube was calculated and documented. Grouting then continued to the next entry tube, until all tubes of the examined sub-area of the masonry were sealed off, either as entry or exit points.

2.4. Applied Methods and Techniques

The fusion of enhanced documentation and information obtained from the grouting process with information obtained from non-destructive techniques is accomplished through three levels of analysis [55].

The first level of grouting data analysis regards the documentation of grouting data and their management with Microsoft Excel® spreadsheet editor software. The use of spreadsheet software for storage, organization, computation, and analysis of grouting data is rather straightforward and facilitates easy in situ entry of data in tabular form and clear calculations of required indices and preparation of graphs. Furthermore, the tabular form of information storage allows for better cooperation with the technicians, in situ. This first level of analysis regards the calculation and report of grouting data per sub-area and zone, analysis of grouting data per grout injection tube, and the assessment of the grouting tube interconnectivity.

The second level of geospatial analysis utilizes the spatial information of each entry or exit grouting tube. The Katholikon has been thoroughly documented during the diagnostic study [58], and a 3D model of the structure has been prepared. However, for the scope of this work, the 3D model is not a prerequisite, and its use to obtain the spatial coordinates of the tubes would be unnecessarily complex. Instead, since the Katholikon church comprises large, rather “flat” surfaces, both at its exterior and interior (with the exception of the arches and domes), it was far more straightforward to use orthophotos of the respective façades. For other use cases, however, of more complex geometry and form, e.g., Ref. [55], the availability of 3D models expedited the process of obtaining geo-information. The orthophotos of the façades of the Katholikon were the geometric product of an automated 3D imaging methodology based on high-resolution digital images, terrestrial laser scanning and high accuracy geodetic measurements. All geospatial data were accurate and georeferenced to local plane projection reference system [58]. The digital products were accessible and managed with Autodesk AutoCAD® for the calculation of the distances between entry and exit grouting tubes.

The third level of co-analysis merges the information obtained from the study of grouting data (first level of analysis) and the information obtained from the study of geospatial data and grouting indices (second level of analysis) with information obtained by non-destructive testing (NDT). Specifically, ground-penetrating radar (GPR) and Infrared Thermography (IRT) were utilized in the Katholikon for the non-destructive evaluation of the pathology of the monument [58–60]. GPR is an established NDT for Cultural Heritage applications, as it can reveal the internal structure and assess the types and extent of structural damage of historic buildings [18,20,28,29,60–70]. It exploits the propagation, diffusion, absorption, and reflection behavior of electromagnetic pulses, that are emitted from the surface of the examined area (masonry), due to the different dielectric properties of the building materials of the prospected structure. In this work, a MALÅ Geoscience ProEx

GPR system with a 1.6 GHz antenna was utilized. Two-dimensional sections (b-scans) were processed with MALÅ Geoscience RadExplorer v.1.41 software. Infrared Thermography (IRT) is another established NDT that can provide valuable information regarding the materials and their decay products, the thermohygric behavior of the examined structure, and the observed pathology [18,29,68–75]. It is based on the detection and mapping of thermal variations at IR wavelengths over the examined surfaces due to the different emissivities of materials. In this work, an FLIR B200 IR camera was used to survey the surfaces of the Katholikon.

3. Results

3.1. Analysis of Detailed Grouting Data

This work regards the analysis of the data from the grouting tubes of the main cell of the Katholikon. The grouting of the domes and the roof is not further elaborated, due to the complex geometry of the upper parts of the Katholikon with its multiple domes and the main dome, as well as the extensive damage to the arches and the upper structural system. These posed certain limitations in the elucidation of the interconnectivity of the interior voids and cracks (see below) and the application of the grouting indices [55]. This remaining phase of the grouting process will be analyzed in a future work.

Approximately >2500 tubes functioned as entry tubes, and >1000 tubes ended up as output tubes. The total volume of grout injected was 28.73 m³ (see Figure 5). The grouted masonry was approximately 309 m³ and 747 m², i.e., demonstrated an average grout “consumption” of 93 L/m³ or 38.5 L/m². The value of 93 L/m³ corresponds to 9.3% of the masonry volume, a rather large percentage, indicating the severe state of damage of the Katholikon, although this includes significant grout consumption that apparently was diverted to the Katholikon foundations (see comments below).

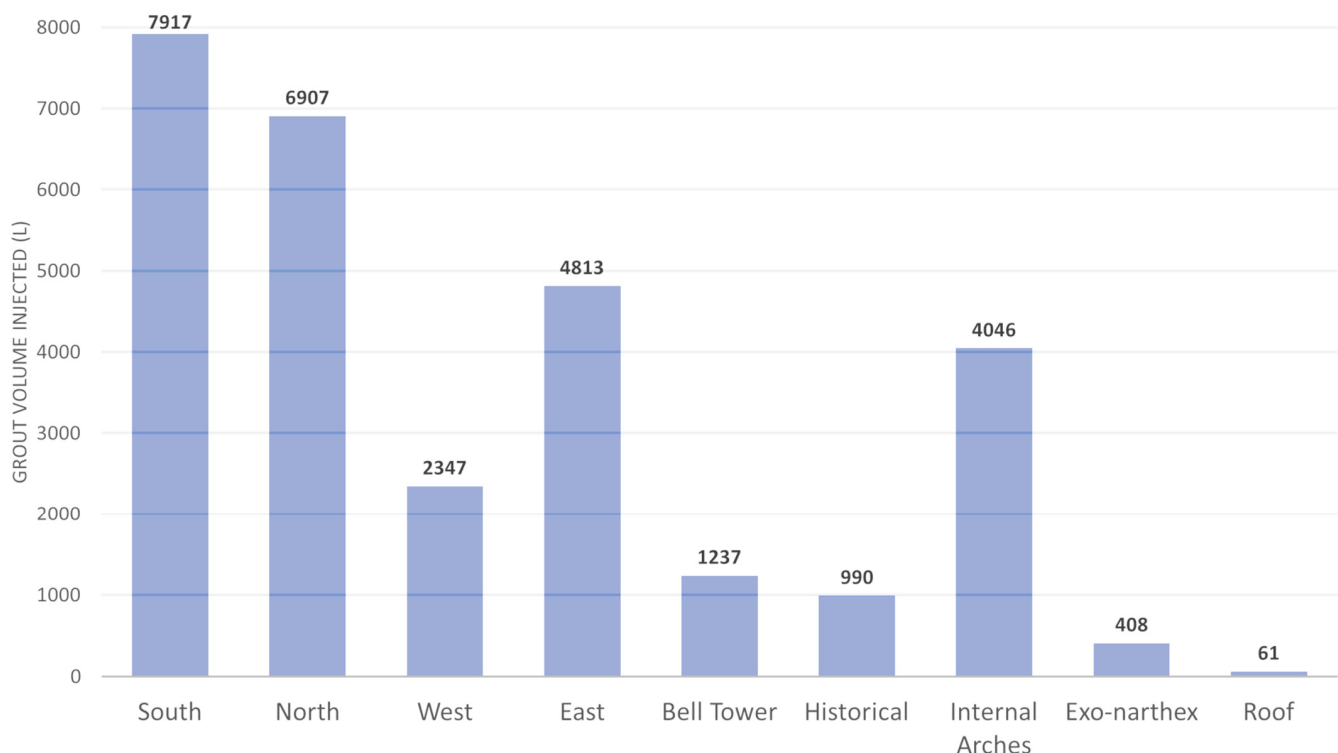


Figure 5. Volume of grout injected per area of the Katholikon.

In certain areas, however, no significant amount of grout could be injected into the tubes, implying that the masonry section in the vicinity of these tubes was in a good state of preservation, with minimal internal voids and/or cracks or relatively small intercon-

tivity. Some entry tubes, although recording measurable grout consumption (sometimes significant), demonstrated no exit points, thereby the analysis of where the grout dispersed within the masonry was difficult. Instead, only 217 entry tubes demonstrated output points and noticeable grout consumption, and these are the tubes included in this analysis. It is worth noting, however, that these entry tubes accounted for 24,604 L of grout consumption, i.e., 85.6% of the total amount of grout injected. Thus, the following analysis can be considered representative.

3.1.1. Analysis of Grouting Data per Area and Sub-Area

At a first level of assessment, the total amount of grout injected per area of the Katholikon was calculated (Figure 5). This general comparison indicates some interesting findings. Specifically, although the south area is approximately 10% smaller—in terms of masonry volume—as compared to the north side, due to the presence of the large south entrance, the south side demonstrated approximately 15% higher grout “consumption”. Correspondingly, although the size of the north area is approximately 2.5 times larger than the west area, and twice as large as the east area of the Katholikon, the injected grout volume ratios (N/W and N/E) are approximately 3 and 1.4, respectively. The corresponding ratios (S/W and S/E) regarding the south side are 3.37 and 1.65, respectively. These observations can be partially justified by the general south–east–north–west grouting progress sequence and the interconnectivity observed between in the northeast corner of the Katholikon (see discussion below). In effect, some amount of the grout injected from the east side may have filled internal voids in the eastern parts of the north masonry, justifying the lower grout “consumption” of the latter, as compared to the rather similarly sized south side. A similar behavior can be justified between the western parts of the south masonry and the bell tower, which exhibited analogous interconnectivity. Thus, taking these into account, the observed variations in grout consumption are to some degree diminished. The exception involves the increased amount of grout injected at the internal arches, although this is expected due to their severe state of preservation, with numerous visible cracks. Correspondingly, the comparatively very low amount of grout injected at the roof can be justified by the removal of most of the filler material and the potential pre-filling of any voids/cracks from the injection of grout from the underlying arches. In general, these kinds of considerations should always be taken into account when the grouting data are compared per overall areas, to justify observed variations.

Figure 6 presents the grout volume injected per sub-area of the Katholikon. Significant variations can be observed, but these should be examined considering the size of each sub-area, its pathology, its apparent interconnectivity with adjacent sub-areas, and the overall grouting sequence.

Worth noting is the large amount of grout injected in sub-area NE. However, this specific sub-area is the largest sized and contains some structural cracks that are attributed to the thrust of the dome towards the north direction (during earthquake—see discussion in previous section) and the presence of a transverse wall (initially the west façade of the original church) and the corresponding cracks on the north masonry [58,60].

Another interesting observation regards the grouting behavior of the south side of the Katholikon. Sub-areas SA, SB, and SC, which correspond to the south parts of the exo-narthex, demonstrate increased amounts of grout injected from the interior tubes, instead from the exterior, which is the opposite situation for the rest of the south side (SD to SH). In comparison, the corresponding north part of the exo-narthex (sub-areas NF, NG) demonstrates a much lower grout volume injection, exclusively from exterior tubes. Even so, an analysis based solely on the total grout volume per sub-area can be misleading; 85% of the total grout volume of sub-area SA corresponds to one interior tube (PS109) which reached 70 exit points, predominantly over the west masonry of the Katholikon. Instead, the analysis should take into account the findings from the Finite Element Modelling (FEM) and dynamic behavior of the building [60] and the observed pathology (Figure 2).

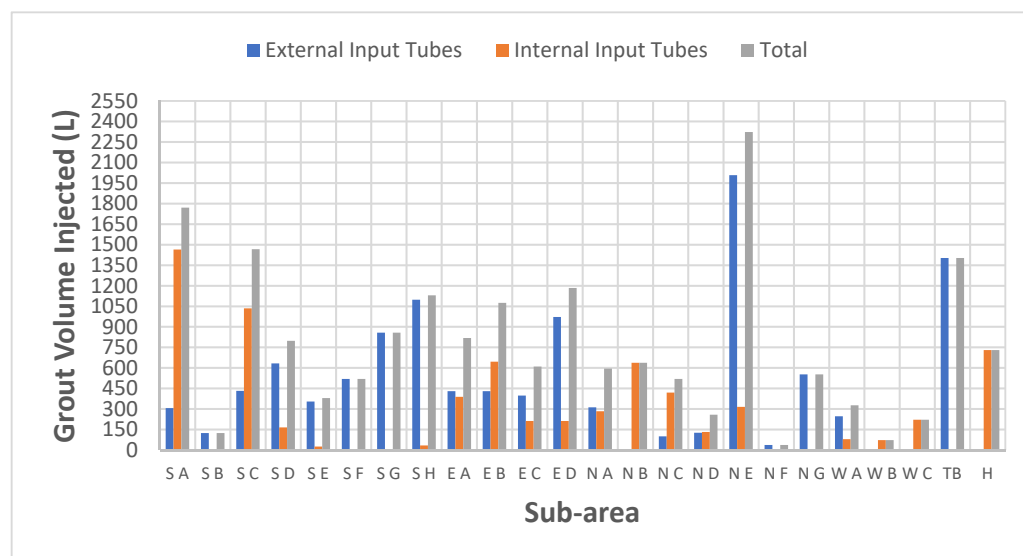


Figure 6. Volume of grout injected per sub-area of the Katholikon.

Specifically, the north part of the exo-narthex demonstrates many macroscopically observed structural cracks (Figure 2), especially at its northwest corner, whereas the south part mainly appears macroscopically intact. The FEM indicated that the northwest part of the Katholikon can “deform” more along the y–y direction (east–west direction, fourth and fifth eigenmodes), as compared to its southwest part which is hindered by the presence of the bell tower. Hence, the creation of a large vertical macroscopic crack, right on the north side of the northwest corner (Figure 2) and the relevant crack (Figure 2, crack D) at the joint of the north façade with the interior transverse wall. Furthermore, GPR prospection of the SA, SB, and SC sub-areas indicated leaf detachment of the exterior stone layer from the filler layer [60]. The correlation of the observed pathology in the exo-narthex with the findings of FEM and GPR indicate a scenario where (a) the north part of the exo-narthex deformed largely “en bloc” along a y–y direction resulting in the aforementioned two large vertical cracks; (b) the south part of the exo-narthex failed through leaf detachment of the exterior stone layer; (c) the west masonry experienced extensive cracking, which required significant amounts of grout injection either directly from sub-areas WA, WB, and WC or through corner entry tubes (e.g., PS109) from the adjoining masonries.

Other notable observations regard the relatively increased amount of grout required for the historical masonry (area H), which may be explained by the fact that this is a much older masonry than the rest of the Katholikon, thereby having sustained more damage along the monument’s history (note: including the explosion of 1826 that destroyed much of the original church).

3.1.2. Analysis of Grouting Data per Grout Injection Tube

Although Figure 6 and the above discussion provide some insight regarding the interconnectivity between sub-areas, it is more prudent to examine the grout volume injected per tube. Figure 7 depicts the cumulative volume of injected grout and the relative volume of grout injected in each tube, throughout the timeline of grout injection for each sub-area. The sub-area codes are shown in Figure 4.

Overall, the curve of the cumulative volume of the injected grout appears largely gradual, and not sigmoidal or grossly stepped which would indicate a significant differentiation between parts of the monument [49]. Nonetheless, certain tubes impart a “localized” sharp increase in the slope of the curve.

Two very prominent “steps” regard tubes in the south part of the exo-narthex (SA, SB, and SC). Tube PS109 is located at the interior corner between sub-areas SA and WC, at a height level of 4 m (Figure 8). It required a grout volume of 1464 lt, reaching 70 exit

points, almost all in the west façade. Tube Si217 is located at the interior, above the south main entrance, at a height level of 3.5 m (Figure 8). Hence, it is located in the south aisle. Nonetheless, most of the 36 exit points were observed at the exterior or interior of the south side of the exo-narthex, while a few were over the byzantine masonry (H). None, however, were observed towards the adjacent SD sub-area. These observations support the scenario of leaf-detachment, as discussed above, and highlight the influence and damage imposed by the transverse historical masonry (H) in this junction area of the building.

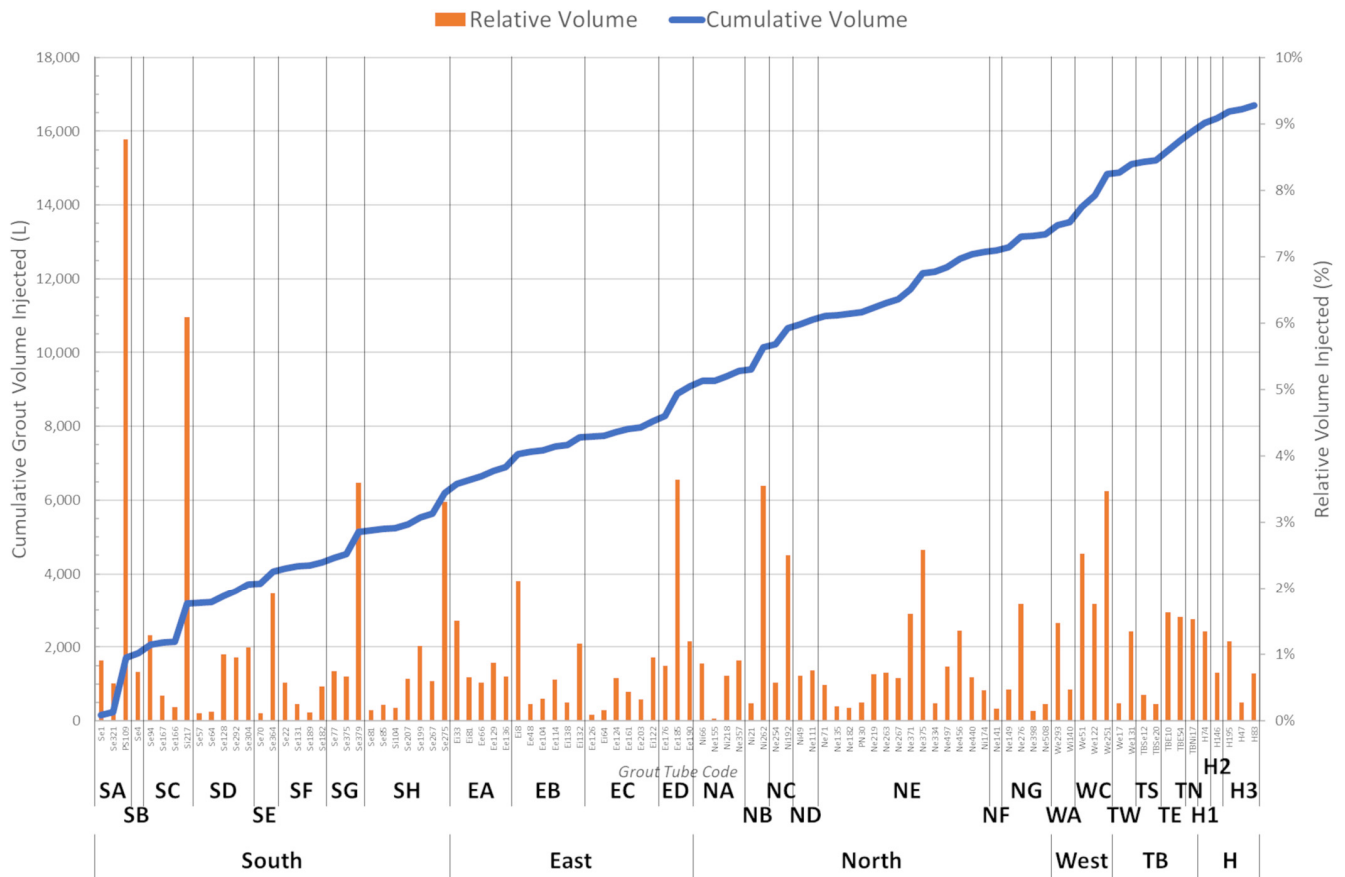


Figure 7. Cumulative volume of injected grout and relative volume of grout injected in each tube throughout the timeline of grout injection for each sub-area. Sub-area codes are shown in Figure 4.

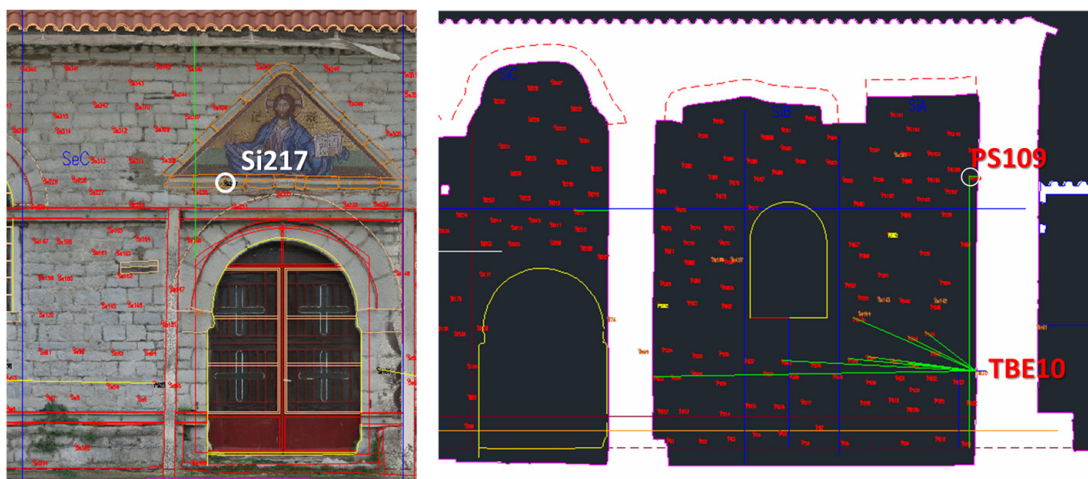


Figure 8. Location of entry tubes PS109 and Si217 which exhibited the highest grout volume injection.

Another interesting “sharp” step regards sub-area SG, and in particular tube Se379. This particular entry tube, which is located above the window of sub-area SG, resulted in 28 exit tubes and required 601 lt of grout injection. However, the vast majority of the exit points were located in the nearby east side of the Katholikon and in the relevant interior sub-areas, with few others located at the lower parts of the south interior in the vicinity of SG. This tube obviously demonstrates significant interconnectivity with the east part of the monument, and its justification should be explored, taking into account the monument’s architecture and pathology. As architect Orlandos points out [56], the main church is separated into a nave and two aisles through two parallel series of columns connected with arches, each row comprising four cylindrical columns (Figure 1). An additional pair of rectangular columns is present at the eastern part of the church. These columns, according to Orlandos, correspond to the byzantine-type walls that divide the apse area into the prothesis, the diaconicon, and the iconostases. These walls have long been removed, providing a homogeneous open space in this eastern area. It is worth noticing that the window in sub-area SG is located between the easternmost pair of the cylindrical columns and the pair of rectangular columns. Moreover, an analogous behavior of tube Se379 is observed in the “mirror” sub-area NB, where the interior tube Ni262 demonstrated 42 exit tubes and required injection of a similar volume of grout. In this case, most of the exit points were located at the exterior sides, mainly at the upper parts of the north masonry. The analogous behavior of these “mirror” areas cannot be considered irrelevant to the architecture of the building and the particular configuration of the eastern part of the Katholikon. The presence of the semicircular apse at the east part of the building, which does not reach the full height of the eastern façade, is also probably relevant to the local pathology and the observed interconnectivity of cracks and voids.

Other notable sub-areas are EC and WC. These sub-areas are located at the northeast and southwest corners of the Katholikon, respectively, and can be considered as diagonally mirrored sub-areas. Sub-area EC demonstrates no significant macroscopic pathology (cracks—see Figure 2), nor significant total grout volume injected, at least as compared to sub-area WC. In comparison, the adjacent sub-area ED required increased amounts of grout (Figure 6), mainly from exterior entry tubes, the vast majority of which reached interior exit points. This variation should be examined in relevance to the dynamic behavior of the Katholikon [60]. Sub-area EC exhibits exceedance of principal stresses in the lower parts of the northeast corner zone of the building. Similar exceedance of principal stresses is also predicted for most of the adjacent sub-area ED, which is the flat masonry above the semi-circular apse (EB). It is theorized that the presence of the semi-circular apse in the east façade—instead of a complete planar masonry height-wise—may have induced a preferential internal cracking during earthquake loadings (especially along the east–west direction), rather than macroscopic structural cracks at the exterior stone layer of the masonry. Such an internal cracking may be more severe for the higher located sub-area ED, due to the thrust of the roof during earthquake movement along the east–west direction, and, thus, justify the difference between grout volumes observed for sub-areas EC and ED.

Sub-area WC, in comparison, did not demonstrate exceedance of principal stresses in the FEM analysis [60]. However, it demonstrated noticeable macroscopic cracking of the stone layers, especially at the upper parts of the west façade (Figure 2). The three entry tubes of interest (We51, We122, and We251) demonstrated a total of 57 exit points and 1300 L of grout injected. We51 and We122, both located at the lower part of sub-area WC, included exit points at the interior of the exo-narthex. In contrast, entry tube We251, which is located higher, demonstrated 24 exit points and required a grout volume injection of 580 L, including 125 L with no visible exit point. All of the exit points were exterior. This behavior appears comparable to the one observed in the EC sub-area; where no macroscopic cracking of the external stone layer is observed, grout injection tends to overflow from interior exit points during filling of voids, and vice versa. To some extent, this should be expected, in the sense that if there are no exit points nearby, the grout will find the closest available. It all depends on the extent and interconnectivity of internal voids and cracks.

3.1.3. Analysis of Grouting Tube Interconnectivity

As discussed above, the analysis of the grout volumes per area (Figure 5) or sub-area (Figure 6) can only provide limited insight regarding the interconnectivity of internal voids and cracks, at the scale of sub-areas. The analysis of grout volumes per grout injection tube (Figure 7) enhances such understanding, but still requires specific additional information for tubes of interest.

When grout is injected through an entry tube in a sub-area and grout material is observed to exit from another tube nearby in the same sub-area, this is an indication of limited crack/voids interconnectivity in this particular sub-area. Nevertheless, the grout volume injected should be taken into account too, in order to interpret cases of a limited number of exit points but large grout volume consumption; it could correspond to either large internal voids or to clusters of interconnecting internal voids of very limited access to exterior or interior surfaces.

Table 1 correlates the number of grout entry tubes per area with the number and spatial distribution (sub-area) of grout exit tubes observed. These values can indicate the degree of interconnectivity observed per sub-area, in relevance to Figure 4, Figure 6, and Figure 7, and their pathology (Figure 2). In general, “deviations” from the diagonal, i.e., entry and corresponding exit tubes being located at different sub-areas of the monument, can be considered as strong indications of increased interconnectivity.

Table 1. Relationship between grout entry and grout exit tubes per sub-area.

No. of Grout Entry Tubes	Entry Sub-Area	Number of Injection Tubes from Which Grout Exited per Sub-Area																									
		Exit Sub-Area																									
		S A	S B	S C	S D	S E	S F	S G	S H	E A	E B	E C	E D	N A	N B	N C	N D	N E	N F	N G	W A	W B	W C	TB	H	Inside	
5	SA	11	3	4																1	11	17	18	16			
1	SB	1																									
7	SC	3	8	41	1																				8		
11	SD			10	26			1																	1	2	
4	SE				9	7	3																			1	
10	SF				2	3	15	6																			
4	SG						6	1	3	9	9															11	
9	SH					3	8	4	26	6	1																
9	EA								6	14	11	7		2													
14	EB									1	43	5															
10	EC										2	15	1	17													
4	ED										1	2	17													12	
10	NA												13	3													
2	NB												19	9	9											6	
3	NC												1	2	31	11	5										
3	ND													1	6	5	8										
27	NE														2	4	151	12	4						9	3	
2	NF																1	1	1								
12	NG																	1	18	26	1					1	
2	WA																		2	17	4						
2	WB																			4	1						
5	WC		6																	7	22	32	6				
19	TB		13	6	1																						
6	H				10																				22		

Sub-area SA demonstrates considerable interconnectivity with the west façade, although this is mostly attributed to tube PS109, as discussed above. The interconnectivity is relevant to the observed pathology and dynamic behavior of the southwest corner of the Katholikon and the joint with the bell tower. Increased interconnectivity can also be seen between sub-areas SG, SH, and EA, as well as between sub-areas EC and NA, which as discussed above are relevant to the architecture of the building and the particular configuration of the eastern part of the Katholikon.

Worth noticing is the large number (151) of exit tubes in sub-area NE. However, it should be pointed out that this is the largest sized sub-area and that this value corresponds to the largest number of entry tubes (27) too. Nonetheless, as evidenced by the large amount of grout injected (Figure 6), this area demonstrates increased interconnectivity (see discussion below), as supported by the large number of exit tubes in the historical

transverse wall. Finally, an increased number of exit tubes is exhibited for the bell tower, but this is to some degree expected based on the observed pathology (Figure 2).

3.2. Assessment of Grouting Indices with Observed Pathology

The above discussion demonstrates the inherent difficulties in trying to describe a process (grouting) that occurs in the three-dimensional volume of the structural system (masonries of the Katholikon) but is documented and assessed in an effectively two-dimensional approach (façades) or cumulatively (Figures 5–7, Table 1). Although such an approach can reveal sub-areas of the structure with increased presence of voids/cracks/interfaces and/or high interconnection with other adjacent sub-areas, it nonetheless allows limited assessment of the internal structure of the masonries. A recent study [55] developed and applied—at a pilot scale—indices that exploit the three-dimensional documentation aspects of the grouting data. These indices are utilized in this work within an enhanced correlation framework involving the architecture [56,57], the pathology, and the dynamic behavior [58,60] of the examined monument.

A detailed description of the grouting indices is provided in [55] and need not be repeated in this work. The following indices are utilized:

$$I_i^{VVL} = \frac{V_i^{GROUT}}{\sum_{j=m}^n \lambda_{ij}} = \frac{V_i^{GROUT}}{TVL_i} \quad (1)$$

where the index I_i^{VVL} regards an entry point (tube) P^{IN_i} through which grout is injected and gradually fills a cluster of internal cracks/voids/interfaces within the masonry, and exits through a series of exit points P^{XT_j} at specific times t_{ij} when the corresponding exit point is sealed. $\Delta V(t_{ij})$ is the differential volume of grout material consumed between time t_{ij-1} and t_{ij} when grout overflowed from exit point P^{XT_j} . The grout volume recorded for entry point P^{IN_i} is $V_i^{GROUT} = \sum_{j=m}^n \Delta V(t_{ij})$. The vector length λ_{ij} is defined as the distance between an entry point P^{IN_i} and each exit point P^{XT_j} . Consequently, Total Vector Length is defined as $TVL_i = \sum_{j=m}^n \lambda_{ij}$.

The degree of crack/void/interface branching is assessed by I_i^{VNX} , defined as follows:

$$I_i^{VNX} = \frac{V_i^{GROUT}}{N_i^{XT}} \quad (2)$$

where N_i^{XT} is the number of exit points for entry point P^{IN_i} .

The type of cluster configuration is assessed by I_i^{VLN} , defined as follows:

$$I_i^{VLN} = \frac{TVL_i}{N_i^{XT}} \quad (3)$$

The detailed calculation of the above indices for the entry tubes presented in Figure 7 is provided in Table A1 of Appendix A. The scope of this work is not to report and justify the grouting indices of each and every grout tube examined. Instead, it aims to present the methodology and highlight the issues to be taken into account when the grouting indices are evaluated. In this framework, certain characteristic parts of the monument are examined below.

Table 2 summarizes the values of grouting indices for the southwest part of the Katholikon, which has demonstrated increased volumes of grout injection and specific pathology as discussed above.

Table 2. Calculation of grouting indices for the southwest part of the Katholikon.

Sub-Area	Entry Tube	N^{XT}	V^{GROUT} (L)	TVL (m)	I^{VVL}	I^{VNX}	I^{VLN}
S A	Se1	4	151.70	5.76	26.35	37.93	1.44
	Se321	5	95.00	15.87	5.99	19.01	3.17
	PS109	70	1464.40	228.78	6.40	20.92	3.27
S B	Se4	1	123.60	1.15	107.91	123.63	1.15
S C	Se94	14	216.00	18.41	11.73	15.43	1.32
	Se167	4	63.50	4.17	15.23	15.89	1.04
	Se166	4	34.90	4.81	7.26	8.72	1.20
	Si217	36	1017.80	72.19	14.10	28.27	2.01
W C	We51	26	423.20	41.41	10.22	16.28	1.59
	We122	7	294.30	8.23	35.77	42.04	1.18
	We251	24	580.00	84.44	6.87	24.17	3.52

Regarding entry tubes PS109 and Si217, it is worth noting that although they demonstrate a very high volume of grout injected and number of exit points, their grouting indices do not show analogous deviations from the mean values of the remaining tubes in this area. For example, PS109 and Se321 show similar values for all three indices, despite being located at comparable positions at the interior and the exterior of sub-area SA, respectively. This indicates that the morphology and cluster of internal cracks and voids filled through these entry tubes is not dissimilar to that achieved from the remaining entry tubes in this area; PS109 only happens to provide access to a continuous cluster of internal voids. The utilization of grouting indices highlights this behavior, which would otherwise be characterized as atypical.

Figure 9 shows the location and (exterior) exit points of tubes Se1 and Se94, which correspond to the extreme boundaries of the south part of the exo-narthex. Based on a typical grouting analysis (e.g., Section 3.1.2), tube Se94 required 40% more grout than tube Se1. According to the grouting indices analysis, entry tube Se1 demonstrated relatively fewer apparent paths N^{XT} , of larger volume per vector length (I^{VVL}) and volume per path (I^{VNX}), as compared to entry tube Se94. However, the average length per path (I^{VLN}) for these tubes is comparable. It is also similar to the values for the remaining entry tubes in the examined area, with the exception of tubes Se321 and PS109 which are located higher. Both tubes demonstrated exit points at the exterior (Figure 9) and at the interior (PS), the adjacent west (WC) and the historical (H) masonries. Tube Se1 demonstrated two exit points, Se5 and PS29 (interior) which are located in sub-area SB, below the window, which both accounted for approximately two-thirds of the total grout volume injected through tube Se1. In addition, entry tube Se4, also located below this particular window, required 124 lt of grout, approximately half of which corresponds to an interior exit point below the window and the remaining volume to no exit point observed. The grout volumes and grouting indices correlate adequately with the observed pathology and the findings from GPR analysis (see below).

The values of grout indices for sub-area WC underline the difficulties encountered in assessing this information. For example, worth noting is the significant difference for index I^{VVL} calculated for We51 (10.22) and Se1 (26.35) which are both located in the corner area. It could be argued that the low value of I^{VVL} for We51 is the result of too many exit points, their vector length potentially double-counted due to their relative vicinity. This situation has been identified in [55]. However, the value of I^{VNX} for We51 is almost half of that for Se1, despite the latter demonstrating 6.5 times less exit tubes than We51. In addition, index I^{VLN} has comparable values for these two tubes (note: mathematically, only two of these indices are independent). In conjunction with the observed pathology in the two respective sub-areas, the above assessment indicates relatively larger voids for the case of tube Se1, as compared to the many smaller but highly dispersed and interconnected voids for the case of tube We51. Worth noting is that tubes We51 and Se94 demonstrated similar values for

all three indices, potentially corresponding to a similar pathology, with many smaller but highly dispersed and interconnected voids.



Figure 9. Location and (exterior) exit points of tubes We51, Se1, and Se94.

Table 3 summarizes the grouting indices for tubes Ne135 and PN30. This pair is located on either sides of the junction of the transverse historical masonry (H) with the north part of the Katholikon (sub-area NE, Figure 4).

Table 3. Calculation of grouting indices for tubes Ne135 and PN30.

Sub-Area	Entry Tube	N^{XT}	V^{GROUT} (L)	TVL (m)	I^{VVL}	I^{VNX}	I^{VLN}
N E	Ne135	1	36.80	1.11	33.15	36.84	1.11
	PN30	6	46.50	5.52	8.42	7.75	0.92

Figure 10 shows the position of these two tubes in relation to the aforementioned junction of the masonries, the observed exterior pathology, and the macroscopic large diagonal crack at the interior. GPR analysis [58,60] (Figure 10E) has indicated that an interior large diagonal macroscopic crack is not extending to the exterior through the three layers of the masonry (interior stone layer; filler layer; exterior stone layer), neither through the junction towards the north part of the exo-narthex. These findings are supported by the pattern of these two tubes.

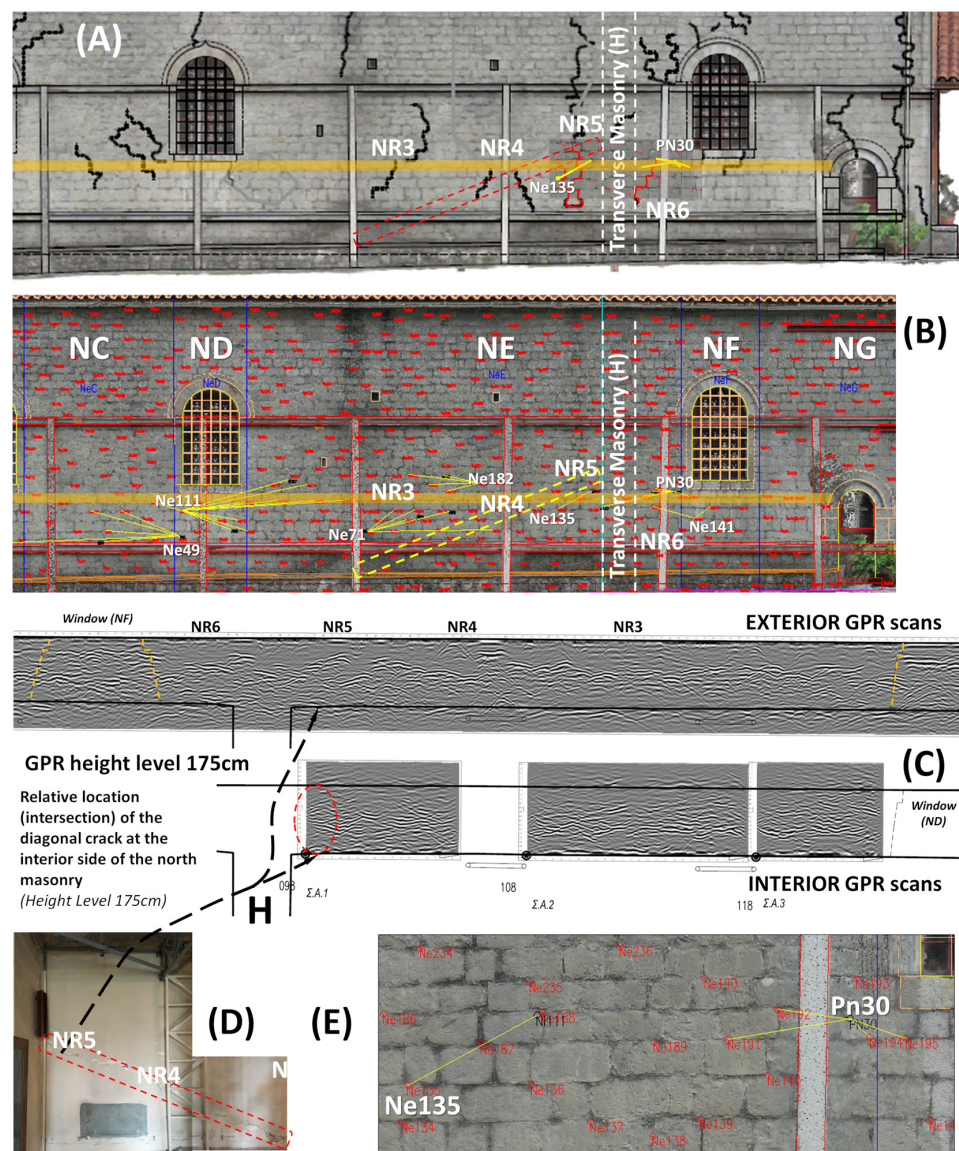


Figure 10. (A) The pathology of the north façade in relation to the junction of the transverse historical masonry and sub-area NE. NR3–NR6 correspond to cluster of macroscopic exterior cracking in the joints of the stone layer; (B) 2D orthophoto created from the 3D model of the Katholikon with location and (exterior) exit points of entry tubes Ne135 and Pn30, as well as entry tubes Ne49, Ne111, Ne71, Ne182, and Ne141; (C) overlay of exterior and interior GPR scans over the plan of the Katholikon at sub-area NE in the vicinity of the junction with the historical wall, H (adapted from [58]); (D) an overview of the interior diagonal macroscopic crack; (E) close-up of the 2D orthophoto for entry tubes Ne135 and Pn30.

Specifically, for both entry tubes, no exit tubes (thus, probably no paths too) are observed that pass through the transverse wall, neither over the transverse historical masonry. The orientation of the vector for tube Ne135 appears to follow closely the orientation of the interior macroscopic crack. It should be reminded that the insertion depth of the tubes (50 cm) effectively injects the grout closer to the opposite stone layer from where the grout is injected. The sole observed exit point for tube Ne135 was at the interior. Two-thirds of the total grout volume corresponded to this exit point, the remainder corresponding to no exit point observed. These remarks agree adequately with the GPR findings and observed pathology. The grout injected from Ne135, close to the interface between the interior stone layer and the filler layer, occupied all available interconnected

voids within. Once it reached the interface between the exterior stone layer and the filler layer, along the general direction of the large crack, it exited from a tube inserted close to this interface, i.e., a tube installed from the interior. Moreover, the grout's apparent paths appear to have stopped prior to intersecting the junction of the masonries. Although similar total grout volumes are observed for Ne135 and PN30, the very values calculated for the grout indices suggest much different crack cluster patterns. This is to some degree expected, since tube Ne135 is located at the main church, whereas PN30 is located at the exo-narthex. These parts influence the overall dynamic behavior of the Katholikon in a different way, and this is expressed in their pathology [58,60].

Noteworthy is the rather limited dispersion of exit points for these two entry tubes, as well as for the nearby entry tube Ne141 (Figure 10B), as compared to tubes located further to the west, Ne182, Ne71, Ne111, and Ne49 (Figure 10B). This is reflected in the values of I^{VVL} which tend to decrease as the dispersion—expressed by N^{XT} and TVL —is increased (Table A1). In conjunction with the observed pathology (Figure 10A) at the lower zone of the junction area, it can be theorized that internal cracking was not as severe as in the case of the upper zone. For example, entry tubes Ne317 and Ne375, located higher, required a total of 700 lt of grout and demonstrated 63 exit points (Table A1). The previous discussion for the corresponding south region (sub-area SC, south entrance) and the influence of the transverse wall (H) agrees well with the above.

3.3. Co-Analysis of Grouting Data, Geospatial Information, and NDT Findings

The final level of co-analysis fuses information generated (a) from the study of grouting data (per area and sub-area); (b) from the exploitation of geospatial data to calculate grouting indices and correlate them with the observed pathology; and (c) findings from the application of non-destructive techniques in areas of interest.

An example of this level of co-analysis regards the aforementioned junction area (Figure 10A,B) and the application of GPR and IRT. Relevant GPR scans, obtained prior to the initiation of restoration works, are shown in Figure 10C.

The GPR analysis indicates that the macroscopic diagonal crack at the interior (Figure 10D) does not appear to expand through the three layers [58,60]. The values of the grouting indices for entry tubes Ne71, Ne182, and Ne135, the grout volume required (Table A1), and their dispersion pattern (N^{XT} , TVL , Figure 10B) are supported by the findings from GPR analysis, at this lower zone of the north masonry. The fusion of such multimodal data indicates rather limited internal cracking (and voids) at this lower zone, in the vicinity of the masonry junction.

An interesting observation regards the dispersion patterns for Ne182, Ne135, and PN30, which do not appear to reach higher exit points. The IRT survey of the north façade (Figure 11) indicated two parallel stone block zones of different thermohygic behavior. These correspond to internal wooden tie beam elements or void spaces where the wood has deteriorated. Actually, as can be seen in Figure 11, the three entry tubes examined are located below the lower wooden tie beam element. Almost half of the grout volume injected from entry tube PN30 corresponded to filling such a void, as verified during the grouting works.

An analogous GPR survey over the north façade provided indications for the type and location of the internal voids filled with grout during the restoration works. Figure 12A depicts the position of GPR scan H175 (Figure 12C) over the north façade, prior to the initiation of restoration works. This scan runs below the aforementioned wooden tie beam element. Figure 12B depicts the (exterior) exit points of entry tubes Ne111, Ne182, and PN30 along the path of the scan. H175, H175B, and H175C are close-ups of this large scan, over which the location of the three entry tubes is indicated. The red outlines indicate the potential voids and internal structure that was filled with grout. The findings correlate adequately with the observed dispersion of exit points, the grout volumes injected, and the pathology of the masonry.



Figure 11. IR thermographs overlaid on the orthophoto of the north façade. Two parallel internal wooden tie beams are discerned, behind the exterior stone layer.

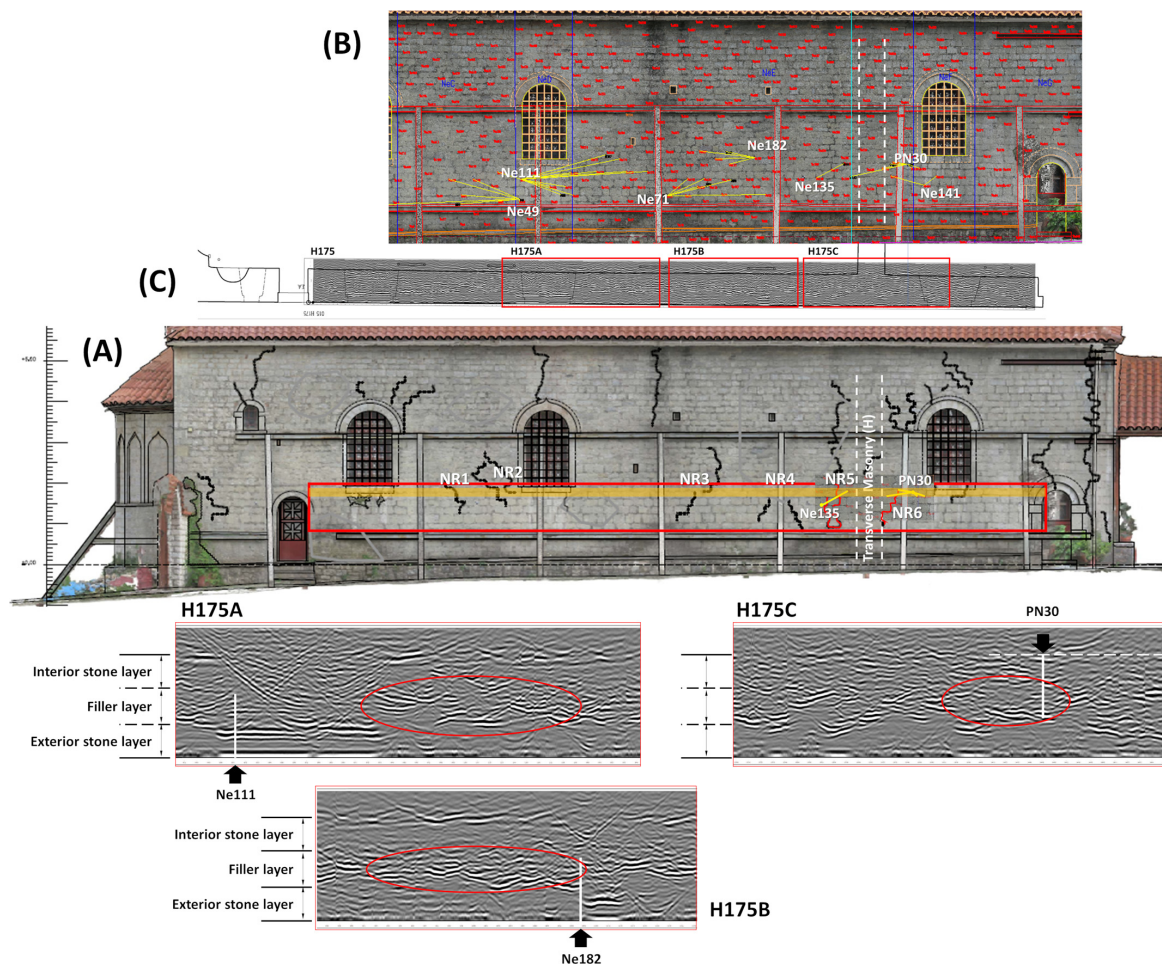


Figure 12. (A) Orange color indicates the position of GPR scan H175 over the north façade. (B) 2D orthophoto created from the 3D model of the Katholikon with location and (exterior) exit points of entry tubes Ne111, Ne182, and PN30 along the path of GPR scan H175; (C) GPR scan H175 overlaid on the plan of the north masonry; the corresponding positions of specific entry tubes is indicated on closeup of parts of the scan (bottom).

Figures 10–12 are typical examples of the type of co-analysis that can be achieved by fusing grouting data, geospatial information, and findings from non-destructive testing.

3.4. The Methodological Approach Proposed from This Study

The above analysis allows for the development and proposal of a methodological approach for the enhanced documentation and evaluation of grouting process, through the fusion of non-destructive information. This approach highlights the importance of the documentation stage and the diagnostic study, not only as the initial starting point for the overall analysis, but also, through parallel contributions to the three levels of analysis discussed above and shown in Figure 13. The proposed methodological approach regards six modules, two preceding grouting, one during grouting, and three post-grouting.

The initial and fundamental module regards the documentation phase (historical, architectural, geometric and mapping of materials) as the supporting element for an integrated diagnostic study that includes characterization of historic materials and their decay products, mapping of decay and damages, and analysis of the pathology of the examined structure. This information then feeds the finite element models of the building and provides the parameters for the dynamic analysis, in order to assess its vulnerability to static and seismic loads. The findings from this module are exploited by the other modules.

The second module deals with the design of the grouting process, based on the identified risks and hazards, and taking into account the vulnerable areas of the examined structure. It regards issues relevant to the grouting material, such as compatibility requirements, performance specifications (desired strength and elastic properties), reproducibility of the selected grout, and technical issues such as the availability and configuration of a worksite with grout production facilities and mixing equipment. The appropriate grouting material is selected based on these factors.

The third module regards the actual implementation of the grouting process. It addresses issues related to the stability of the selected grout material (sustainment of desired rheological characteristics) and the careful reproduction of the appropriate water-to-mortar ratio. A typical grouting process was described in Section 2.3. Prior to the implementation of the grouting process, the geospatial data of all installed injection tubes are carefully documented. When the grouting process initiates, the following crucial data are then recorded: (a) the exit point, (b) the volumes of grout consumed per pair of entry/output tubes, (c) time, (d) sequence of grout tubes and sub-areas, (e) any adjustments required. The information recorded in this module is preferably managed by appropriate tables, spreadsheets or databases.

The fourth module regards the analysis of the grouting data, as described in Section 3.1. The analysis is performed at three “scales”: at the “macroscale”, i.e., at sub-areas of increased grout consumption, where the results are correlated with the architecture and geometry of the building and its pathology; at the “mesoscale”, i.e., per grout injection tube that demonstrates increased grout consumption, where the results are correlated with the (local) pathology and local architectural features, as well as with findings from the FEM and dynamic analysis (see first module).; at the “interscale”, i.e., regarding interconnectivity aspects between the entry and exit tubes, which are correlated with local or area pathology, specific architectural features of the building, and specific findings from FEM and dynamic analysis.

The fifth module regards the geospatial analysis of the entry and exit point, as described in Section 3.2. This module utilizes special grouting indices that correlate the position of the entry and exit tubes with the documented grout consumptions. The values of these indices are then correlated with the observed pathology, at all three aforementioned “scales” are required, and specific architectural, geometrical or construction features of the building and findings from FEM analysis that can justify or interpret such values and behavior. The dispersion of the exit points is taken into consideration.

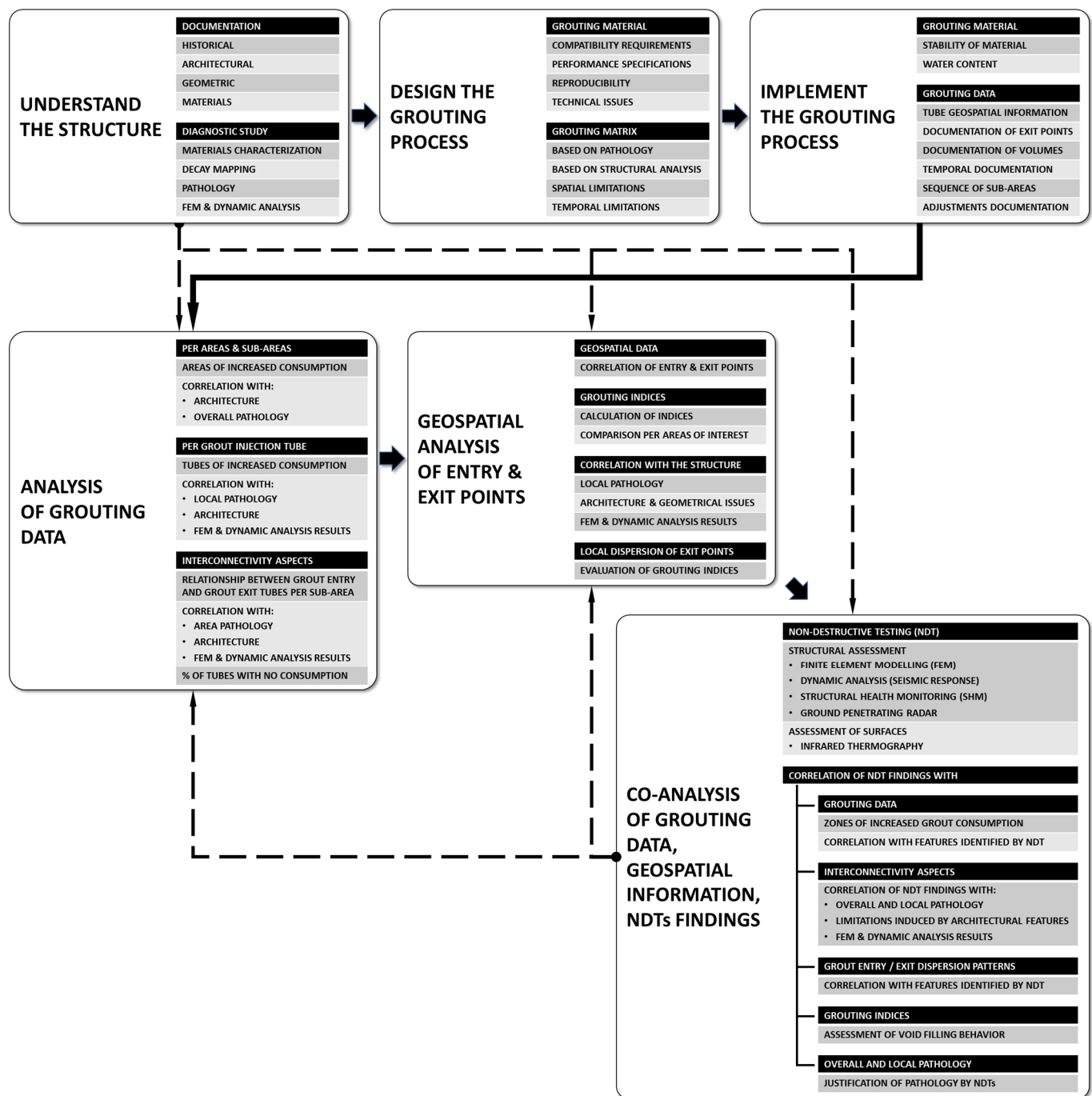


Figure 13. Proposed methodological approach for the enhanced documentation and evaluation of grouting process, through the fusion of non-destructive information.

The sixth module regards the co-analysis of grouting data geospatial information and NDTs findings. Findings regarding the structural assessment from NDTs and analytical methods applied prior, during (where feasible), and after the completion of the grouting process are correlated with (a) the grouting data, including specific features identified by the NDTs; (b) the interconnectivity aspects, as expressed by the relevant tables and as interpreted by the pathology, architectural/geometrical features and findings from FEM and dynamic analyses; (c) the dispersion characteristics of the exit tubes, in relevance to NDT findings; (d) the comparison per area or sub-area of the calculated grouting indices, in relevance to the above, and (e) the overall and local pathology as justified or expressed by findings from non-destructive testing. This module, in a feedback process, may provide

additional information or meta-data that can be re-evaluated by the preceding fourth and fifth modules, as indicated in Figure 13.

The approach takes into account the design and implementation of the grouting process, stages that can influence significantly the quality and analytical resolution of the initial raw grouting data. In this framework, Information Systems [76,77] such as the RESPECT platform [78] and Arches project [79] can support an integrated management and analysis of heterogeneous multi-spectral data. The three-level approach encompasses feedback procedures to optimize findings from each level of analysis. Progressively, the approach manages 2D information, which is enhanced with the incorporation of 3D data and non-destructive analyses, and evolves into a 2.5D approach. All the relevant issues, with emphasis on the structure itself, are taken into account.

4. Discussion

The results and the proposed methodology reveal the strengths and limitations of this enhanced documentation and evaluation approach. The use case of Katholikon, in comparison with the use case of the Holy Aedicule [55], allows for a co-analysis of grouting data, geospatial information, and NDTs findings that is less dependent on the “peculiarities” of its form, architecture, and geometry. This, nonetheless, does not imply that the proposed methodology is not applicable to more “complex” or even larger use cases. It only emphasizes the need to proceed step-by-step, acquiring experience and standardizing analytical phases from potentially simpler cases to more comprehensive ones. In this framework, the Katholikon of the Varnakova Monastery with its largely typical form and “straightforward” damages (earthquake) proved to be an effective case study, for further development.

The main benefit of the proposed methodological approach is that it provides a tool for a concise co-analysis of data obtained from the grouting process, with pre-grouting (and post-grouting where feasible) information regarding the characteristics of the building, with findings revealed from the application of NDTs and analytical testing. In the future, such co-analysis will be supported by information management systems. As more research is conducted in the relevant fields, this will become more standardized and automated, e.g., through artificial intelligence (AI), deep learning (DL), and machine learning (ML). The use of grouting indices, as described in this work, can provide computational means for such an advanced future approach.

An apparent limitation regards the use of NDTs during the actual grouting process. Ideally, one would desire to “monitor” the evolution of the grout insertion within the masonry structure through the aforementioned NDTs. However, GPR is severely influenced by two factors: (a) the high humidity content during the actual grouting session which hinders (or even blocks) the propagation of the electromagnetic pulse (hence severely decreases the analytical capability), and (b) the spatial limitations imposed by the presence of hundreds of injection tubes which preclude the movement of the GPR antenna over the examined surfaces along a useful survey matrix. Effectively, GPR can be utilized upon completion of the grouting process, after much of the grout-induced humidity has receded, and after the protruding injection tubes have been cut off. In the case of this work, the restoration activities have not been completed prior to the implementation of this study. An extensive GPR survey is planned, and its results will be presented in a future publication.

In contrast, theoretically, IRT is not hindered likewise by the presence of humidity. Actually, IRT is often utilized to study the thermohygric behavior of masonries and structures. However, IRT is a surface documentation technique with a very small prospection depth. The internal features of an examined structure are revealed indirectly through their projected thermal influence on the surface. In effect, the different thermal characteristics of a non-solidified grout, in relevance to the surrounding masonry structure, are homogeneously “scattered” upon the surface. As a result, although a grouted masonry demonstrates a different thermal behavior as compared to the original situation [52], it is very difficult to discern useful differentiations that can safely and quantitatively be attributed to the void cluster filled with grout. Thus, IRT is more efficiently utilized to

provide an overall assessment of the thermal behavior of the grouted structure, after the completion of the restoration. However, technological advancements in the resolution of the IRT cameras and increasing use of AI, DL, and ML promise to overcome such limitations in the future.

Other non-destructive techniques such as sonic tests and ultrasonic tomography [42,52–54] show potential for application in actual complex historic structures; currently, they are focusing on model masonries or small specimens as a prerequisite for the standardization of the analysis.

5. Conclusions

The grouting process can provide far more information than typically expected from an otherwise technical process. To achieve this, raw data created during the actual grouting process are progressively transformed into higher-level information through a co-analysis with geospatial information and input from the documentation and diagnostic studies and non-destructive analyses. This methodological approach was applied in the restoration of the Katholikon of the Panagia Varnakova Monastery. This case study highlighted and demonstrated the fusion of multi-modal information through characteristic parts of the monument. It emphasized the need to fully understand the examined building, since it provides constructive information that can correlate with the grouting data and can justify the observed grout volume consumptions. It emphasized the need for geospatial management of information as the prerequisite base of joint analysis of multimodal data. The application of the proposed methodological approach, despite certain identified limitations, can evolve in a more comprehensive documentation and evaluation tool, if progressively applied to other cultural heritage assets.

Author Contributions: Conceptualization and methodology, K.L.; software, S.R.; validation, K.L. and S.R.; formal analysis, K.L.; investigation, S.R., K.L., E.D., E.T., V.K., A.B. and A.M.; resources, A.M.; data curation, K.L. and S.R.; writing—original draft preparation, S.R. and K.L.; writing—review and editing, K.L.; visualization, K.L, S.R. and E.T.; supervision, project administration, and funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Monastery of Panagia Varnakova.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank his Eminence the Metropolitan of Phocis Most Rev. Theoktistos and Abbess Theodosia and the Sisterhood of the Varnakova Monastery for motivating all parties involved in this project and especially the Sisterhood for undertaking the financial cost of the rehabilitation with their own resources. The restoration project is supervised by the Ephorate of Antiquities of Phocis, Ministry of Culture and Sports, Athanasia Psalti. Acknowledgements are also attributed to the Directorate for the Restoration of Byzantine and Post-Byzantine Monuments, and especially Themistoklis Vlachoulis for his continuous presence and assessment of the studies and ongoing works. The Directorate of Conservation of Ancient and Modern Monuments and especially, Maria Mertzani, is acknowledged for her contribution, interest, and cooperation with the Ephorate of Antiquities of Phocis and the other parties involved regarding the conservation studies and interventions within the Katholikon. The contractor of the project is Yioid P. Zafeiri Techniki EPE, Vassilios Zafeiris, civil engineer. Technical supervision of the implementation of the project studies is provided by Georgios Andriotakis, architect, Charalampos Mouzakis, NTUA—civil engineer and Alexandros Nikolaidis, mechanical engineer. Scientific supervision of the restoration project is provided by the National Technical University of Athens, interdisciplinary team for monument protection; chief scientific officer responsible is Antonia Moropoulou. Additional acknowledgements are offered to Timoleon Kouimtoglou, architect, George Bletsas-Yfantis, civil engineer, and Zografia Karekou, architect, for their contributions in the geometric and architectural documentation and documentation of the pathology of the Katholikon, as members of the NTUA team for the interdisciplinary diagnostic study and proposals for the rehabilitation of the Katholikon. Special acknowledgements are attributed to Giorgos Stasinou and Christina Alexopoulou, civil engineer, who advised Abbess Theodosia to invite NTUA and A. Moropoulou to undertake this complex challenge and venture.

Acknowledgements are also attributed to the local authorities. We thank the anonymous referees for their useful comments.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of this study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Calculation of grouting indices for selected main entry tubes.

Sub-Area	Entry-Tube	N^{XT}	V^{GROUT} (L)	TVL (m)	I^{VVL}	I^{VNX}	I^{VLN}
S A	Se1	4	151.70	5.76	26.35	37.93	1.44
	Se321	5	95.00	15.87	5.99	19.01	3.17
	PS109	70	1464.40	228.78	6.40	20.92	3.27
S B	Se4	1	123.60	1.15	107.91	123.63	1.15
S C	Se94	14	216.00	18.41	11.73	15.43	1.32
	Se167	4	63.50	4.17	15.23	15.89	1.04
	Se166	4	34.90	4.81	7.26	8.72	1.20
	Si217	36	1017.80	72.19	14.10	28.27	2.01
S D	Se57	1	18.90	1.04	18.22	18.95	1.04
	Se64	1	23.30	0.82	28.30	23.31	0.82
	Se128	10	167.20	19.72	8.48	16.72	1.97
	Se292	9	158.80	20.38	7.79	17.65	2.26
	Se304	7	184.10	13.95	13.20	26.30	1.99
S E	Se70	1	20.00	0.91	22.03	20.00	0.91
	Se364	17	321.40	27.04	11.88	18.91	1.59
S F	Se22	5	96.30	16.38	5.88	19.27	3.28
	Se131	4	42.30	7.09	5.97	10.58	1.77
	Se189	1	21.20	1.03	20.63	21.21	1.03
	Se182	4	86.80	2.93	29.59	21.70	0.73
S G	Se77	5	124.90	7.44	16.78	24.98	1.49
	Se375	5	112.00	9.38	11.94	22.41	1.88
	Se379	28	601.00	162.8	3.69	21.46	5.81
S H	Se81	1	26.60	0.84	31.63	26.63	0.84
	Se85	1	41.20	1.29	31.94	41.21	1.29
	Si104	3	32.80	2.09	15.69	10.93	0.70
	Se207	5	105.90	5.38	19.69	21.18	1.08
	Se199	8	188.30	12.77	14.75	23.54	1.60
	Se267	4	99.40	4.99	19.92	24.85	1.25
	Se275	24	552.40	61.69	8.95	23.02	2.57
E A	Ei33	11	251.60	43.09	5.84	22.87	3.92
	Ei81	5	109.00	4.29	25.39	21.79	0.86
	Ee66	4	95.20	8.26	11.53	23.80	2.06
	Ee129	6	145.90	10.75	13.57	24.31	1.79
	Ee136	4	112.20	12.67	8.86	28.05	3.17
E B	Ei8	3	353.50	2.88	122.52	117.82	0.96
	Ee48	8	42.30	7.3	5.79	5.28	0.91
	Ee104	4	55.00	2.94	18.71	13.74	0.73
	Ee114	4	103.70	4.55	22.77	25.93	1.14
	Ei138	6	46.50	7.77	5.98	7.75	1.29
	Ei132	12	194.80	18.74	10.39	16.23	1.56
	Ee126	4	14.80	7.79	1.90	3.70	1.95
E C	Ei64	1	27.60	0.69	40.00	27.60	0.69
	Ee124	5	107.90	8.14	13.26	21.58	1.63
	Ee161	5	73.80	4.63	15.93	14.77	0.93
	Ee203	6	54.70	9.1	6.01	9.12	1.52
	Ei122	9	158.80	10.84	14.66	17.65	1.20
E D	Ee176	6	137.60	11.94	11.53	22.94	1.99
	Ee185	16	609.30	100.4	6.07	38.08	6.27
	Ee190	9	198.80	9.56	20.79	22.09	1.06

Table A1. Cont.

Sub-Area	Entry-Tube	N ^{XT}	V ^{GROUT} (L)	TVL (m)	I ^{VVL}	I ^{VNX}	I ^{VLN}
N A	Ni66	7	143.90	8.82	16.31	20.55	1.26
	Ne155	3	6.40	1.93	3.31	2.13	0.64
	Ni218	4	114.30	6.33	18.07	28.58	1.58
	Ne357	6	152.20	8.54	17.82	25.37	1.42
N B	Ni21	1	44.50	1.71	26.04	44.52	1.71
	Ni262	42	592.60	79.76	7.43	14.11	1.90
N C	Ne254	9	95.30	12	7.94	10.59	1.33
	Ni192	40	418.80	92.62	4.52	10.47	2.32
N D	Ni49	7	114.30	11.95	9.56	16.33	1.71
	Ne111	12	126.00	20.69	6.09	10.50	1.72
N E	Ne71	7	90.00	8.82	10.21	12.86	1.26
	Ne135	1	36.80	1.11	33.15	36.84	1.11
	Ne182	4	31.80	4.08	7.80	7.95	1.02
	PN30	6	46.50	5.52	8.42	7.75	0.92
	Ne219	11	116.30	16.47	7.06	10.58	1.50
	Ne263	11	120.80	12.02	10.05	10.98	1.09
	Ne267	11	107.90	15.72	6.86	9.81	1.43
	Ne371	23	268.80	101.4	2.65	11.69	4.41
	Ne375	40	431.40	90.97	4.74	10.79	2.27
	Ne334	7	44.20	11.98	3.69	6.32	1.71
	Ne497	7	135.50	13.05	10.38	19.36	1.86
	Ne456	24	226.40	41.42	5.47	9.43	1.73
	Ne440	10	110.10	15.85	6.95	11.01	1.58
	Ni174	3	76.10	2.25	33.78	25.37	0.75
	Ne141	2	30.70	1.23	24.94	15.34	0.62
N F N G	Ne149	5	78.30	10.77	7.27	15.66	2.15
	Ne276	25	294.10	52.16	5.64	11.76	2.09
	Ne398	3	25.60	2.88	8.87	8.53	0.96
	Ne508	3	42.10	5.15	8.17	14.04	1.72
W A	We293	13	246.70	17.3	14.26	18.97	1.33
	Wi140	10	79.40	13.36	5.94	7.94	1.34
W B							
W C	We51	26	423.20	41.41	10.22	16.28	1.59
	We122	7	294.30	8.23	35.77	42.04	1.18
	We251	24	580.00	84.44	6.87	24.17	3.52
TB (west)	We17	3	44.60	2.42	18.40	14.86	0.81
	We131	5	225.50	9.83	22.93	45.09	1.97
TB (south)	TBSe12	7	65.60	6.01	10.92	9.37	0.86
	TBSe20	4	42.20	6.75	6.25	10.55	1.69
TB (east)	TBE10	17	273.20	30.17	9.06	16.07	1.77
	TBE54	16	260.50	28	9.30	16.28	1.75
TB (north)	TBNi17	8	256.10	23.22	11.03	32.01	2.90
H1	H74	15	224.10	34.53	6.49	14.94	2.30
H2	H146	7	120.60	12.06	10.00	17.23	1.72
	H195	3	198.80	2.33	85.33	66.28	0.78
	H47	2	46.50	1.69	27.50	23.24	0.85
H3	H83	4	118.40	2.69	44.00	29.59	0.67
Total	95 (tubes)	915	16,706.30				

References

1. Miltiadou-Fezans, A.; Delinikolas, N. The restoration of the Katholikon of Daphni Monastery: A challenging project of holistic transdisciplinary approach, novel methodologies and techniques and digital modelling. In *Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultural Heritage*; Communications in Computer and Information, Science; Moropoulou, A., Korres, M., Georgopoulos, A., Spyarakos, C., Mouzakis, C., Eds.; Springer: Cham, Switzerland, 2019; Volume 962, pp. 59–77.
2. Moropoulou, A.; Lampropoulos, K.; Apostolopoulou, M.; Tsilimantou, E. Novel, sustainable preservation of modern and historic buildings and infrastructure. The paradigm of the Holy Aedicule's rehabilitation. *Int. J. Archit. Herit.* **2021**, *15*, 864–884. [[CrossRef](#)]

3. Malovrh Rebec, K.; Deanovič, B.; Oostwegel, L. Old buildings need new ideas: Holistic integration of conservation-restoration process data using Heritage Building Information Modelling. *J. Cult. Herit.* **2022**, *55*, 30–42. [\[CrossRef\]](#)
4. Fassi, F.; Fregonese, L.; Ackermann, S.; De Troia, V. Comparison between laser scanning and automated 3d modelling techniques to reconstruct complex and extensive cultural heritage areas. In *3D-ARCH 2013—3D Virtual Reconstruction and Visualization of Complex Architectures*; Boehm, J., Remondino, F., Kersten, T., Fuse, T., Gonzalez-Aguilera, D., Eds.; ISPRS: Hannover, Germany, 2013; Volume XL-5/W1, pp. 73–80.
5. Lai, L.; Sordini, M.; Campana, S.; Usai, L.; Condò, F. 4D recording and analysis: The case study of Nuraghe Oes (Giave, Sardinia). *Digit. Appl. Archaeol. Cult. Herit.* **2015**, *2*, 233–239. [\[CrossRef\]](#)
6. Vieira, M.M.; Ribeiro, G.; Paulo, R.; Bessa, M.; Sousa, F.R.; Moreira, E.; Mesquita, E. Strategy for HBIM implementation using high-resolution 3D architectural documentation based on laser scanning and photogrammetry of the José de Alencar theatre. *Digit. Appl. Archaeol. Cult. Herit.* **2023**, *30*, e00287. [\[CrossRef\]](#)
7. Mouaddib, E.M.; Pamart, A.; Pierrot-Deseilligny, M.; Girardeau-Montaut, D. 2D/3D data fusion for the comparative analysis of the vaults of Notre-Dame de Paris before and after the fire. *J. Cult. Herit.* **2023**, *65*, 221–231. [\[CrossRef\]](#)
8. Moropoulou, A.; Georgopoulos, A.; Korres, M.; Bakolas, A.; Labropoulos, K.; Agraftiotis, P.; Delegou, E.T.; Moundoulas, P.; Apostolopoulou, M.; Lambrou, E.; et al. Five-Dimensional (5D) Modelling of the Holy Aedicule of the church of the Holy Sepulchre through an innovative and interdisciplinary approach. In *Mixed Reality and Gamification for Cultural Heritage*; Ioannides, M., Magnenat-Thalmann, N., Papagiannakis, G., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 247–270. [\[CrossRef\]](#)
9. Adamopoulos, E.; Rinaudo, F. 3D interpretation and fusion of multidisciplinary data for Heritage Science: A review. In *Proceedings of the 27th CIPA International Symposium “Documenting the Past for a Better Future”, Avila, Spain, 1–5 September 2019*; Gonzalez-Aguilera, D., Remondino, F., Toschi, I., Rodriguez-Gonzalez, P., Stathopoulou, E., Eds.; ISPRS: Hannover, Germany, 2019; Volume XLII-2/W15, pp. 17–24.
10. Tsilimantou, E.; Delegou, E.T.; Nikitakos, I.A.; Ioannidis, C.; Moropoulou, A. GIS and BIM as integrated digital environments for modeling and monitoring of historic buildings. *Appl. Sci.* **2020**, *10*, 1078. [\[CrossRef\]](#)
11. Godinho, M.; Machete, R.; Ponte, M.; Paula Falcão, A.; Gonçalves, A.B.; Bento, R. BIM as a resource in heritage management: An application for the National Palace of Sintra, Portugal. *J. Cult. Herit.* **2020**, *43*, 153–162. [\[CrossRef\]](#)
12. Younus, I.; Al-Hinkawi, W.; Lafta, S. The role of historic building information modeling in the cultural resistance of liberated city. *Ain Shams Eng. J.* **2023**, *14*, 102191. [\[CrossRef\]](#)
13. Yang, X.; Grussenmeyer, P.; Koehl, M.; Macher, H.; Murtiyoso, A.; Landes, T. Review of built heritage modelling: Integration of HBIM and other information techniques. *J. Cult. Herit.* **2020**, *46*, 350–360. [\[CrossRef\]](#)
14. López, F.J.; Lerones, P.M.; Llamas, J.; Gómez-García-Bermejo, J.; Zalama, E. A review of Heritage Building Information Modeling (H-BIM). *Multimodal Technol. Interact.* **2018**, *2*, 21. [\[CrossRef\]](#)
15. Moyano, J.; Pili, A.; Nieto-Julián, J.E.; Della Torre, S.; Bruno, S. Semantic interoperability for cultural heritage conservation: Workflow from ontologies to a tool for managing and sharing data. *J. Build. Eng.* **2023**, *80*, 107965. [\[CrossRef\]](#)
16. Messaoudi, T.; Véron, P.; Halin, G.; De Luca, L. An ontological model for the reality-based 3D annotation of heritage building conservation state. *J. Cult. Herit.* **2018**, *29*, 100–112. [\[CrossRef\]](#)
17. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul. Model. Pract. Theory* **2015**, *57*, 71–87. [\[CrossRef\]](#)
18. Binda, L.; Saisi, A.; Tiraboschi, C. Investigation procedures for the diagnosis of historic masonries. *Constr. Build. Mater.* **2000**, *14*, 199–233. [\[CrossRef\]](#)
19. Krentowski, J.R.; Knyziak, P.; Pawłowicz, J.A.; Gavardashvili, G. Historical masonry buildings’ condition assessment by non-destructive and destructive testing. *Eng. Fail. Anal.* **2023**, *146*, 107122. [\[CrossRef\]](#)
20. Giuseppe Faella, G.; Frunzio, G.; Guadagnuolo, M.; Donadio, A.; Ferri, L. The Church of the Nativity in Bethlehem: Non-destructive tests for the structural knowledge. *J. Cult. Herit.* **2012**, *13*, e27–e41. [\[CrossRef\]](#)
21. Sesana, E.; Gagnon, A.S.; Bonazza, A.; Hughes, J.J. An integrated approach for assessing the vulnerability of World Heritage Sites to climate change impacts. *J. Cult. Herit.* **2020**, *41*, 211–224. [\[CrossRef\]](#)
22. Sesana, E.; Gagnon, A.S.; Ciantelli, C.; Cassar, J.A.; Hughes, J.J. Climate change impacts on cultural heritage: A literature review. *WIREs Clim Chang.* **2021**, *12*, e710. [\[CrossRef\]](#)
23. Kilic, G. Assessment of historic buildings after an earthquake using various advanced techniques. *Structures* **2023**, *14*, 538–560. [\[CrossRef\]](#)
24. Spyarakos, C.C.; Maniatakis, C.A.; Moropoulou, A. Preliminary assessment of the structural response of the Holy Tomb of Christ under static and seismic loading. In *Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultural Heritage*; Moropoulou, A., Korres, M., Georgopoulos, A., Spyarakos, C., Mouzakis, C., Eds.; Springer: Cham, Switzerland, 2019; Volume 961, pp. 44–57. [\[CrossRef\]](#)
25. Ravankhah, M.; Schmidt, M.; Will, T. An indicator-based risk assessment framework for World Heritage sites in seismic zones: The case of “Bam and its Cultural Landscape” in Iran. *Int. J. Disaster Risk Reduct.* **2021**, *63*, 102405. [\[CrossRef\]](#)
26. Soleymani, A.; Jahangir, H.; Nehdi, M.L. Damage detection and monitoring in heritage masonry structures: Systematic review. *Constr. Build. Mater.* **2023**, *397*, 132402. [\[CrossRef\]](#)

27. Spyrakos, C.C. Bridging performance based seismic design with restricted interventions on cultural heritage structures. *Eng. Struct.* **2018**, *160*, 34–43. [\[CrossRef\]](#)
28. Moropoulou, A.I.; Labropoulos, K.C. Non-destructive testing for assessing structural damage and interventions effectiveness for built cultural heritage protection. In *Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures*; Asteris, P.G., Plevris, V., Eds.; IGI-Global: Hershey, PA, USA, 2015; pp. 448–499.
29. Alexakis, E.; Delegou, E.T.; Lampropoulos, K.C.; Apostolopoulou, M.; Ntoutsis, I.; Moropoulou, A. NDT as a monitoring tool of the works progress and the assessment of materials and rehabilitation interventions at the Holy Aedicule of the Holy Sepulchre. *Constr. Build. Mater.* **2018**, *189*, 512–526. [\[CrossRef\]](#)
30. Kong, X.; Hucks, R.G. Preserving our heritage: A photogrammetry-based digital twin framework for monitoring deteriorations of historic structures. *Autom. Constr.* **2023**, *152*, 104928. [\[CrossRef\]](#)
31. Binda, L.; Modena, C.; Baronio, G.; Abbaneo, S. Repair and investigation techniques for stone masonry walls. *Constr. Build Mater.* **1997**, *11*, 133–142. [\[CrossRef\]](#)
32. Gkournelos, P.D.; Triantafyllou, T.C.; Bournas, D.A. Seismic upgrading of existing masonry structures: A state-of-the-art review. *Soil Dyn. Earthq. Eng.* **2022**, *161*, 107428. [\[CrossRef\]](#)
33. Vintzileou, E. Three-Leaf Masonry in Compression, Before and After Grouting: A Review of Literature. *Int. J. Archit. Herit.* **2011**, *5*, 513–538. [\[CrossRef\]](#)
34. Vavričuk, A.; Bokan-Bosiljkov, V.; Kramar, S. The influence of metakaolin on the properties of natural hydraulic lime-based grouts for historic masonry repair. *Constr. Build. Mater.* **2018**, *172*, 706–716. [\[CrossRef\]](#)
35. Faria, P.; Duarte, P.; Barbosa, D. New composite of natural hydraulic lime mortar with graphene oxide. *Constr. Build. Mater.* **2017**, *156*, 1150–1157. [\[CrossRef\]](#)
36. Müller, U.; Miccoli, L.; Fontana, P. Development of a lime based grout for cracks repair in earthen constructions. *Constr. Build. Mater.* **2016**, *110*, 323–332. [\[CrossRef\]](#)
37. Pachta, V.; Papadopoulos, F.; Stefanidou, M. Development and testing of grouts based on perlite by-products and lime. *Constr. Build. Mater.* **2019**, *207*, 338–344. [\[CrossRef\]](#)
38. Yang, Z.; Cheng, X. A performance study of high-strength microbial mortar produced by low pressure grouting for the reinforcement of deteriorated masonry structures. *Constr. Build. Mater.* **2013**, *41*, 505–515. [\[CrossRef\]](#)
39. Apostolopoulou, M.; Delegou, E.; Alexakis, E.; Kalofonou, M.; Lampropoulos, K.; Aggelakopoulou, E.; Bakolas, A.; Moropoulou, A. Study of the historical mortars of the Holy Aedicule as a basis for the design, application and assessment of repair mortars: A multispectral approach applied on the Holy Aedicule. *Constr. Build. Mater.* **2018**, *181*, 618–637. [\[CrossRef\]](#)
40. Gameiro, A.; Silva, A.S.; Faria, P.; Grilo, J.; Branco, T.; Veiga, R.; Velosa, A. Physical and chemical assessment of lime-metakaolin mortars: Influence of binder: Aggregate ratio. *Cem. Concr. Compos.* **2014**, *45*, 264–271. [\[CrossRef\]](#)
41. Kalagri, A.; Miltiadou-Fezans, A.; Vintzileou, E. Design and evaluation of hydraulic lime grouts for the strengthening of stone masonry historic structures. *Mater. Struct.* **2010**, *43*, 1135–1146. [\[CrossRef\]](#)
42. Jorne, F.; Henriques, F.M.A.; Baltazar, L.G. Evaluation of consolidation of different porous media with hydraulic lime grout injection. *J. Cult. Herit.* **2015**, *16*, 438–451. [\[CrossRef\]](#)
43. Bras, A.; Henriques, F.M.A. Natural hydraulic lime based grouts—The selection of grout injection parameters for masonry consolidation. *Constr. Build. Mater.* **2012**, *26*, 135–144. [\[CrossRef\]](#)
44. Luso, E.; Lourenço, P.B. Bond strength characterization of commercially available grouts for masonry. *Constr. Build. Mater.* **2017**, *144*, 317–326. [\[CrossRef\]](#)
45. Papayianni, I.; Pachta, V. Experimental study on the performance of lime-based grouts used in consolidating historic masonries. *Mater. Struct.* **2015**, *48*, 2111–2121. [\[CrossRef\]](#)
46. Miltiadou-Fezans, A.; Vintzileou, E.; Papadopoulos, E.; Kalagri, A. Mechanical properties of three-lead stone masonry after grouting. In *Structural Analysis of Historical Constructions, Proceedings of the 5th International Conference, New Delhi, India, 24–27 November 2021*; Lourenço, P.B., Roca, P., Modena, C., Agrawal, S., Eds.; Macmillan India Ltd.: New Delhi, India, 2006; Volume 2, pp. 785–792.
47. Illampas, R.; Silva, R.A.; Charmpis, D.C.; Lourenço, P.B.; Ioannou, I. Validation of the repair effectiveness of clay-based grout injections by lateral load testing of an adobe model building. *Constr. Build. Mater.* **2017**, *153*, 174–184. [\[CrossRef\]](#)
48. Moropoulou, A.; Bakolas, A. Range of acceptability limits of physical, chemical and mechanical characteristics deriving from the evaluation of historic mortars. In *Compatible Materials for the Protection of European Cultural Heritage*; PACT J. European Study Group on Physical, Chemical, Biological and Mathematical Techniques Applied to Archaeology; Biscontin, G., Moropoulou, A., Erdik, M., Rodrigues, J.D., Eds.; Technical Chamber of Greece: Athens, Greece, 1998; Volume 56, pp. 165–178.
49. Moropoulou, A.; Bakolas, A.; Moundoulas, P.; Aggelakopoulou, E. Reverse engineering: A proper methodology for compatible restoration of mortars. In *Proceedings of the International Workshop on Repair Mortars for Historic Masonries*, Delft University of Technology, Delft, The Netherlands, 26–28 January 2005; RILEM Proceedings Pro 67. pp. 278–291.
50. Apostolopoulou, M.; Aggelakopoulou, E.; Bakolas, A.; Moropoulou, A. Compatible mortars for the sustainable conservation of stone in masonries. In *Advanced Materials for the Conservation of Stone*; Hosseini, M., Karapanagiotis, I., Eds.; Springer: Cham, Switzerland, 2018; pp. 97–123.
51. Loureiro, A.M.S.; Paz, S.P.A.; Veiga, M.D.R.; Angélica, R.S. Assessment of compatibility between historic mortars and lime-metakaolin restoration mortars made from amazon industrial waste. *Appl. Clay Sci.* **2020**, *198*, 105843. [\[CrossRef\]](#)

52. Bosiljkov, V.; Uranjek, M.; Žarnić, R.; Bokan-Bosiljkov, V. An integrated diagnostic approach for the assessment of historic masonry structures. *J. Cult. Herit.* **2010**, *11*, 239–249. [\[CrossRef\]](#)
53. Jorne, F.; Henriques, F.M.A.; Baltazar, L.G. Evaluation of consolidation of grout injection with ultrasonic tomography. *Constr. Build. Mater.* **2014**, *66*, 494–506. [\[CrossRef\]](#)
54. Valluzzi, M.R.; Cescatti, E.; Cardani, G.; Cantini, L.; Zanzi, L.; Colla, C.; Casarin, F. Calibration of sonic pulse velocity tests for detection of variable conditions in masonry walls. *Constr. Build. Mater.* **2018**, *192*, 272–286. [\[CrossRef\]](#)
55. Lampropoulos, K.C.; Apostolopoulou, M.; Tsilimantou, E.; Moropoulou, A. The grouting process as an innovative tool for the assessment of the state of preservation and internal features of the holy aedicule of the Holy Sepulchre. *Heritage* **2022**, *5*, 61–87. [\[CrossRef\]](#)
56. Orlandos, A.K. *The Monastery of Virgin Mary of Varnakova*; Doric Association: Athens, Greece, 1922. (In Greek)
57. Kardamitsi-Adami, M. The Katholikon of the Monastery Varnakova and the Architect Andreas Gasparis Kalandros. *Archaiologia* **2011**, *6*, 78–84.
58. Moropoulou, A.; Mouzakis, C. *Interdisciplinary Diagnostic Study and Proposals for the Rehabilitation of the Katholiko and the Monastic Cells of the Varnakova Monastery in Fokida*; Technical Report NTUA; 2020. (In Greek)
59. Moropoulou, A.; Mouzakis, C.; Andriotakis, G.; Vobiri, J.; Zafeiris, V.; Apostolopoulou, M.; Keramidas, V.; Delegou, E.; Lampropoulos, K.; Roumeliotis, S.; et al. Interdisciplinary approach: Evolution of rehabilitation works, supervision, monitoring and control at the Varnakova Monastery Katholikon. *Building* **2024**, *14*, under review.
60. Keramidas, V.; Lampropoulos, K.; Bletsas-Yfantis, G.; Tsilimantou, E.; Mouzakis, C.; Moropoulou, A. Nondestructive evaluation of the pathology of the Katholikon of the Monastery of Panagia Varnakova with ground penetrating radar. In *Advanced Nondestructive and Structural Techniques for Diagnosis, Redesign and Health Monitoring for the Preservation of Cultural Heritage*; Osman, A., Moropoulou, A., Eds.; Springer Proceedings in Materials: Cham, Switzerland, 2022; Volume 16, pp. 83–95.
61. Binda, L.; Saisi, A.; Tiraboschi, C.; Valle, S.; Colla, C.; Forde, M. Application of sonic and radar tests on the piers and walls of the Cathedral of Noto. *Constr. Build. Mater.* **2003**, *17*, 613–627. [\[CrossRef\]](#)
62. Cataldo, R.; De Donno, A.; De Nunzio, G.; Leucci, G.; Nuzzo, L.; Siviero, S. Integrated methods for analysis of deterioration of cultural heritage: The Crypt of “Cattedrale di Otranto”. *J. Cult. Herit.* **2005**, *6*, 29–38. [\[CrossRef\]](#)
63. Labropoulos, K.; Moropoulou, A. Ground penetrating radar investigation of the bell tower of the church of the Holy Sepulchre. *Constr. Build. Mater.* **2013**, *47*, 689–700. [\[CrossRef\]](#)
64. Solla, M.; Caamaño, J.C.; Riveiro, B.; Arias, P. A novel methodology for the structural assessment of stone arches based on geometric data by integration of photogrammetry and ground-penetrating radar. *Eng. Struct.* **2012**, *35*, 296–306. [\[CrossRef\]](#)
65. Gabellone, F.; Leucci, G.; Masini, N.; Persico, R.; Quarta, G.; Grasso, F. Non-destructive prospecting and virtual reconstruction of the chapel of the Holy Spirit in Lecce, Italy. *Near Surf. Geophys.* **2013**, *11*, 231–238. [\[CrossRef\]](#)
66. Lampropoulos, K.C.; Moropoulou, A.; Korres, M. Ground penetrating radar prospection of the construction phases of the Holy Aedicula of the Holy Sepulchre in correlation with architectural analysis. *Constr. Build. Mater.* **2017**, *155*, 307–322. [\[CrossRef\]](#)
67. Lampropoulos, K.C.; Korres, M.; Moropoulou, A. A Transdisciplinary Approach to Reveal the Structural Evolution of the Holy Aedicule in the Church of the Holy Sepulchre. In *Nondestructive Evaluation and Monitoring Technologies, Documentation, Diagnosis and Preservation of Cultural Heritage*; Osman, A., Moropoulou, A., Eds.; Springer: Cham, Switzerland, 2019; pp. 107–120. [\[CrossRef\]](#)
68. Diz-Mellado, E.; Mascort-Albea, E.J.; Romero-Hernández, R.; Galán-Marín, C.; Rivera-Gómez, C.; Ruiz-Jaramillo, J.; Jaramillo-Morilla, A. Non-destructive testing and Finite Element Method integrated procedure for heritage diagnosis: The Seville Cathedral case study. *J. Build. Eng.* **2021**, *37*, 102134. [\[CrossRef\]](#)
69. Riminesi, C.; Manganelli Del Fà, R.; Brizzi, S.; Rocco, A.; Fontana, R.; Bertasa, M.; Grifoni, E.; Impallaria, A.; Leucci, G.; De Giorgi, L.; et al. Architectural assessment of wall paintings using a multimodal and multi-resolution diagnostic approach: The test site of the Brancacci chapel in Firenze. *J. Cult. Herit.* **2024**, *66*, 99–109. [\[CrossRef\]](#)
70. Kilic, G. Using advanced NDT for historic buildings: Towards an integrated multidisciplinary health assessment strategy. *J. Cult. Herit.* **2015**, *16*, 526–535. [\[CrossRef\]](#)
71. Spodek, J.; Rosina, E. Application of Infrared Thermography to Historic Building Investigation. *J. Archit. Conserv.* **2009**, *15*, 65–81. [\[CrossRef\]](#)
72. Sfarra, S.; Marcucci, E.; Ambrosini, D.; Paoletti, D. Infrared exploration of the architectural heritage: From passive infrared thermography to hybrid infrared thermography (HIRT) approach. *Mater. Construcción* **2016**, *66*, e094. [\[CrossRef\]](#)
73. Tejedor, B.; Lucchi, E.; Bienvenido-Huertas, D.; Nardi, I. Non-destructive techniques (NDT) for the diagnosis of heritage buildings: Traditional procedures and futures perspectives. *Energy Build.* **2022**, *263*, 112029. [\[CrossRef\]](#)
74. Resende, M.M.; Gambare, E.B.; Silva, L.A.; Cordeiro, Y.S.; Almeida, E.; Salvador, R.P. Infrared thermal imaging to inspect pathologies on façades of historical buildings: A case study on the Municipal Market of São Paulo, Brazil. *Case Stud. Constr. Mater.* **2022**, *16*, e01122. [\[CrossRef\]](#)
75. Williams, J.; Corvaro, F.; Vignola, J.; Turo, D.; Marchetti, B.; Vitali, M. Application of non-invasive active infrared thermography for delamination detection in fresco. *Int. J. Therm. Sci.* **2022**, *171*, 107185. [\[CrossRef\]](#)
76. Meyer, E.; Grussenmeyer, P.; Perrin, J.-P.; Durand, A.; Drap, P. A web information system for the management and the dissemination of Cultural Heritage data. *J. Cult. Herit.* **2007**, *8*, 396–411. [\[CrossRef\]](#)
77. Nova, N.A.; González, R.A.; Beltrán, L.C.; Nieto, C.E. A knowledge management system for sharing knowledge about cultural heritage projects. *J. Cult. Herit.* **2023**, *63*, 61–70. [\[CrossRef\]](#)

78. RESPECT Project: An Exemplary Information System and Methodology for the Integrated Management, Analysis, and Dissemination of Digital Cultural Heritage Data Coming from the Rehabilitation of the Holy Aedicule of the Holy Sepulchre (T2EDK-3741), Funded by EPAnEK 2014–2022 Operational Program Competitiveness Entrepreneurship Innovation, EU. Structural & Investment Funds, Scientific Responsible A. Moropoulou. Available online: <https://www.respect-project.gr/> (accessed on 6 March 2024).
79. Arches Project: *Information and Task Management Platform for Heritage Institutions*. Getty Conservation Institute, World Monuments Fund. Available online: <https://www.archesproject.org/> (accessed on 6 March 2024).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.