Monuments of Greece classified according to seismic behavior and case study for seismic vulnerability index

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ABSTRACT

The protection of the cultural heritage of a country with seismic activity involves the structural assessment of the country's monuments with the greatest possible accuracy. A subsequent stage of evaluating the optimal design of the required reinforcement measures ascertains minimal intervention to the monument character.
The classification of the Greek monuments is based mainly on the geometry of the shells. First-degree-pre-earthquake assessment data sheets were developed for several structural typologies, while a representative structure of type A2 is selected and evaluated using the sheets.
The scope of this research is the pilot application of the first degree pre-earthquake assessment evaluation datasheet. It is pointed out that the rating procedure during this assessment, provides an administrative tool for a comparative classification of historical buildings in order to help the state authorities set the priorities for the design of interventions.

Keywords: seismic classification, structural types of monuments, vulnerability assessment of monuments, ECPFE

INTRODUCTION

Safeguarding a country's cultural heritage, especially in seismically active regions, involves two critical steps: first, achieving the highest possible accuracy in the structural assessment of the monument, and second, meticulously developing the optimal, minimally invasive reinforcement and intervention measures.
Therefore, the primary focus should be placed on refining the methodologies used to calculate the structure's seismic response, rather than focusing resources on single-sidedly inventing new intervention techniques. Selecting a reliable model to simulate the structure's behaviour is paramount; it is the deciding factor for accurately assessing structural vulnerability and designing the least intrusive interventions necessary to ensure the monument's extended longevity.
Standard vulnerability assessment practices rely heavily on creating structural simulation models and calculating the resulting stress and deformation metrics. However, a more critical task of reducing the uncertainties inherent in other crucial problem parameters should be first taken into consideration. These uncertainties include:

- Anticipated Seismic Excitation: The actual level of earthquake shaking expected at the site.
- Numerical Model Reliability: The trustworthiness and fidelity of the simulation models themselves.
- Material Characteristics: The true properties of the materials used in the original construction.
- Construction History: Incomplete knowledge regarding the monument's historical building phases.

The primary objective therefore should be the advancement of the understanding of a monument's unique seismic performance prior to any extensive analytical or numerical calculations. This preliminary step will allow for the selection of the most fitting pre-earthquake assessment data sheet for the initial structural evaluation. Furthermore, it will be the foundation for the creation of a dependable numerical simulation during a more detailed, "second-degree" assessment.

This goal can be accomplished by creating a typology of structural forms based on their shared characteristics in seismic response, enabling an educated initial assessment and classification.

In previous actions of the European Centre on Prevention and Forecasting of Earthquakes (ECPFE) and more specifically the 2015 action entitled "Classification of structural types of Monuments and determination of parameters affecting their structural behavior" an attempt was made to classify the monuments in the Greek area based on the criterion of geometry of the shells, as was proposed respectively for Italy by the professor of the University of Genoa, Sergio Lagomarsino. In the following actions, importance was given to examining the characteristics of certain categories that emerged from the above action and the parameters that affect the vulnerability of the monuments that belong to them. First-degree- pre-earthquake assessment data sheets were developed and improved by performing parametric tests while representative structures were selected and evaluated using the Forms.

In this subsequent step, emphasis is placed on further explanation and development of the categories by including more subcategories covering all the monuments found in the Greek area and representative examples of constructions were given for all the categories of the table so that it is easy to understand.

The purpose of this research is to present the methodology of the first degree vulnerability assessment and implement it for a case study. The methodology consists of three stages, according to the flowchart of Figure 1. In the first stage, the proper monument category is selected according to Table 1. The second stage contains an on-site visit and completion of the datasheet. The last stage, which is presented in this paper in detail, contains the rating of the monument vulnerability according to the datasheet. The output is the vulnerability index. The secondary assessment procedures are not included in this paper.

Figure 1: Flowchart methodology for first degree vulnerability assessment.

STAGE 1. MONUMENT CATEGORISATION.

The attempt to categorize the monuments of the Greek area, based on the structural systems' characteristics, mainly geometry and bearing system type has led to the modification and enrichment of existing structures categorization to a total of 11 categories (see Table 1). The structures are categorized considering their common structural system characteristics, characteristics that determine their vulnerability and seismic behavior thus, their expected dominant failure mechanism. A detailed approach is targeted, emphasizing the common structural systems of the monuments in Greece. They constitute the most important category of the listed historical buildings made of masonry and timber, or masonry and individual elements of reinforced concrete, and floors or roofs made of timber or stone masonry (vault structures etc.). It is noted that the presence of underground structures (Pelli et al., 2006, Yiouta-Mitra et al., 2007) has not been considered in this approach.
The current study establishes the groundwork for subsequent research that will proceed in two main areas:

- Expansion of Primary Assessment: The methodology developed herein needs to be extended to encompass all the defined structural categories. This involves determining the precise parameters that must be investigated for any construction during an initial pre-earthquake seismic capacity evaluation.
- Guidance for Secondary Assessment: The findings will be used to generate instructions and recommendations for the more detailed secondary seismic capacity assessment phase. This

essential guidance will help engineers select the most suitable modeling and analysis methodology based on the monument's classification (Drygiannakis et al., 2022).

Table 1. *Summary of structural categories and their basic features*

Struct. Categ.	General Description	Subcategories
A	Structures with vertical bearing elements and horizontal floors, roofs (flat or inclined) or vaults.	A.1 Structures of small dimensions A.2 Small or middle-sized churches. A.3 Single or multi-storey buildings of large dimensions with dense partitioning A.4 Two or multi-storey buildings of middle and large sized dimensions with dense partitioning and mixed vertical load-bearing elements
AB	Constructions consisting of wide spaces, with no or few internal load-bearing walls, connected to the perimeter walls, with or without intermediate floors and timber or steel roofs, that transfer loads only to the external walls.	AB.1 Single or multi-storey buildings with wide spaces AB.2 Medium or large-sized buildings, with non-load-bearing internal walls
B	Structures characterized by wide spaces, with few or no internal walls, in which distinct structural macro-elements are often found, for which independent failure mechanisms are developing.	B.1 Temples with domes, porches etc B.2 Ottoman public buildings B.3 Public buildings dating back to the Venetian and Italian rule Period
C	Structures in which the vertical dimension prevails over the others. As these buildings are often characterized by significant slenderness, their seismic response may be assumed as a global flexural behaviour	C.1 Towers C.2 Bell towers C.3 Minarets C.4 Lighthouses C.5 Chimneys
D	Structures with large length compared to their width and height, with arches and vaults characterized by in-plane failure	D.1 Apses (triumphal arches) D.2 Aqueducts D.3 Bridges
E	Massive constructions in which the substantial thickness of walls, compared to other dimensions, doesn’t allow the idealization as plane structural element.	E.1 Earth walls E.2 Walls of large thickness (free standing walls) E.3 Walls with abutments
F	Single isolated constructions, which do not delimit an interior space. Single isolated constructions, which do not delimit an interior space.	F.1 Free standing columns F.2 Trilithes (Monolithic columns with architrave) F.3 Free standing walls, of sufficient height, surviving parts of older standing buildings F.4 Colonnades
G	Historical centres, or other clusters of buildings made of ordinary historical and traditional buildings’ aggregates. The seismic response must consider the interaction among adjacent buildings.	G.1 Buildings with common adjacent walls G.2. Statically independent buildings in contact
H	Archaeological sites consisting of ordinary masonry remains of small height which are mainly vulnerable to environmental threats other than earthquakes	
I	Underground structures, often constructed with the cut-and-cover procedure, or structures carved in soft bedrock or caves.	I.1 Cave structures I.2 Catacombes I.3 Tunnels I.4 Tombs in tumulus

In the following paragraph, an overview of Category A provides clear examples depicting the main parameters that must be distinguished in the load bearing system of a structure, to be classified in one of its subcategories.

OVERVIEW OF CATEGORY A

This category collects of small sized buildings or buildings of larger dimensions with relatively dense partitioning with internal load-bearing walls, satisfactorily connected to each other and to the perimeter walls. As long as the floors or roofs are adequately connected to the vertical load-bearing elements, the building presents box-behaviour.
The structures in this category, are characterized by the presence of walls with height to width ratio close to one, in which their behaviour is connected to the in-plane failure, as the dominant failure mode. In case of small-scale buildings, the out of plane failure is prevented due to the building's small dimensions, which is practically developing box behaviour. In case of relatively large-scale buildings, the out of plane failure is prevented due to the presence of several internal load-bearing walls (satisfactorily connected to each other and to the perimeter ones) and to the presence of horizontal diaphragms at the levels of floors, roofs (flat or inclined), as long as these sufficiently connect the vertical load-bearing elements to each other.

Subcategory A.1. – Structures of Small Dimensions

Small scale structures, usually single or double chambered, well connected to each other and often having relatively flexible horizontal diaphragms. Characteristic projects of this category are small-scale residences, as well as small-scale industrial units (olive mills, water mills, etc.). Due to their small size, they are at risk of in-plane failure of their walls ("box" behaviour).

Subcategory A.2. – Small or middle-sized churches

These structures usually have few internal load-bearing walls, but due to their relatively small size and/or the presence of flooring structures that ensure the cooperation between the walls (eg masonry vaulted ceilings and ties), they behave as a box.

Subcategory A.3. – Single or multi-storey buildings of large dimensions with dense partitioning

Buildings of large dimensions, whose seismic behaviour is determined by their dense partitioning with internal load-bearing walls satisfactorily connected to each other and to the perimeter, and/or with horizontal diaphragms that adequately connect the vertical elements. Typical projects of this category are public buildings (hospitals, schools), commercial buildings, hotels, mixed-use buildings, etc.

Subcategory A.4. – Two or multi-storey buildings of middle and large sized dimensions with dense partitioning and mixed vertical load-bearing elements

In this category, historical constructions of mixed construction systems consisting of masonry and timber, or masonry and concrete, located in the Greek area and dating from the post-Byzantine and later periods, are classified. These buildings have vertical load-bearing elements of stone or brick masonry, combined with walls of timber frame (with infill or bagdati (traditional building technique, which combines timber net frame with masonry infill, usually made of clay)) or load-bearing elements of masonry and individual elements of reinforced concrete (columns).
Characteristic examples in Greece, are most buildings from the Ottoman period (post- Byzantine buildings), which includes both residential buildings and buildings of greater size and importance (mansions, etc.). Often in these buildings, there are more than one construction systems on the same or different floors, e.g. stone masonry and walls with a timber frame, which are connected to each other in height by means of timber ties. The main characteristic of these buildings is the use of "posted beam" type roofs, which also transfer loads (vertically and horizontally) to the internal walls (timber or stone) and not only to the external masonry walls, distributing them to all the vertical bearing elements of the building. In these constructions, the roof and the floor are tied to the timber walls and to the stone or brick masonry walls, through the timber ties. All the above, result in the improvement of the overall behaviour of the building, especially in seismic loads ("box" behaviour). The alternation and cooperation of construction systems and materials, also results in the improvement of the anti-seismic capacity of the structure, due to the reduction of its mass and the capability of receiving significant deformations without collapse, especially in the upper floors where timber load-bearing walls were used.

STAGE 2: TYPE A2 GREEK MONUMENTS CASE STUDY - TAXIARCHES CHURCH

This category collects architectonic assets with two main bearing structural elements: vertical walls and horizontal floors or roofs. If they are properly connected, mutual cooperation between the structural elements allows the building to behave as a box or a number of boxes classifying it within type A monuments.
This structural type, with many variations, refers to a great number of Christian churches, orthodox, catholic, protestant etc.
In Greece, this type has appeared mainly during the last four centuries 16th to20th, during and after the Turkish occupation. A lot of them have been classified as monuments, some because of their interesting mural paintings and iconostasia, or their architectural type, and some due to their historic role.
Those monuments may be classified in two main groups, according to their general dimensions.

- 1st group: small scale churches
- 2nd group: medium scale basilicas

More specifically, the chosen case study is a one-spaced church with masonry walls and wooden roof, belonging to the 2nd group.

History

The monument is a single-aisle, timber-roofed basilica dating to the post-Byzantine period, built on the foundations of an early three-aisle Early Christian Basilica (5th – 6th century), incorporating original sections of its masonry. This reconstruction is dated to the Late Byzantine period and is associated with the remains of a chapel—uncovered during recent works—adjacent to the northern side.
The interior fresco decoration dates to various periods up to the 19th century; it includes fragments of 13th-century wall paintings as well as 18th-century frescoes of the Georgios Markos School. Numerous sculpted members of the original Early Christian Basilica are embedded in the built iconostasio (templon). Of particular interest, regarding its type and function, is the twin shrine on its northern side. The three wings of roofed spaces in the western part of the enclosure belong to a small monastic complex established around the church during the late post-Byzantine period.

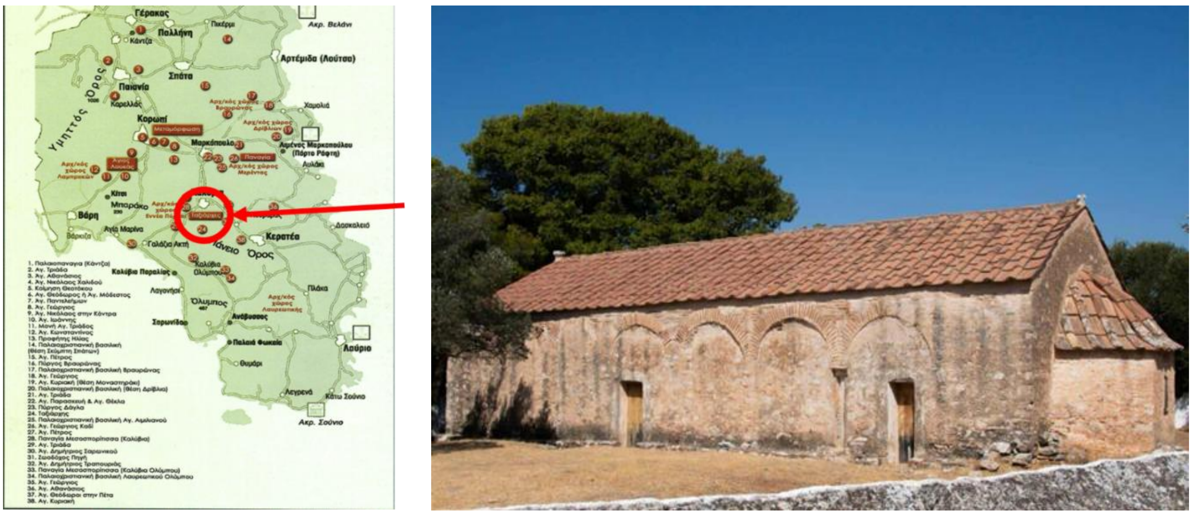

Figure 2. *Location (left) and general view (right) of the monument*

Pre-Earthquake assessment datasheet

This is a first approach of assessment and preliminary rating of the church of Taxiarches in Kalyvia Thorikou, according to its seismic behaviour and vulnerability.
The procedure includes the completion of the Pre-earthquake assessment datasheet:

- Section A: Identity Data
- Section B: Technical Data
- Section C: Seismic Action
- Section D: Pathology

and the accompanying documentation sheets: “Field survey – Design and photographic documentation”, “Seismicity-environment” with instructions, “Pathology”

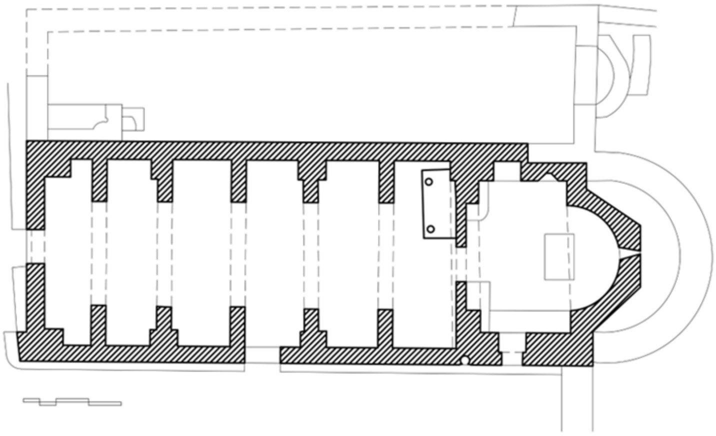

Figure 3. *Plan view of the monument*

Figure 4. *Interior of the monument with visible timber roof (left) and painted decoration with frescoes of the 18th century, from the school of Georgios Markos (right).*

Figure 5. *Interior apses of the church (left). External view of the arcades and the remnant of the large semi-circular apse (right)*

It is pointed out that the rating procedure following this assessment, provides an administrative tool for a comparative classification of historical buildings in order to help the state authorities set the priorities for the design of interventions. It is not and should not serve as a substitute for the complete scientific diagnosis of the problems of each monument, an in all cases, a restoration design project should follow. From the site investigation, it was found that the Church is in good condition in terms of pathology, since it has been repaired in the last decade. Additional favourable conditions include the low seismicity of the Saronikos municipality, which belongs to Zone I, the good geomorphological conditions and the fact that the structure is situated in an area that is free on all sides. Consequently, there is no risk of pounding with adjacent structures.
The good present condition of the church and the preservation of murals of 3 different historical periods, prove that the church has been seismically resistant due to the continuous care and maintenance of the villagers.
Additionally, the fact that it was founded on the existing walls of the well-built palaiochristianic basilica has also proven helpful. There are no specific references about damages due to former earthquakes (Psycharis et al., 2016).
An exemplary completion of the pre-earthquake assessment datasheet (stage 2 in Figure 1) is provided as supplement of this paper and can be found at this LINK.

STAGE 3: ESTIMATION OF THE SEISMIC VULNERABILITY INDEX

For the section concerning the structural vulnerability of the building, it is assumed that all questions contribute equally to the calculation of the vulnerability index. Additionally, the omission of any of the questions results in an increase in the weighting of the remaining answers, proportional to the percentage of unanswered questions, in shaping the final vulnerability index. The proposed estimation of the influence of Section B: “structural and geometrical characteristics” to the vulnerability index is therefore calculated according to the equation:

$$B = Q/Q_a \cdot R \quad (1)$$

where Q is the total number of questions, Q_a the total number of answered questions and R the total rating of method of construction section.
The proposed estimation of the influence of Section C: “seismic action” to the vulnerability index is calculated according to the following equation:

$$C = 75 \cdot (a.G)/(a_m\, G_m) \cdot I_{54} \cdot I_{55} \quad (2)$$

where a is the seismic coefficient value for the most favourable seismic zone of the country, G is the most favourable ground type of the country according to Table 3.1. of Eurocode 8, a_m is the seismic coefficient value for the monument, G_m is the monument ground type and I_{54} και I_{55} are influencing coefficients depending on environmental conditions and neighboring structures. All ratings come from the tables of Section C Seismic action (p. 14 in paper supplement) in the pre-evaluation sheet. Different foundation typologies are not yet considered.
The estimation of the influence of Section D: “Pathology” to the vulnerability index is calculated as the worst (smallest) rating of the 3 subcategories 56, 57 and 58 of same section, i.e. D can be either 75 or 50 or 25.

Calculation of vulnerability index for the Taxiarches church

Figures 5, 6 and 7 contain the entire assessment of the seismic vulnerability index of the case study according to the proposed classification of seismic behaviour. Figure 5 presents solely identity information for the monument. Figure 6 presents the rating for Section B, aka Method of Construction and Figure 7 the rating for Section C – Seismic Action and Section D – Pathology. The ratings are noted in the green column on the right side of the pre-assessment datasheet, the total number of questions answered is noted in the blue column and the vulnerability index is calculated in steps in the red column.

Calculation of B according to equation (1): There are 25 questions, 5 of which were answered in the vertical bearing elements section adding up to a total of 12 rating points, 4 questions were answered for the horizontal bearing elements yielding 8 points and 5 questions answered concerning geometrical characteristics and yielding 10 points. Substitution in equation (1) gives

$$B = (25/14) \cdot 30 = 53.57 \quad (3)$$

α/α	PRE-EARTHQUAKE ASSESMENT DATASHEET FOR SINGLE SPACED ONE-STOREY HISTORICAL BUILDINGS (monuments of STRUCTURAL CATEGORY A) number of Data sheet:			Rating	Number of completed questions	Calculation of the Vulnerability Index
	SECTION A: IDENTITY DATA					
1	Name	Mainname	TAXIARCHES CHURCH			
2		Other				
3	Location	Municipality	SARONIKOS			
4		Town	KALYVIATHORIKOU			
5		Address	17, ST.TAXIARCHES ST.			
6		Nameoflocalspot	-			
7		Geodetic coordinates	37.779449, 23.996720-			
8		Codenumber registeredinthe archaeological archive	-			
9	Description	Number of storeys	1			
10		Area (m2)	134			
11		Typology according touse	ORTHODOX CHURCH			
12	Use and ownership	Present owner	CHURCH COUNCIL			
13		Initial use	CHURCH			
14		Current use	CHURCH-VISITABLE MONUMENT			
15		Number of users	20-30			
16		Frequency of use	RANDOM			
17	Age	Monument'sage according to the period of construction	POST-BYZANTINE FOUNDEDON PALAEOCHRISTIANIC BASILICA			
18	Protection	Issue protected	ARCHITECTURE, MURALS, SCULPTURE			
19		Legal status of protection	MAJOR (OLDERTHAN1453)			
20		Responsible protection Service	MINISTRY OF CULTURE			
21		Responsible restoration Service	MINISTRY OF CULTURE			

Figure 6. *Section A for the case study of Taxiarches church*

Calculation of C according to equation (2): For Field 50, the seismic hazard zone is selected, and its influence is taken into account along with the soil category. For Field 51, the data concerning the seismic hazard of the building's area, according to the completed microzonation study, are taken into account, if available.

Section B : METHOD OF COSTRUCTION

23	STRUCTURAL CATEGORY	A X	AB	B	C	D	E	F	Don't know
24	Description of the structural system elements	Well-built three leaf rubble masonry incorporating the arched walls of the palaiochristianic aisle. The long walls have strong lateral ribs with lateral arches forming triangles. It has an inclined timber roof with beams connected to the arches.							

METHOD OF COSTRUCTION

A) Vertical bearing elements

	Evaluation	C	B	A		
25	Interconnection of stone or brick elements		X		2	25
26	Type of stone or brick elements		X		2	
27	Binding mortar of the outer leaves		X		2	
28	Core filling material if it can be identified (it refers to three leaf masonry only)				Not completed	
29	Vertical Ribs (buttresses, pilasters)			X	3	
30	Corners and edges with chiseled stones			X	3	
31	Chainages (placement)				Notcompleted	
32	Chainages (type)				Notcompleted	
33	Chainages (number of horizontal layers)				Not completed	
34	Connections between chainage elements (mortices, joints)				Not completed	
35	Chainage (condition of building materials: wood, reinforced concrete, steel)				Not completed	
36	One-sided reinforced concrete coating				Notcompleted	
37	Double sided reinforced concrete coating				Not completed	

B) Horizontal or inclined bearing elements

	Evaluation	C	B	A		
						5
38	Timber or steel trusses (condition of materials and connections between the elements)		X		2	

39	Bearing elements of horizontal roof (condition of materials and connections between the elements)				Not completed		
40	Connection with vertical walls	X			1		
41	Chainage at the connection area				Not completed		
42	Domes or apses				Notcompleted		
43	Arched ribs			X	3		
44	Tendons, ties		X		2	4	
	Γ) Geometrical Characteristics						
	Evaluation	C	B	A			
45	Ratio of wall length to wall thickness	X			1		
46	Ratio of wall height to wall thickness		X		2		
47	Additional height of pediment or bell tower (vertical cantilever)	X			1		
48	Arrangement of openings			X	3		
49	Openings near the corners			X	3	5	53,57

Figure 7. *Section B completed for the case study of Taxiarches church*

For Fields 52-53 the soil category is derived based on study, research data or a cautious estimation: The Seismic Hazard Zone according to EK-8 and National Annex here is I and the relevant coefficient a is 1.60, which is also the most favorable seismic zone. Similarly, according to EK-8 the soil category is A and the relevant coefficient a is 0.85, again the most favorable ground type. There are no unfavorable environmental conditions, nor any other buildings in the surroundings, therefore the two influencing factors are takn as 1. Substituting the above in equation (2) gives

$$C = 75 \cdot (1.60 \cdot 0.85)/(1.60 \cdot 0.85) \cdot 1 \cdot 1 = 75 \quad (4)$$

Calculation of D: Using Documentation Sheet 3 as a guide, as well as the recorded damages of the Monument, a score (A, B, C) is assigned to each of the three subcategories based on total pathology in masonry, pathology in vaults and arches, pathology in roofs and floors. From the scores assigned to the subcategories, the most unfavorable is selected as the overall score and the contribution of the pathology to the vulnerability index. Scores A, B, and C correspond to grades of 75, 50, and 25, respectively.

Thus, based on the above, the proposed estimation of the influence of Section D: “Pathology” to the vulnerability index responds to the worst (lowest) rating of the 3 subcategories in fields 56, 57 and 58 of this section. Conclusively, the influence of this section (D) is either 75 or 50 or 25 where the worst case is represented by the rate 25. According to the condition of this case study, the value of the coefficient is D = 75.
The final vulnerability index is expressed as the sum of B+C+D. After filling in according to the above the vulnerability index, 203.57 is derived (Pelli et al., 2025).

Section C: SEISMIC ACTION

(the completion of the cells should be made with english letter x)

No.		I	II	III	
50	SEISMIC ZONE ACCORDING TO EC-8 and National Annex	X			1,6
51	Data from microzonation study (if elaborated)				

No.	Ground type	A	B	C	D	E	S1 S2	
52	Based on scientific data/survey							0
53	Estimation (not certain)	X						0,85

ADDITIONAL DATA INFLUENCING SEISMIC ACTION

No.	Evaluation of influence	Influence coefficient	Influence coefficient of Additional Data
	Negative impact of geomorpholo-gical or environmental conditions		1
54	Danger of stroke by neighboring buildings		1

Section D: PATHOLOGY

(the completion of the cells should be made with english letter x)

GENERAL CONDITION OF DAMAGES

No.	Evaluation	C	B	A	
55	General condition of masonry damages			X	75
56	Damages in domes, apses, arches			X	75
57	Damages on roofs and floors			X	75

SERIOUS LOCAL DAMAGE:

58 **Description of the problem:**

59 **Proposed urgent measures:**

60 **Proposed urgent investigations/surveys:**

The questions of Seismic Action should always be completed

Vulnerability Index of the Seismic Action Section: 75,00

Vulnerability Index of the Pathology Section: 75,00

Final Vulnerability Index: 203,57

Figure 8. *Calculation of Sections C and D for the case study of Taxiarches church*

It is of course understandable that this “vulnerability index” is only a relative number that can serve as an administrative tool for a comparative classification of historical buildings in order to help the state authorities to set the priorities for the design of restoration interventions on monuments at a large scale. It is not and should not serve as a substitute for the complete scientific diagnosis of the problems of each monument. In all cases, a restoration design project should follow.

CONCLUSIONS

- The worst - case scenario is the one with the lowest score.
- The “vulnerability index” is only a relative number, that can serve as an administrative tool for a comparative ranking of Monuments, of the same structural type based on the vulnerability they exhibit, in order to rationally support prioritization processes and intervention decision-making.
- The proposed rating procedure is based on empirical methods. It should therefore be verified by numerical ones, especially specific parameters of the pre-earthquake assessment, such as Fields 40, 45, 46, 49 and 52.
- Future work should consider the inclusion of the effects of the presence of underground structures or cavities in the vicinity of the monuments.

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