«Atlas of the Monuments of Greece classified according to their seismic behavior»

1st action of EPPO

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December 2022

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1 INTRODUCTION

The protection of the cultural heritage of a country with seismic activity is primarily based on the structural assessment of the monument with the greatest possible accuracy and on the optimal design of the minimally required intervention-reinforcement measures. For this reason, more importance must be given to the methodologies followed for the calculation of the seismic response rather than the development of new intervention-reinforcement methods in the monument. The choice of a reliable method of simulating the behavior of the structure is a decisive factor in the assessment of the structural vulnerability and in the design of the minimum intervention for the further life of the monument.

The usual vulnerability assessment methods are based on the creation of the simulation model of the structure and the determination of the stress-deformations results. However, quite often, more attention is given to the construction of complex and geometrically accurate numerical model and time-consuming nonlinear static and dynamic analyzes, than to the elimination of the uncertainties that exist in the remaining parameters of the problem and are related to a) the level of seismic excitation expected in the area, b) the reliability of the numerical models or in other words the numerical simulations, c) the characteristics of the materials existing in the construction and finally the partial knowledge of the construction stages of the monument.

The purpose of this research is to contribute to the recognition of each monument's response to seismic excitation, before any analytical or numerical calculation is carried out, so that the appropriate pre-earthquake assessment data sheet for the initial assessment of the structure is chosen, or in the context of the second-degree assessment a reliable numerical simulation is created. This purpose can be achieved by the classification of structural types of monuments with common seismic response.

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 action, emphasis was placed on the 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.

2 CLASSIFICATION OF HISTORICAL CONTRUCTIONS AND MONUMENTS OF THE GREEK AREA

In this chapter, it is attempted to categorize the monuments of the Greek area, based on the structural systems' characteristics, mainly geometry and bearing system type. The structures are categorized taking into account their common structural system characteristics, characteristics that determine their vulnerability and seismic behavior thus, their expected dominant failure mechanism. It is attempted, within this project, to present as completely as possible, the common structural systems of the monuments in Greece, which 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).

The present work can be the base for future research concerning two main directions: a) to extent to all the proposed categories, the determination of the appropriate parameters that should be examined for a construction, in the frame of a primary pre-earthquake seismic capacity assessment and b) to prepare instructions and recommendations, for the phase of the secondary, more detailed, seismic capacity assessment, as the necessary guidance to engineers, for the selection of the appropriate methodology for the modelling and analysis of the structure, based on its categorization.

The following table summarizes the resulting categories, as well as the main parameters that must be distinguished in the load bearing system of a structure, in order to be classified in one of them.

Structural Category	Category description	Subcategory
A	Structures with **vertical bearing elements and horizontal floors, roofs (flat or inclined) or vaults.** 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-behavior.	A.1 Structures of small dimensions (residential buildings, small-scale industrial units – olive mills, watermills, etc) A.2 Small or middle-sized churches. A.3 Single or multi-storey buildings of large dimensions with dense partitioning (public buildings: hospitals/schools, commercial buildings, buildings of mixed use etc). 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.	AB1. Single or multi-storey buildings with wide spaces (basilica churches, industrial buildings, warehouses, Local markets, cinemas, theaters, etc) AB2. Medium or large-sized buildings, with non-load-bearing internal walls (public buildings, residences, etc.)
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 (domes, out-door galleries, apses, wings, etc.)	Single or multi-storey structures with wide spaces and distinct macroelements: B.1 Temples (churches,mosques) with domes, proches etc B.2 Ottoman public buildings (Madrasas, hammams, etc) 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 behavior	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 wide thickness of walls, compared to other dimensions, doesn't allow the idealization as plane structural element. Local failure occurs as, for example, the detachment of external leaf. Geotechnical aspects play as well important role	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.	F.1 Free standing collumns 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 centers, 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 (with or without double wall between them)
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. In these particular structures the geotechnical aspect is of main importance	I.1 Cave structures I.2 Catacombs I.3 Tunnels I.4 Tombs in tumulus

3 ANALYTICAL PRESENTATION OF THE CATEGORIES-CHARACTERISTIC PROJECTS OF THE GREEK AREA PER CATEGORY

3.1 Category A

Structures with vertical bearing elements and horizontal floors, roofs (flat or inclined) or vaults.

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-behavior.

The structures in this category, are characterized by the presence of walls with height to width ratio close to one, in which their behavior 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 behavior. 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.

3.1.1 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" behavior).

CHARACTERISTIC PROJECTS OF SUBCATEGORY A.1

1. Watermill Gravia (Katarraktis) at Sgara, Prefecture of Arta

It is located in the settlement of Sgara Katarrakti, Prefecture of Arta, owned by Christos Gravias: Ground floor stone masonry building of traditional architecture with a rectangular floor plan. The building is covered with a stone slate roofing.

Source: ΥΑ ΥΠΠΟ/ΔΙΛΑΠ/Γ/1642/34908/23-6-1992 - ΦΕΚ 493/Β/30-7-1992

Overview of the monument

Source: http://odysseus.culture.gr/h/2/gh251.jsp?obj_id=6148&era=4&group=15

2. Olive mill at Akovo, Prefecture Arkadia

It is an old stone masonry building, built in 1890 as a two-storey building, with the olive mill located on the ground floor and a primary community school on the first floor. In its current form, it is a ground-floor building with a timber roof covered with Byzantine tiles. The masonry is unplastered and there are corner stones that ensure the cooperation between transverse walls. The building is connected to the productivity and the economy of the small and poor community of Akovos.

Overview of the monument

Source: http://odysseus.culture.gr/h/2/gh251.jsp?obj_id=19378&era=4&group=15

3.1.2 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.

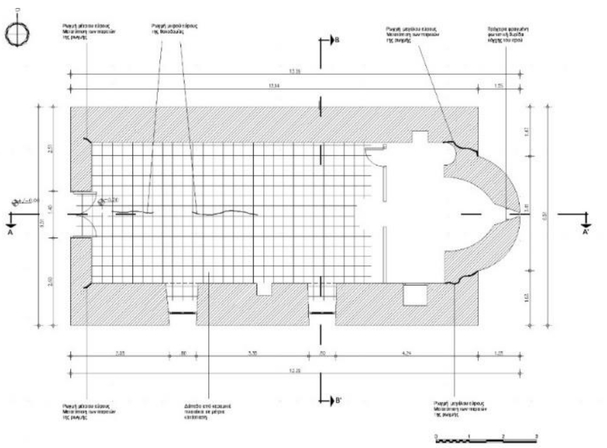
CHARACTERISTIC PROJECTS OF SUBCATEGORY A.2

1. H.T of Saint Dimitrios, Marousi

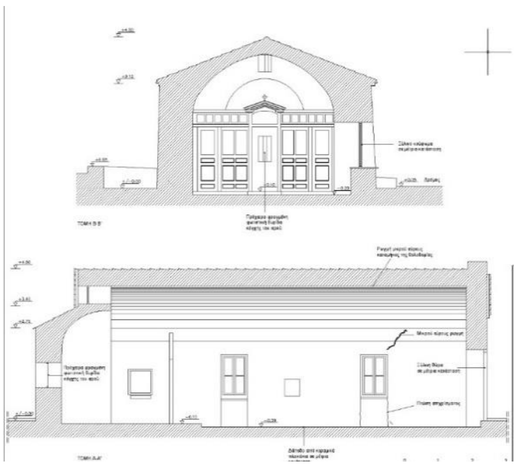
The Holy Temple of Saint Dimitrios in Marousi is a religious monument of the post-Byzantine period with frescoes dating back to the 16th century.

It consists of a simple three-leaf irregular stone masonry construction with irregular stones and tsivikia (small pieces of stone or tile placed between the gaps of stone masonry). It has a skewed earth-block masonry buttress with clay plaster on the south wall and rebuilt wall ending. It is covered with a barrel vault of wedge-shaped stones and had a stone belfry on the W. Pediment, which was removed after 1981, due to lack of stability. Because the ratio of its sides is less than 2 and the ratio of the largest free opening (longest side without including the transverse masonry) to the height of the building does not exceed 1/9, as well as the covering of the building by a stone barrel vault, the building is included in construction category A, where no significant out-of-plane displacements occur. The existence of a skewed buttress to support the South wall, also contributes to this fact, where, despite the different construction technique, there is a good engagement between buttress and wall.

General view of the monument at different time periods



Ground floor plan



Longitudinal and transverse section

Source: Pre-earthquake Assessment of Monuments (ΟΑΣΠ-2016), Research team: I.Psycharis, E.Delinikola, A.Miltiadou, J.Dourakopoulos, K.Papantonopoulos, E.Toumpakari, Architectural Survey for the Directorate for the Restoration of Byzantine and Post-byzantine Monuments (Ministry of Culture and Sports).

3.1.3 Subcategory A.3: SINGLE OR MULTI-STOREY BUILDINGS OF LARGE DIMENSIONS WITH DENSE PARTITIONING

Buildings of large dimensions, whose seismic behavior 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.

CHARACTERISTIC PROJECTS OF SUBCATEGORY A.3

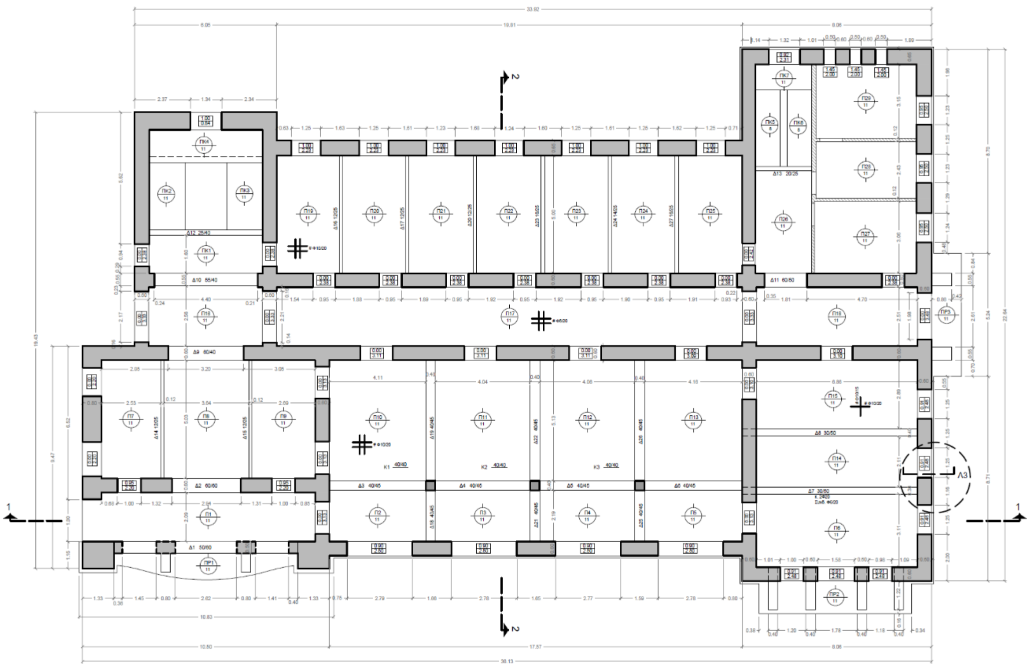
1. Sanatorium MANNA, Magouliana, Monicipality of Gortynia, Prefecture of Arcadia

General view of the building

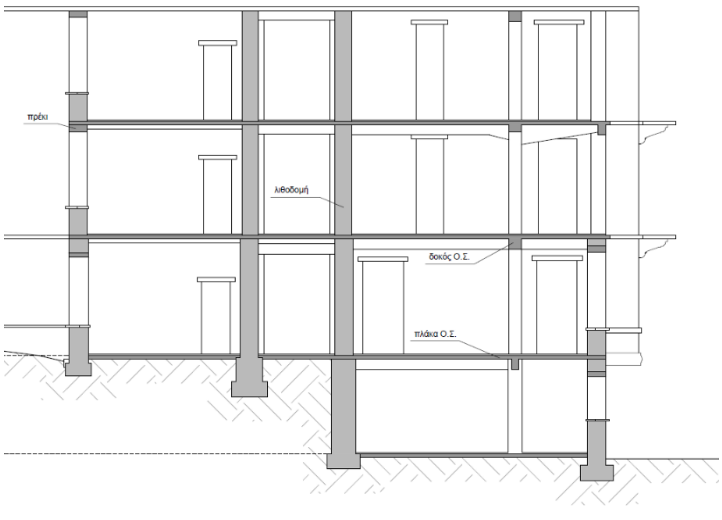
View detail

Horizontal bearing system made of Reinforced Concrete that ensures a strong diaphragm behavior

Three-storey building with basement, with maximum external floor plan dimensions of 36.0 m x 22.70 m. The building was constructed around 1927. For the vertical load-bearing system, load-bearing masonry technology was generally used with walls about 60 cm thick. In the southern part of the ground floor, where there was a requirement to create a large single-span space, 3 Reinforced Concrete columns were constructed. The building, due to its use, presents a relatively dense partitioning with the presence of several internal stone walls, of similar thickness to the external ones, and satisfactorily connected to them. In addition, the horizontal load-bearing system on all levels (except the last one, which is assumed to have been a timber roof), is formed exclusively of Reinforced Concrete elements, i.e. slabs and beams, which are supported on the stone walls, almost along their entire width, ensuring a strong diaphragm behavior, and thus preventing the out-of-plane failure of walls.



Ground floor plan (Structural Analysis survey)



Representative section (Structural Analysis survey)

Source: Study on the conversion of the former Sanatorium MANNA, into a 5 star hotel unit, at Maguliana, Prefecture of Arkadia (2019). Architectural study : : k-studio D. Karampatakis, Structural Analysis: N. Psylla

3.1.4 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 the majority of 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 of the above, result in the improvement of the overall behavior of the building, especially in seismic loads ("box" behavior). 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.

CHARACTERISTIC PROJECTS OF SUBCATEGORY A.4

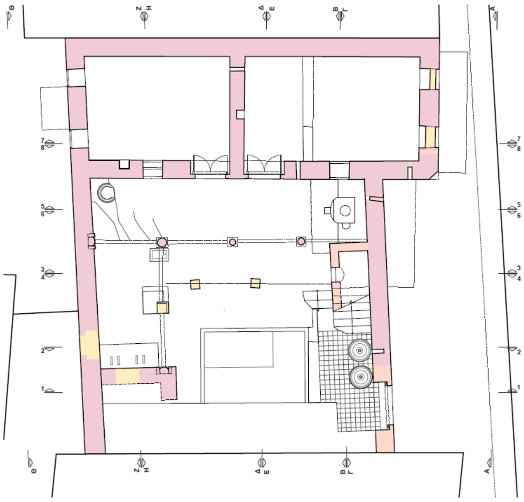
1. Ottoman Mansion at Paidon Street, Chalkida

The building consists of three levels. The main part of the building is an elongated rectangle of 9.0m. x 6.0m dimensions. The ground as well as the middle floor have stone load-bearing masonry walls 60 - 75 cm thick. On the first floor there are 2 stone walls, while the rest are timber framed walls with infill (bricks). The roof has been constructed with the "posted beam" system, ensuring improved behavior of the building in seismic loads ("box" behavior).

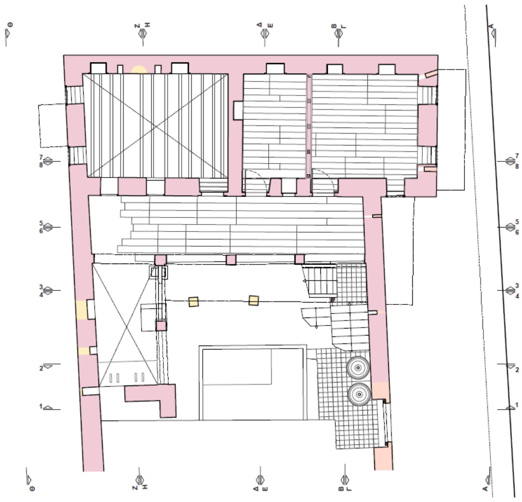
Overview of the building (Existing condition)

Timber framed external walls

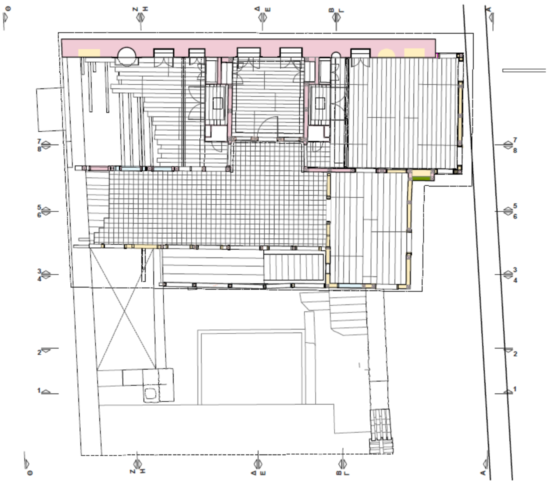
Timber framed internal walls



Ground floor plan (survey)



Middle floor plan (survey)



Top floor plan (survey)

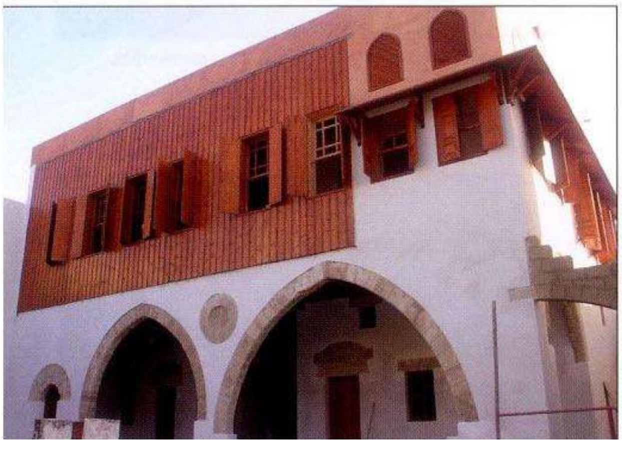
Photorealistic illustration of restoration proposal (Architectural study, X. Basoukos).

Source: Restoration study of an Ottoman mansion in Paidon Street, Chalkida (2020). Architectural study: H. Basoukos, Consultant: G. Kizis. Structural Analysis: N. Psylla , L. Panoutsopoulou. Advisor: E. Tsakanika.

2. Ottoman period mansion, Ierocleous street, Rhodes

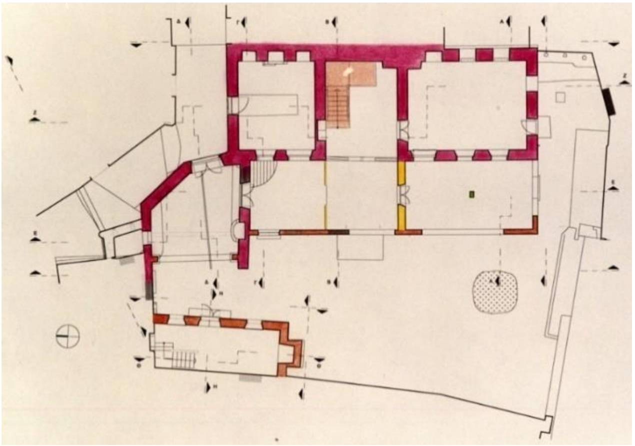
The Mansion on Ierocleous Street is located next to the Monastery of Agios Georgios in the Old Town of Rhodes. It is a two-storey structure of the Turkish period, with a rectangular floor plan measuring 16.30 m x 9.70 m (and overall dimensions of approximately 21.0 m x 10.0 m). It has timber floors and a horizontal timber roof. The ground floor is made of 60-70cm thick stone masonry and arches, 25 cm wide. Most of the floor's masonry walls are only 22 cm thick and are made of a single stone. It is a single-stone, perforated due to its many openings, load-bearing masonry. The rear eastern wall of the floor is 65 cm thick, while a part of its main facade is timber. It was found that, in order to deal with the vulnerability of the floor against the seismic risk, a special construction system was used to tie the building, through timber elements (timber ties) that lock together and which were placed at 3 levels: at the top of the ground floor walls, at the level of the lintels of the floor and at the level of the flat roof. In addition, on the upper level, timber elements were found that "tied" the walls to the flat roof, preventing their out-of-plane loading during seismic actions. The building is included in this category due to its dense partitioning with load-bearing walls, as well as the mixed use of stone and timber framed walls on the floor.

(α)

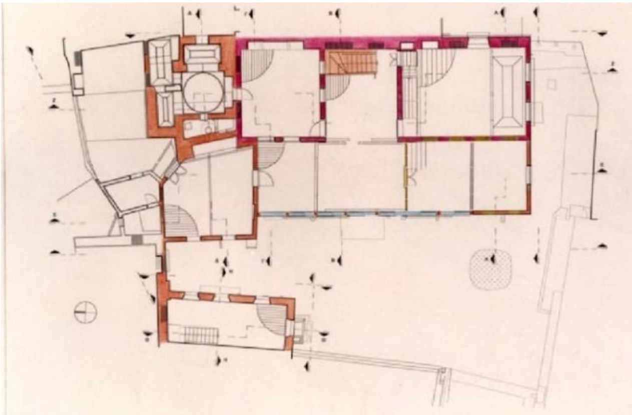


(β)

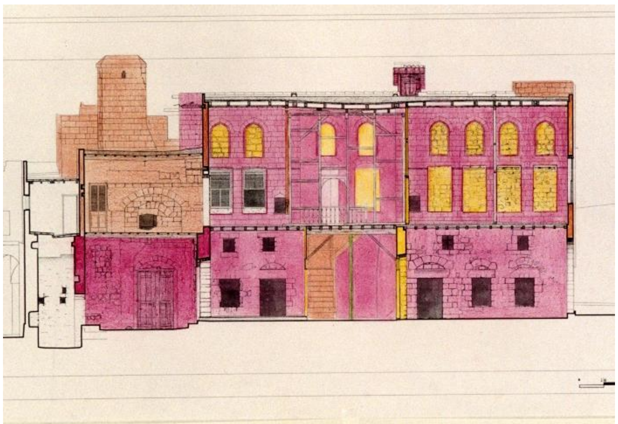
Overview of the building (a) before and (b)after the restoration project



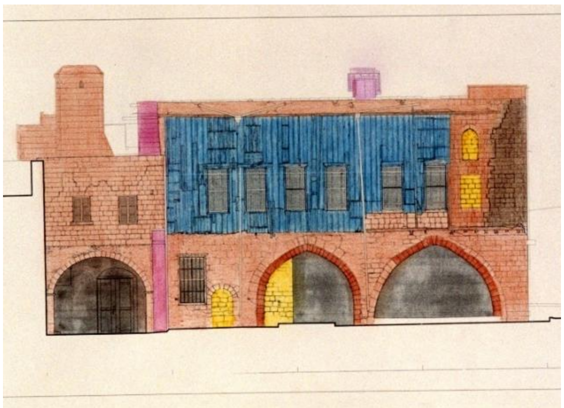
Ground floor plan (survey)



Top floor plan (survey)



Characteristic section



Main view

Source: Study for the restoration of a Turkish-era mansion on Ierocleous Street in Rhodes (2001). Architectural study: G. Della and M. Zerlentis, Structural Analysis: E. Tsakanika and K. Athanasiadis

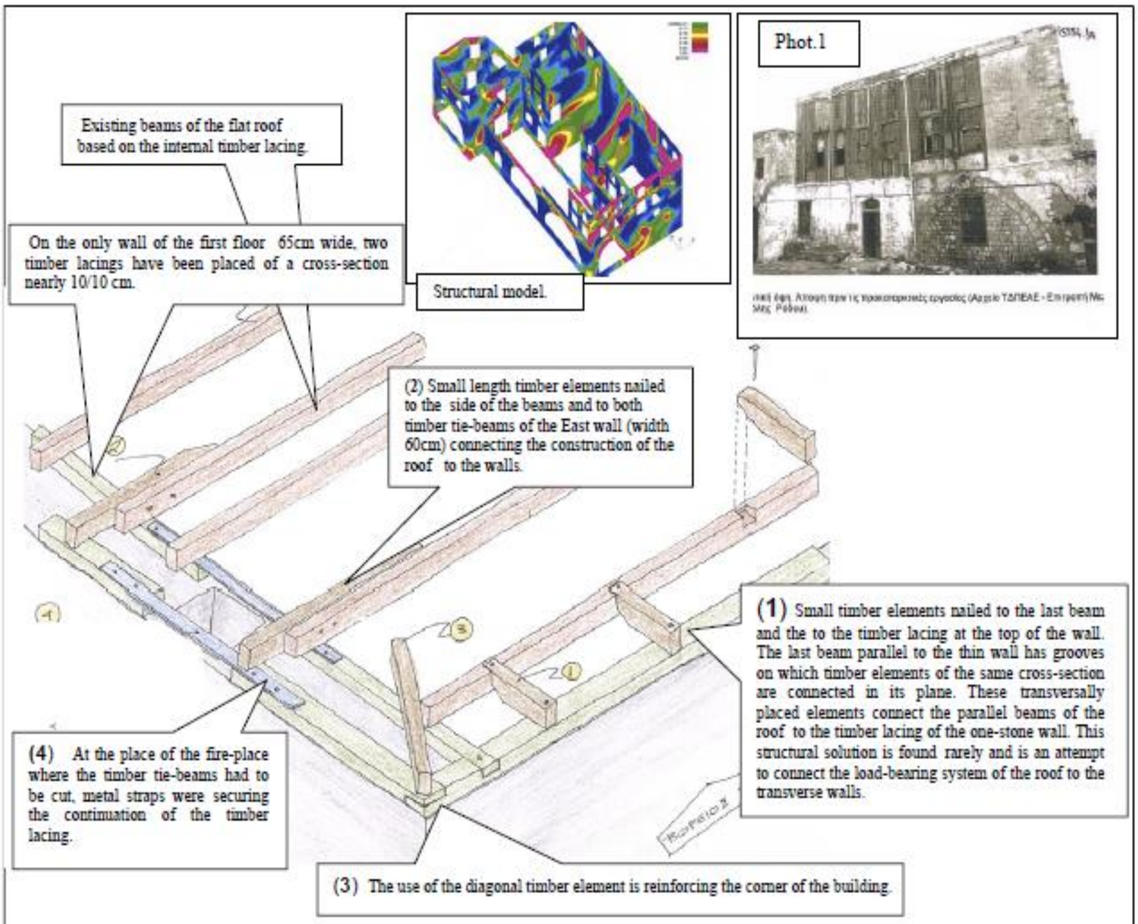


Fig.1 The constructional analysis revealed the effort of the traditional builder to tie the walls of the building in order to withstand the severe eartquakes of the area.

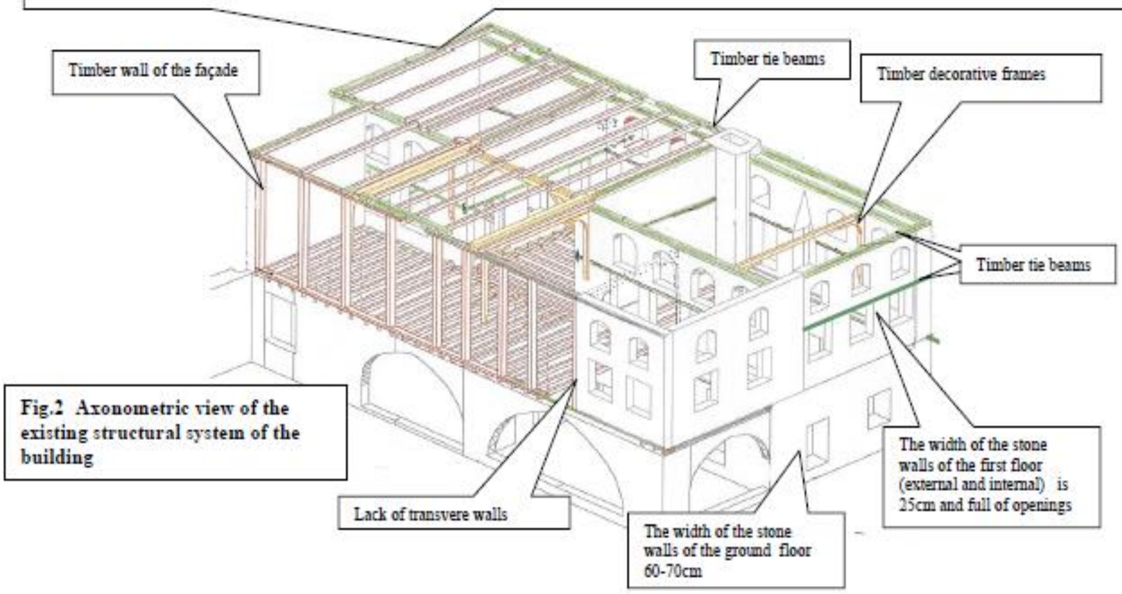


Fig.2 Axonometric view of the existing structural system of the building

Building's structural system

Source: E. Tsakanika, «Methodology concerning the restoration of Historical Buildings. CASE STUDIES : The Turkish Mansion and the Hagi Mehmet Aga Mosque in Rhodes» (ed: G. Tampone), International Conference «Conservation of Historic Wooden Structures", Florence 2005, vol. 2., p.194-203.

Category AB

Constructions which consist of wide spaces, without or with few internal load-bearing walls, connected to the perimeter ones, with or without intermediate floors. The timber (king post truss) or steel roofs (trusses), etc., of these buildings, transfer the loads only to the external walls. Typical example of this category are basilica churches, industrial buildings, warehouses, local markets, cinemas, theaters, etc. This category also includes medium and large-sized buildings, such as public buildings, residences, etc., with non-bearing interior walls.

The constructions of this category are characterized by the **out-of-plane failure** of their perimeter walls, as a dominant form of failure, especially when the roofs are not tied to the masonry through timber ties or other types of bracing at the top of the walls.

3.1.5 Subcategory AB.1: SINGLE OR MULTI-STOREY BUILDINGS WITH WIDE SPACES

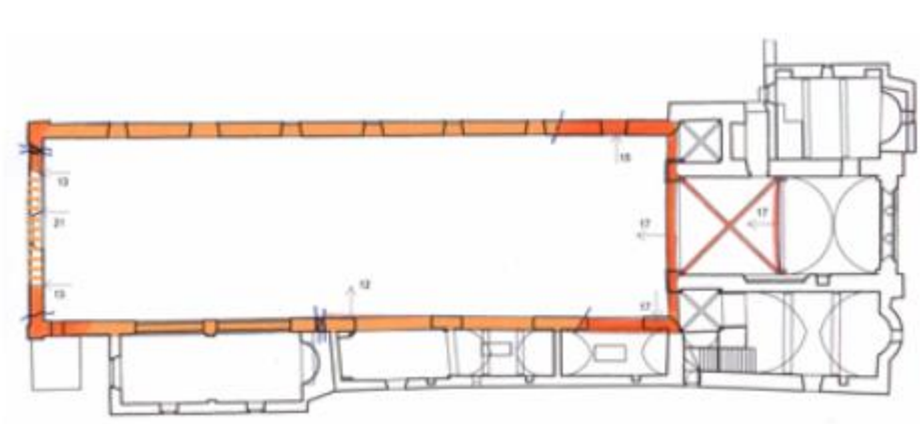
CHARACTERISTIC PROJECTS OF SUBCATEGORY AB.1

1. Agios Petros of the Dominican order, Heraklion

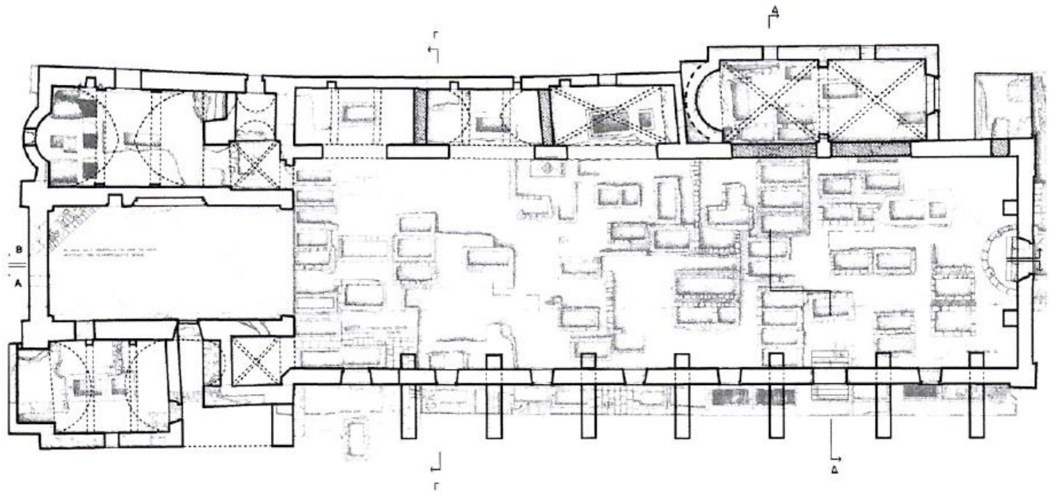
It is a one-room, timber-roofed Basilica with internal dimensions of the central nave of 39.0mx 11.30m and a height of 11.30 m. It was built in the second half of the 13th century and is one of the first churches built by the Dominicans, as the catholicon of the monastery of Agios Petros in Heraklion, Crete, and in which a lot of interventions and reconstructions have been implemented. Although it has a Presbytery and chapels covered with cross vaults or barrel vaults which are developed along its eastern and southern sides respectively, the structural behavior of the monument is determined by the particularly large dimensions of the central nave in relation to the small thickness of the perimeter masonry walls, which in combination with the absence of other supporting and stiffness elements against horizontal actions, they constitute a statically insufficient bearing system, particularly vulnerable to out-of-plane horizontal seismic actions. In order to remove these weaknesses and in order to improve the structural system of the building, the timber roof was restored with trusses and corbels that were connected to the perimeter masonry walls, while its diaphragm behavior was improved with a special invisible coating of plywood of great thickness and length. In addition, the structural capacity of the ensemble was enhanced by the construction of 8 steel buttresses with stone coating, with corresponding internal built-in ribs on the north free wall, as well as three smaller buttresses on the south wall in conjunction with the restoration of all the ruined chapels abutting this wall.

Overview of the monument and its surrounding area during the 1990s, before the restoration work.

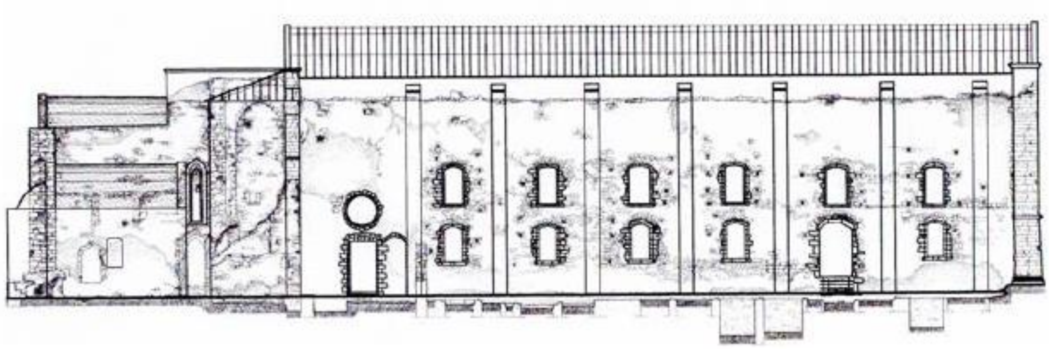
Overview of the monument and its surrounding area, after the restoration work (2007-2010).



Floor plan of the monument, before the restoration work.



(α)



(β)

Final restoration proposal with roof diaphragm and buttresses (a) top view, (b)north view

Source: E. Delinikola, D. Chronaki and D. Kalomoirakis (2008). In Proc. of the International symposium "Routes of Faith in the Medieval Mediterranean", Thessalonike, 7-10/11/2007.

3.1.6 Subcategory AB.2: MEDIUM OR LARGE-SIZED BUILDINGS, WITH NON-LOAD-BEARING INTERNAL WALLS

CHARACTERISTIC PROJECTS OF SUBCATEGORY AB.2

1. Stables of the former royal estate of Tatoi

The Stable belongs to the farm unit of the former royal estate of Tatoi and in particular to the livestock complex, It was built during the first period of reconstruction of the former royal estate of Tatoi (1873-78). It is rectangular in plan with external dimensions of 25.00mx8.50m. The perimeter walls are stone masonry and have an average thickness of about 60cm (three-layer masonry with a small core thickness - outer and inner face about 25cm and filling 10cm). The building is covered by a wooden roof, the trusses of which consist of wooden beams of sawn natural timber, with cross-sectional dimensions of 150mm x 175mm. The trusses are arranged at distances of every 2.0 m

Today, the building is used as a warehouse. The ground floor consists of a single space measuring 19m x 7m, a much smaller one where the ladder to the floor is placed, as well as a unit of very small auxiliary spaces with the use of a kitchen and sanitary area. The floor has 7 rooms that are separated by low-height single-layer glass brick structures that do not reach the height of the ceiling. The first floor consists of wooden boards, on wooden beams which rest on the masonry and are spaced 55cm apart.

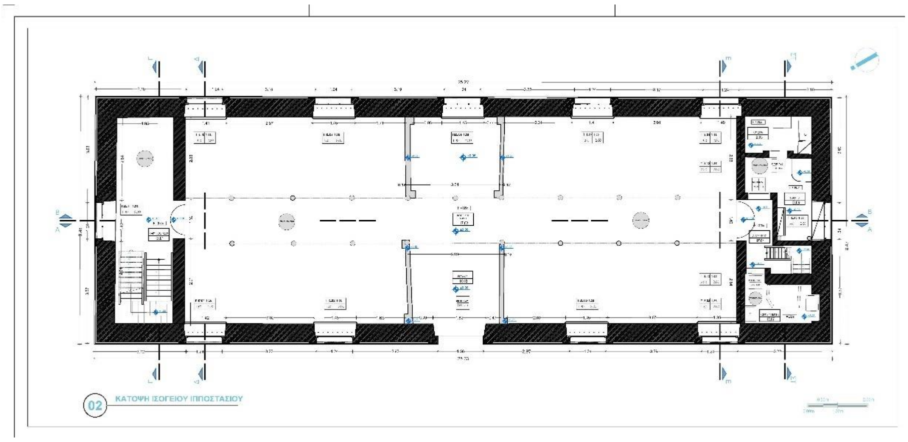
The building belongs to construction category AB due to its dimensions, since one side is at least twice as long as the other and the diaphragm function depends on the condition of the wooden floor, the wooden support beams and the conditions of their bearing on the masonry.


(α)


(β)

(a), (b): Overview of the building

Detail of the roof truss



Ground floor plan

Source: Technical Description of the Imprinting of the Stable Building for DPANSSM (2022). J. Dourakopoulos, S. Christodoulou.

2. S.T. Dormition of the Virgin Mary in Pades, Ioannina

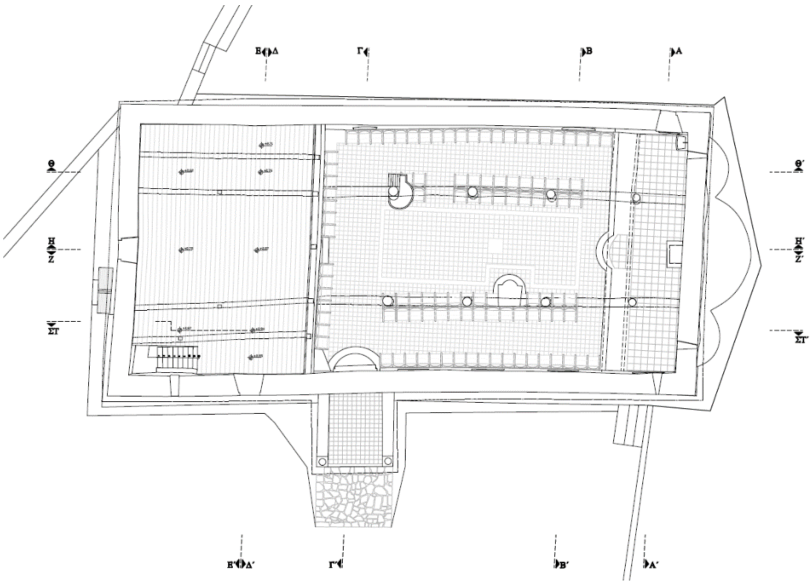
It is a three-aisled basilica with a timber roof. The aisles are separated by colonnades of timber pillars. The church was built in 1784 and has floor plan dimensions of 13.30 m x 26.80 m. It has a Narthex on the floor of which, there is the gynaikonitis (area of the church appointed for women). The Narthex is separated from the main church by a stone load bearing wall on the ground floor. The external irregular masonry structures are 90-96cm thick, while the internal partition wall of the ground floor is 75cm. The timber roof is a typical example of the "seated" roofs of the basilicas of the Ottoman era in Greece ("posted beam" system). Although "beam-on-post" type roofs generally improve the overall behavior of the building (especially against horizontal loads), sharing the loads (vertically and horizontally) and tying the walls together, in the case under consideration, on the one hand, the continuity of the roof beams is interrupted due to the presence of a raised ceiling in the central aisle, while there is a significant difference in stiffness between the vertical elements (stiff stone masonry walls and flexible timber columns).

Overview of the temple

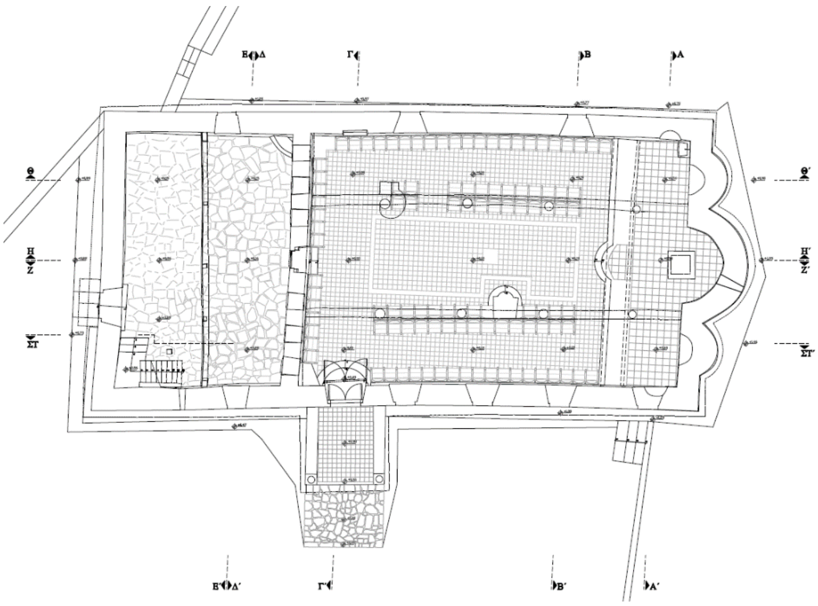
East view

Southwest view

Internal colonnades



Ground floor plan



Plan at the the gynaikonitis (area of the church appointed for women) level

Source: Restoration study of I. N. Dormition of the Virgin Mary in Pades Ioannina (2021). Architectural study: M. Alexiou, Historical documentation: S. Tsouka, Structural Analysis: N. Psylla , E. Tsakanika and S. Tsouka.

3.2 Category B

This category includes 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 (domes, out-door galleries, apses, temple wings, etc.). Typical projects of this category are single-storey or two-storey buildings such as places of worship (churches and mosques with domes, porches, etc.), Ottoman public buildings (Madrasas, Hammams, etc.) as well as Public buildings dating back to the Venetian and Italian rule Period.

3.2.1 Subcategory B.1: TEMPLES (WITH DOMES, PORCHES ETC)

CHARACTERISTIC PROJECTS OF SUBCATEGORY B.1

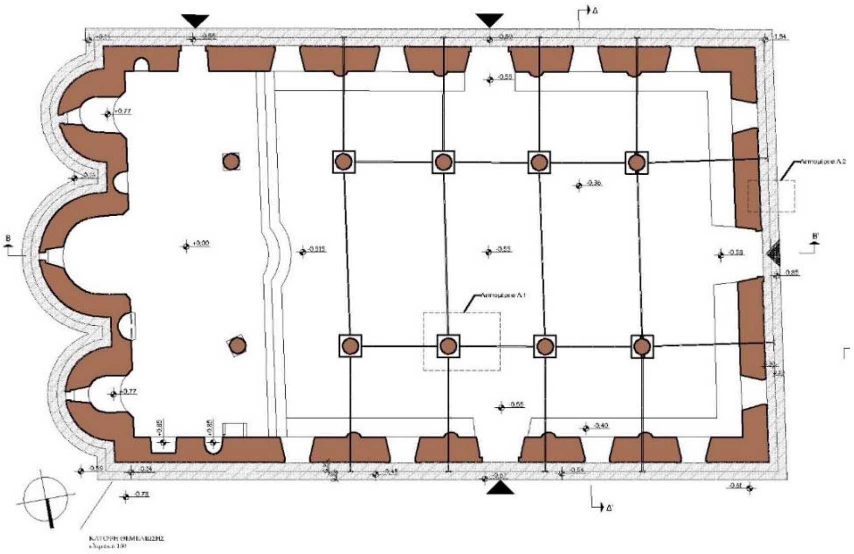
1. Panagia Emporeiou, Kasos

The church of Panagia is located in the northern part of the island of Kasos. The construction of the temple began in 1843 and was completed in 1846. Its external dimensions are 14.08 x 22.08 m (W-S) and 14.12 x 22.17 m (A-B). The middle nave projects above the level of the roof of the side aisles and is covered by a large semi-cylindrical barrel vault. The vault rests on longitudinal walls that end into two colonnades, each of which consists of five columns, connected to each other by semicircular arches. Above the Sanctuary another semi-cylindrical barrel vault, of smaller dimensions, intersects the first one vertically, forming an unequal cross. The transverse small vault ends in blind drums. The drums of the great dome project on the east and west faces with small circular openings. The side aisles are covered by monastic-style cross vaults. The side walls are made of horizontal, more or less level layers of well-cut ashlars, mixed with a few hard local stones, interspersed with random use of bricks at the horizontal and vertical joints.

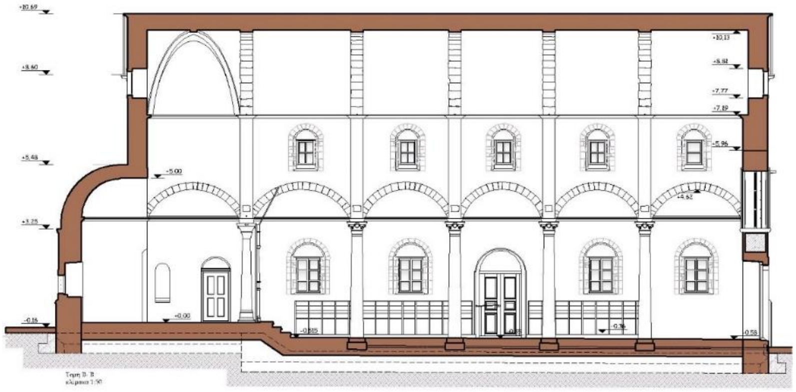
The construction is included in category B due to the large interior spaces (external dimensions 14X22 m). It has no interior walls and the three aisles are separated by two rows of colonnades. It also has a number of macroelements which can develop independent behavior and damage mechanism. Such macro-elements are vaults, barrel, cross and semi-circulars, as well as the internal colonnade, which, due to its significantly lower stiffness compared to the the vertical walls, is not expected to have the same deformation as the rest of the structure.

Overview of the temple (northwest)

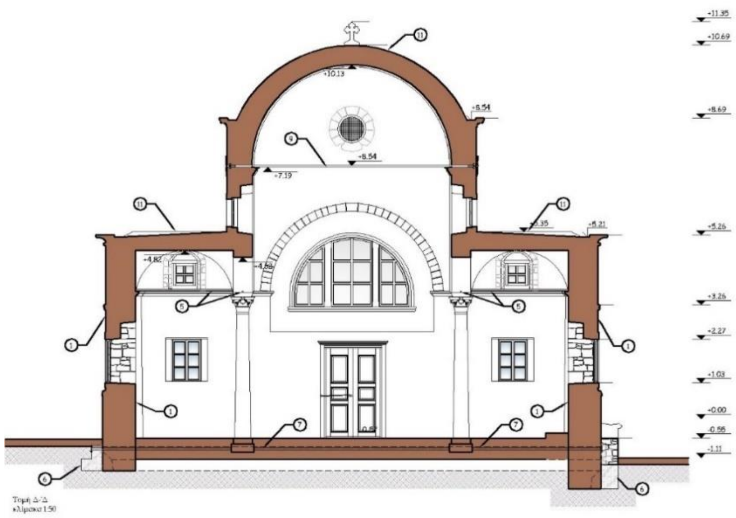
View of the colonnade and the cross vaults



Floor plan of the temple



(α)



(β)
Representative sections

Source: A.Chatzidakis, (2021). Structural Analysis

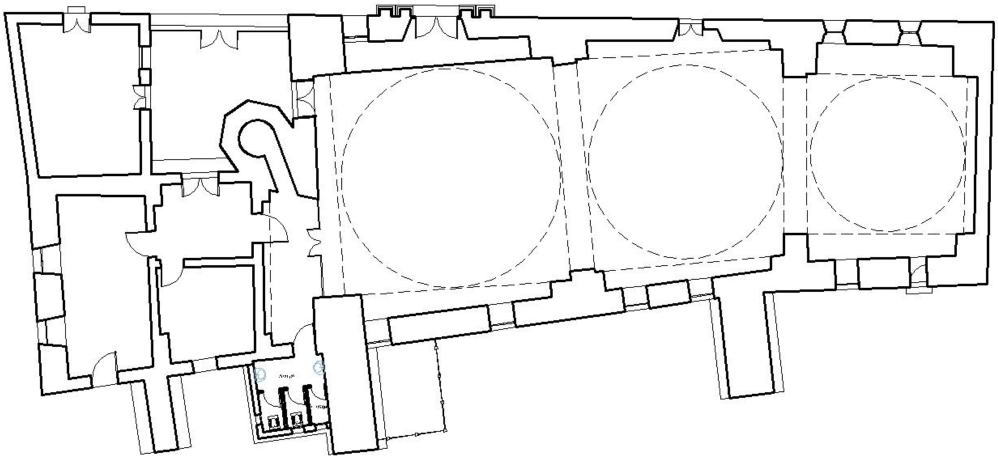
2. Neratze mosque, Rethymno old town

The mosque was founded in 1646, immediately after the occupation of Crete by the Ottomans, and it emerged from the conversion of the catholicon of the monastery of Panagia of the Augustinian monks. It consists of vertical walls and hemispherical domes. The external dimensions of the building are 42.66 X 19.08m. The thickness of the perimeter walls varies from 96 to 230 cm. Due to its previous use, the building was not able to withstand the horizontal thrusts coming from the domes, resulting in the construction of three stone masonry buttresses on the south side of the mosque.

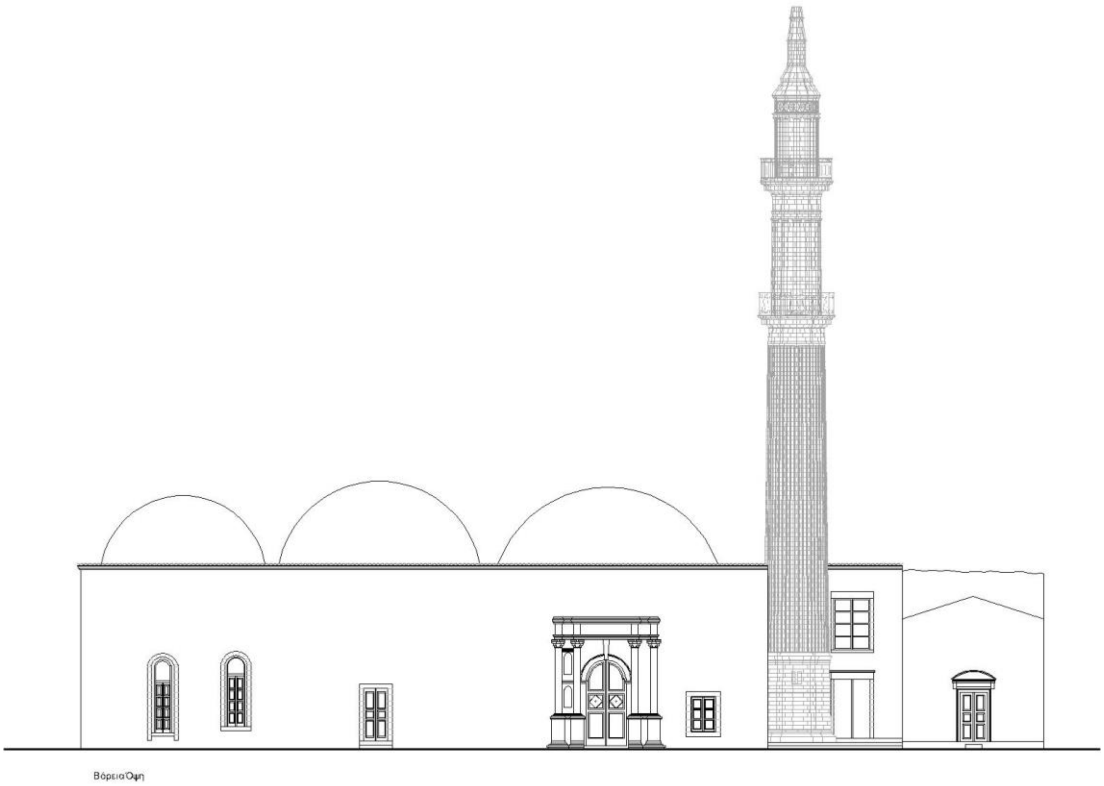
The classification of this monument in category B, results from the presence of a large single interior space, without intermediate supports. Another reason is the configuration of the roof with hemispherical domes, which, as can be seen from the pathology of the building before its repair, had developed a damage mechanism independently of the rest of the structure.

Overview of the mosque (Southwest view)

Overview of the mosque Northwest view)



Floor plan of the mosque



North view of the mosque

Source: Restoration Study. Civil Engineering Consultants Aris X. SMPC, (2018)

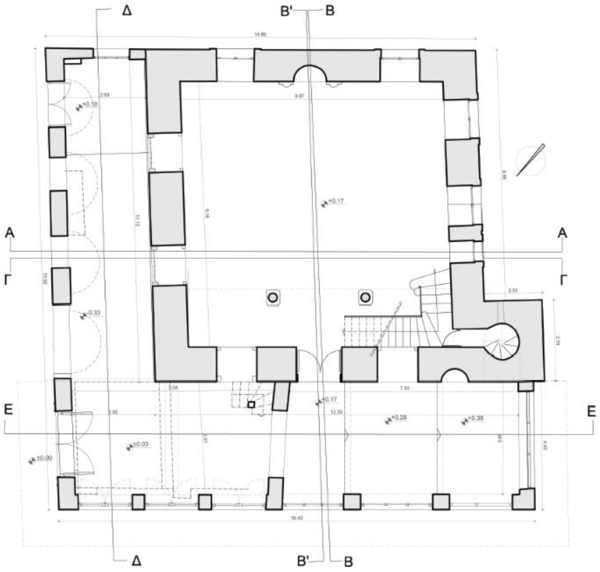
3. Kaloutsiani mosque, Ioannina city

The monument consists of a main hall with floor plan dimensions of 11.40m. x 11.45m. The thickness of the perimeter walls is 115 cm and the thickness of the dome is 36 cm. It has an interior balcony - gynaikonitis (area of the mosque appointed for women) with a wooden floor that is based on the perimeter masonry walls and an internal colonnade, unconnected to the stone walls of the perimeter. It has porches on both sides with arches, forming a floor plan of total dimensions of 16.40m. x 15.90m. It is classified in this category, due to the presence of the large single interior space, the presence of the external arches and the configuration of the roof with hemispherical dome, as well as the presence of distinct structural macro-elements which, as observed, had developed failure mechanisms independent of those of the main structure.

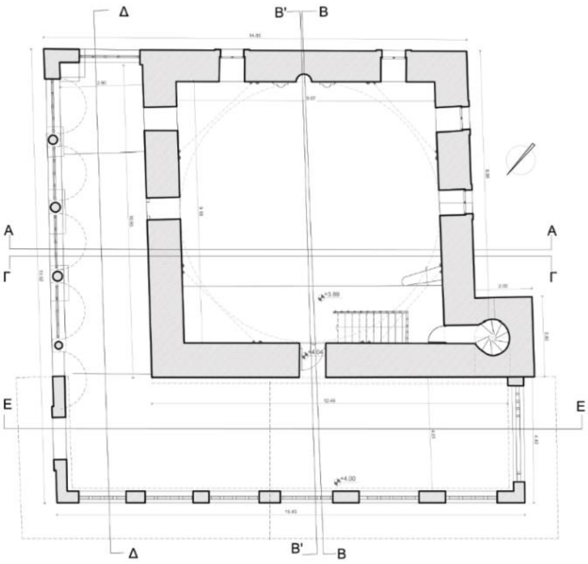
Overview of the mosque (West view) at heir initial form and after the neoclassic interventions

NW and SE view of the mosque at the existing condition after the neoclassic interventions

Interior view of the main hall. The dome and the internal arches of the gynaikonitis can be observed



Survey Floor plan (level +1.70m)



Survey Floor plan (level +4.20m)

Section A-A - Survey

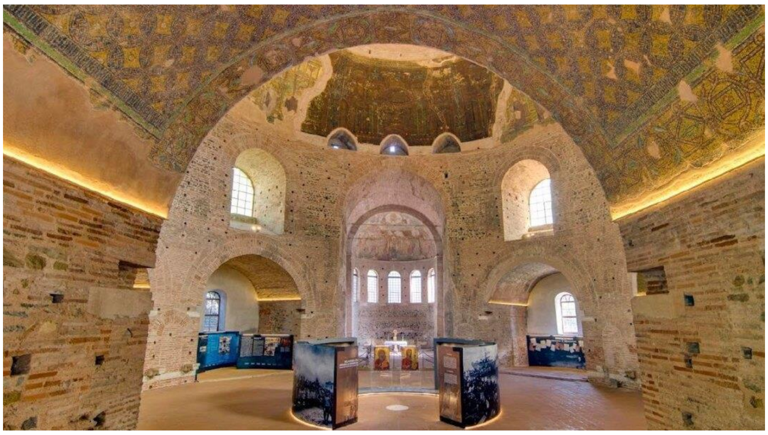
Source: Restoration Study. Architectural study: K Moretti, N. Xanthos, Structural Analysis: N. Psylla , Photogrammetric survey: T. Kouimtzoglou. Advisors: E. Tsakanika, E. Efesiou,, X. Mouzakis

4. Rotunda, Thessaloniki

Rotunda was built in the years of Caesar Galerius, around 306 AD, as a temple of Zeus or Caverius or, according to others, as Galerius Mausoleum. The monument was converted into a Christian temple during the early Christian period. During the restoration of the building, after a strong earthquake in the early 7th century, two external buttresses were added. In 1590/1 it was converted into a mosque by Sheikh Suleiman Hortatzis Efendi. After the liberation of Thessaloniki in 1912, it was once again converted into a Christian church.

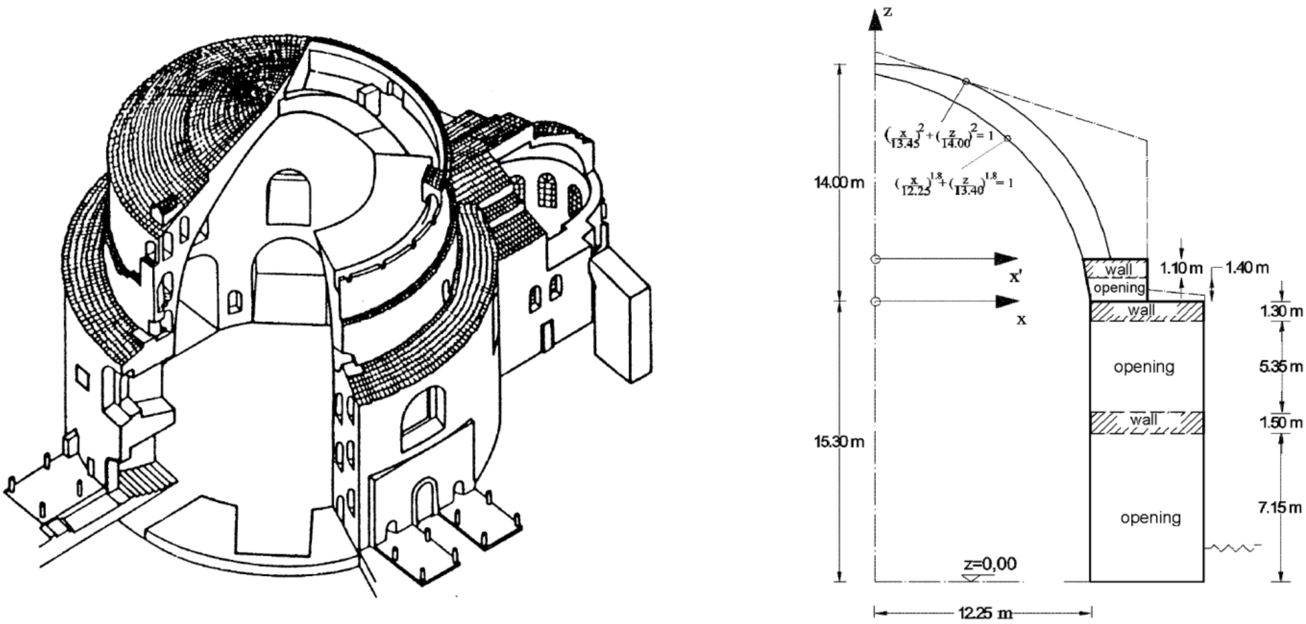
East view of Rotunda

Source: Giannis Triantafullopoulos



Source Menelaos Sykovelis

The building, with a diameter of 24.50m, is covered by an equidimensional dome made of solid bricks, which reaches a height of 29.80m. The cylindrical wall, 6.30m thick, constructed of successive layers of stone and brick masonry, is divided internally into eight rectangular apses, of which the southern one formed the main entrance. It is classified in category B, due to its macro-elements (central dome, apses) that can develop independent out of plane failure mechanisms.



(α) (β)

a) Axonometric drawing, b)Representative vertical section of Rotunda

Source: Doudoumis, Ioannis N., and Emmanouil D. Kallioudakis. "Seismic response of Rotunda monument due to the Thessaloniki 1978 earthquake." Proc. 13th European Conference on Earthquake Engineering. 2006.

3.2.2 Subcategory B.2: OTTOMAN PUBLIC BUILDINGS (MADRASAS, HAMMAMS, ETC)

CHARACTERISTIC PROJECTS OF SUBCATEGORY B.2

1. Hammam, Nikiforos Fokas street 89, Rethymno

The bathhouse is located on Nikiforos Fokas Street, in the old Town of Rethymno. The building changed its use in 1925 and was converted into a bakery, as a result of which the large hemispherical dome of the dressing room was removed, on the traces of which a new construction-floor of the overlying residence of a family was erected. Spherical semi-cones are formed at the four corners, through which the transition was made from the octagonal drum (on which the dome used to be supported) to the perimeter masonry walls. The building is used today as a hotel.

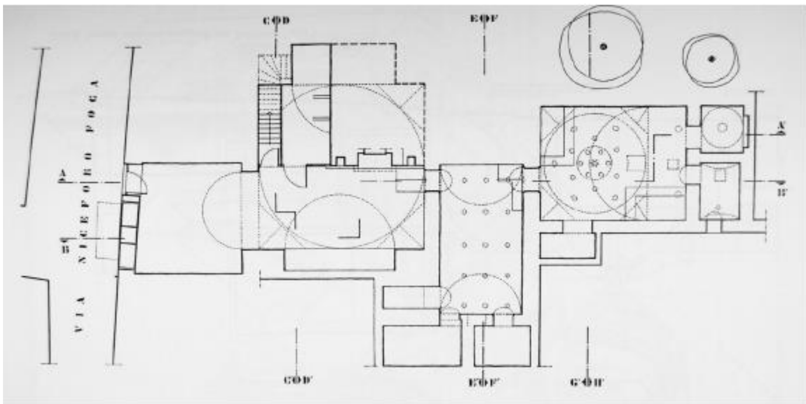
The "lukewarm" space has dimensions of 3X5.55 m and is covered by a hemispherical dome with 15 lighting holes. The "warm" apartment, measuring 5.30X4.20 m, is also covered by a hemispherical dome 4.80 m high, which has three rows of concentric hexagonal light holes and which is supported by an arch on the southwest side. Externally it is covered with kourasani (type of traditional mortar). This apartment is connected to two more small spaces, measuring 1.70X1.50m and 2.10X1.40m, respectively, covered by a low hemispherical dome and an arch.

The hammam is built with stone masonry, with medium to large semi-regular stones. The building is classified in category B due to the presence of macro elements (domes, arches) that are expected to develop independent damage mechanisms.

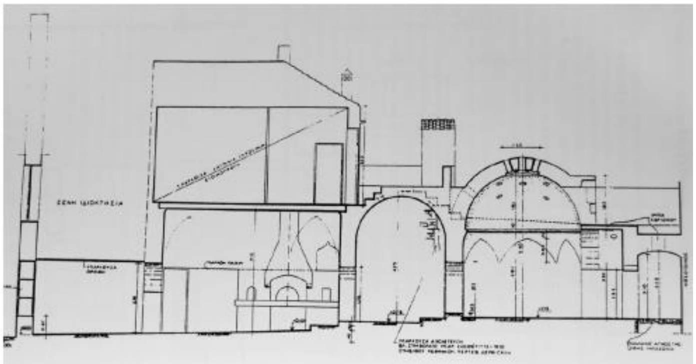
External view of the building housing the hammam

Internal view of the hammam's dome

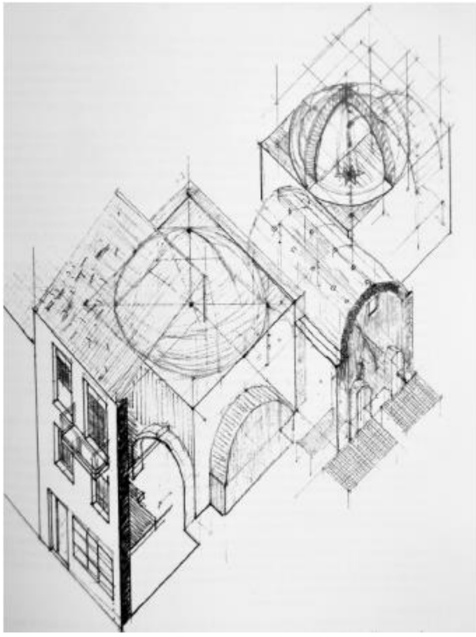
Detail of the hammam's dome



Ground floor plan



Section A



Axonometric drawing of the hammam

Source: Ottoman hammams in the Greek territory, Eleni I. Kanetaki

3.2.3 Subcategory B.3: PUBLIC BUILDINGS DATING BACK TO THE VENETIAN AND ITALIAN RULE PERIOD

CHARACTERISTIC PROJECTS OF SUBCATEGORY B.3

1. Governor's Palace of Rhodes

One of the most important buildings of the Italian occupation in Rhodes is the Governor's Palace, where the Prefecture of Dodecanese is housed today, on the beach of Mandraki, in the city of Rhodes. It was built around 1927 by the architect Florestano Di Fausto, chief architect of the then governor Mario Lago and creator of many important public buildings, urban planning and restoration projects, etc. It is an imposing two-storey building, built with the prevailing system of the time, stone masonry walls and horizontal diaphragms of reinforced concrete. Its floor plan is surrounded by a roofed gallery at the street level.

Overview of the monument

Source: Ministry of Culture and Sports / Governor's Palace (culture.gr)

3.3 Category 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 behavior.

3.3.1 Subcategory C.1: TOWERS

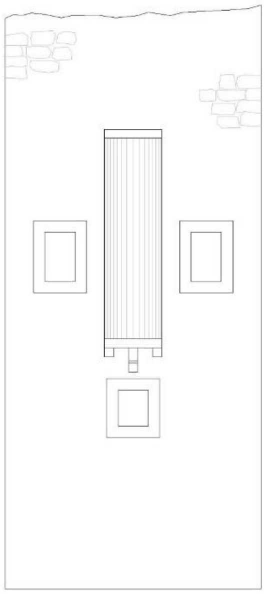
CHARACTERISTIC PROJECTS OF SUBCATEGORY C.1

1. Maroula tower, Prefecture of Rethymno

It was built during the Venetian rule in Crete 15th-16th century in the village of Maroulas, Prefecture of Rethymno. Its use was continued during the Turkish occupation period as a garrison base and base of operation. External dimensions 5.3X4.2 m and height of 9.7 m. Vertical stone masonry walls and horizontal timber floors on the intermediate levels. The intermediate timber floors do not have an adequate connection to the vertical walls.

It is classified as category C, because it has a large height compared to the thickness of the outer walls and the outer plan dimensions. These characteristics make the construction vulnerable to seismic loads, with dominant flexural behavior.

Overview of the tower



Southwest view of the tower

Source: Supporting Measures Study. Civil Engineering Consultants Aris X. SMPC, (2019).

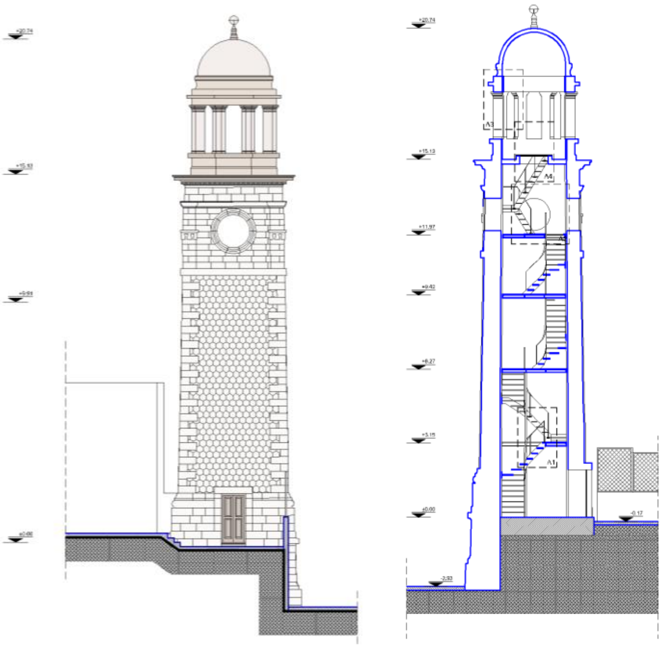
2. Clock tower, Chania

The clock is located in the north-east corner of the Municipal Garden of Chania at the junction of Dimokratis and Valaoritou streets. It was built between 1924 and 1927.

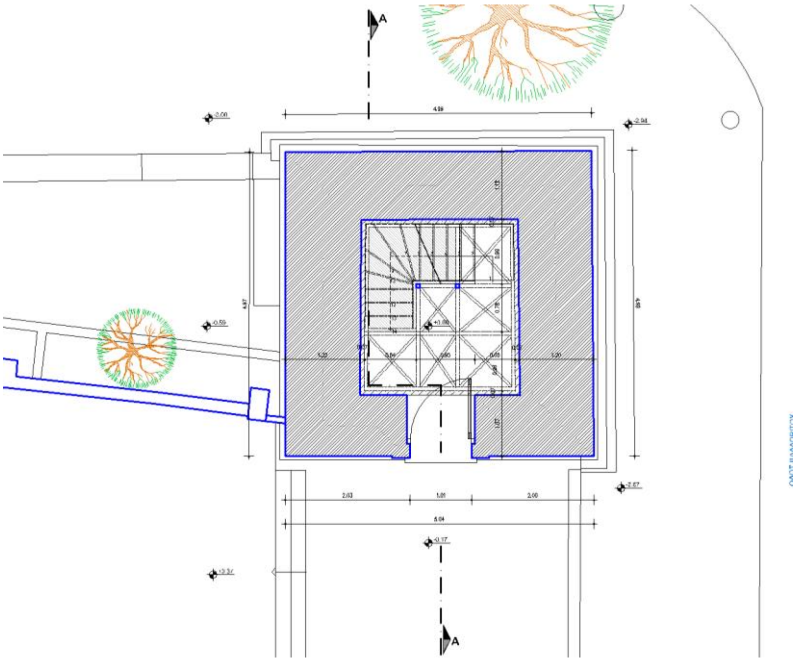
The clock is tower-shaped with a square plan on its main stone masonry section, that rises with a slight upward Inclination to the height where the clock mechanisms are located. The main part ends with a protruding frame and at this height is placed a circular ring of lightly reinforced concrete about 45 cm thick, from which 8 concrete pillars rise. These pillars have a similar polygonal and then circular rim section made of lightly reinforced concrete on which rests a hemispherical dome made of solid bricks.

The building is classified as Category C due to its great height and slender elements at the top, which are sensitive to flexural buckling.

Overview of the tower



Southwest view and vertical section of the tower



Horizontal section of the tower
Source: Structural Analysis. Civil Engineering Consultants Aris X. SMPC, (2016).

3.3.2 Subcategory C.2: BELL TOWERS

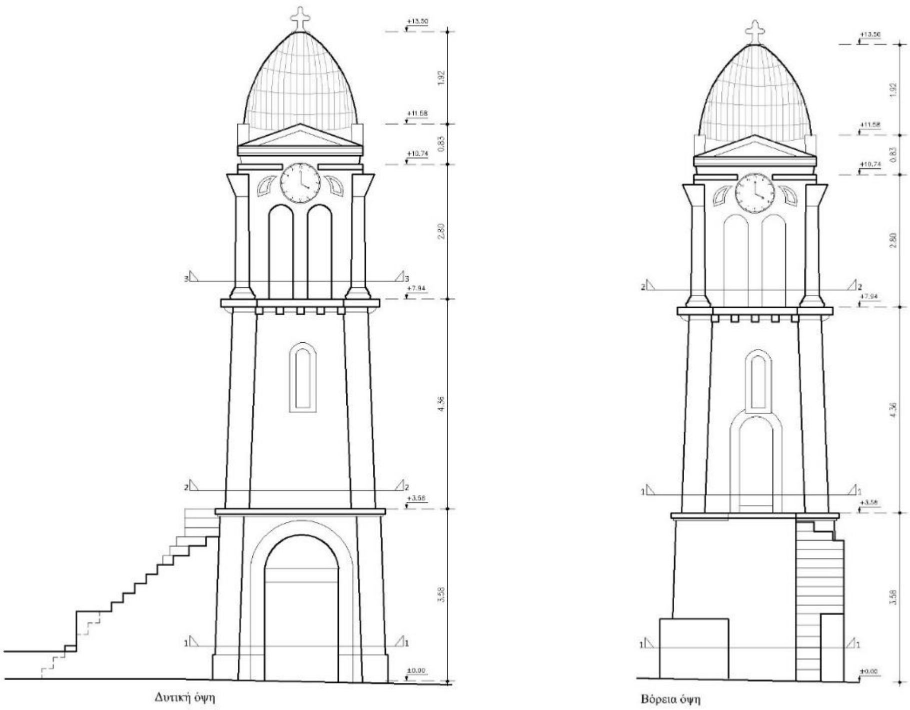
CHARACTERISTIC PROJECTS OF SUBCATEGORY C.2

1. Bell tower Vistagi, Municipality of Amari, Prefecture of Rethymno

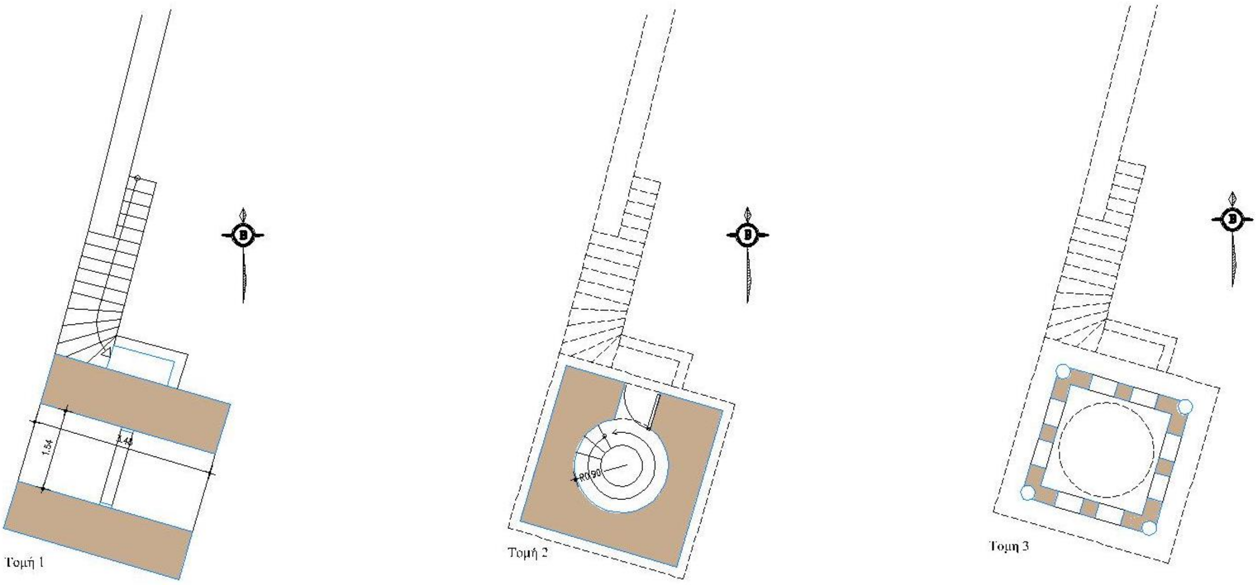
It was built in the 19th century, with a height of 13.50 m and dimensions at the base equal to 3.64 x 6.34 m. The belfry is entirely made of stone masonry with an internal circular staircase, having an internal diameter of 1.80 m, with the stone steps projecting from the stonework. The minimum thickness of the masonry in the lower part of the bell tower is 70 cm. The pillars are made of cut stones while we also observe steel ties between the stones in the horizontal frames.

The bell tower has a significant height in relation to the other dimensions. The construction has great slenderness, with the weakest part of the bearing system being the upper part where the openings form thin pillars, with low flexural strength.

Overview of the bell tower (Southeast and North view)



Bell tower’s view plans



Horizontal sections of the bell tower

Source: Restoration Study. Civil Engineering Consultants Aris X. SMPC, (2021).

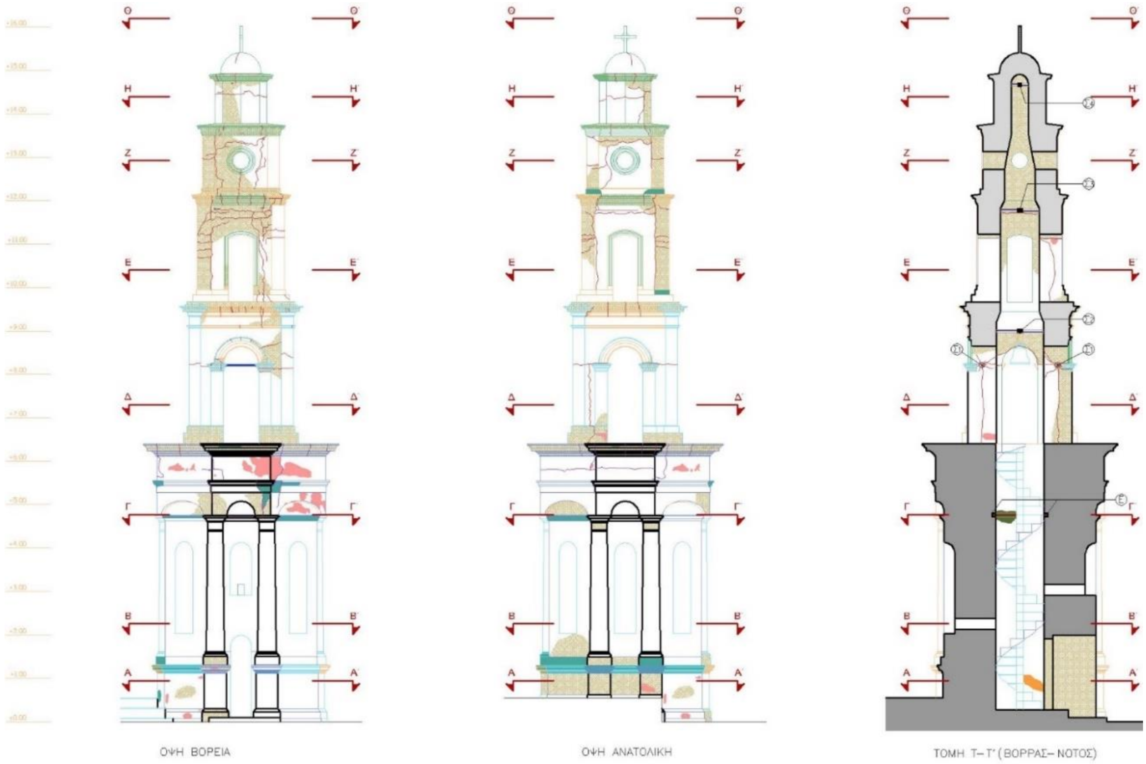
2. Agia Marina bell tower, Kasos

The bell tower is a construction of the 19th century and is located on the island of Kasos in the southeastern Dodecanese.

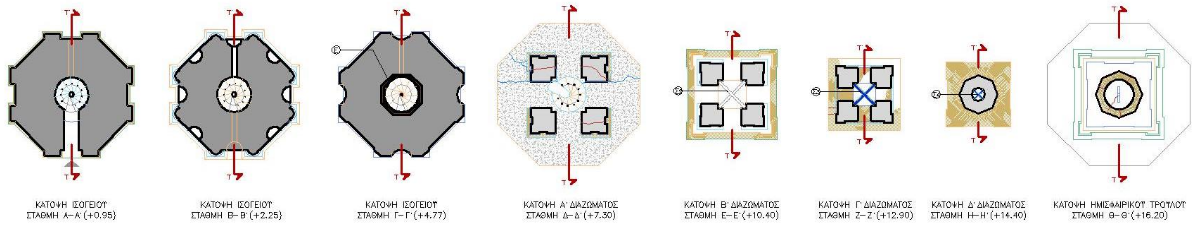
The bell tower, with a total height of 15.41 m, is a slender structure with variations in the geometry along its height, which divide it into 5 different sections. The first octagonal section forms the base of the bell tower. The base is made of semi-regular stone masonry, of medium-sized stones. In the center of the base there is a circular staircase which consists of cut stones, connected to the surrounding masonry. The rest of the bearing system consists of brick masonry made with solid bricks. The second and third parts consist of four square columns on each level which are connected to each other by arched spandrels. The fourth part has a square cross-section with circular holes in the middle of each wall, while the last part has octagonal geometry on which a dome rest.

The construction is classified as category C due to its great height. Especially the upper part, where the columns are formed, has significant flexibility, resulting in the flexure being the dominant mode of failure.

Overview of the bell tower (North view)



Views and vertical sections of the bell tower



Horizontal sections of the bell tower

Source: Structural Analysis. Civil Engineering Consultants Aris X. SMPC, (2018).

3.3.3 Category C3: MINARETS

CHARACTERISTIC PROJECTS OF SUBCATEGORY C.3

1. Neratze minaret, Old town of Rethymno

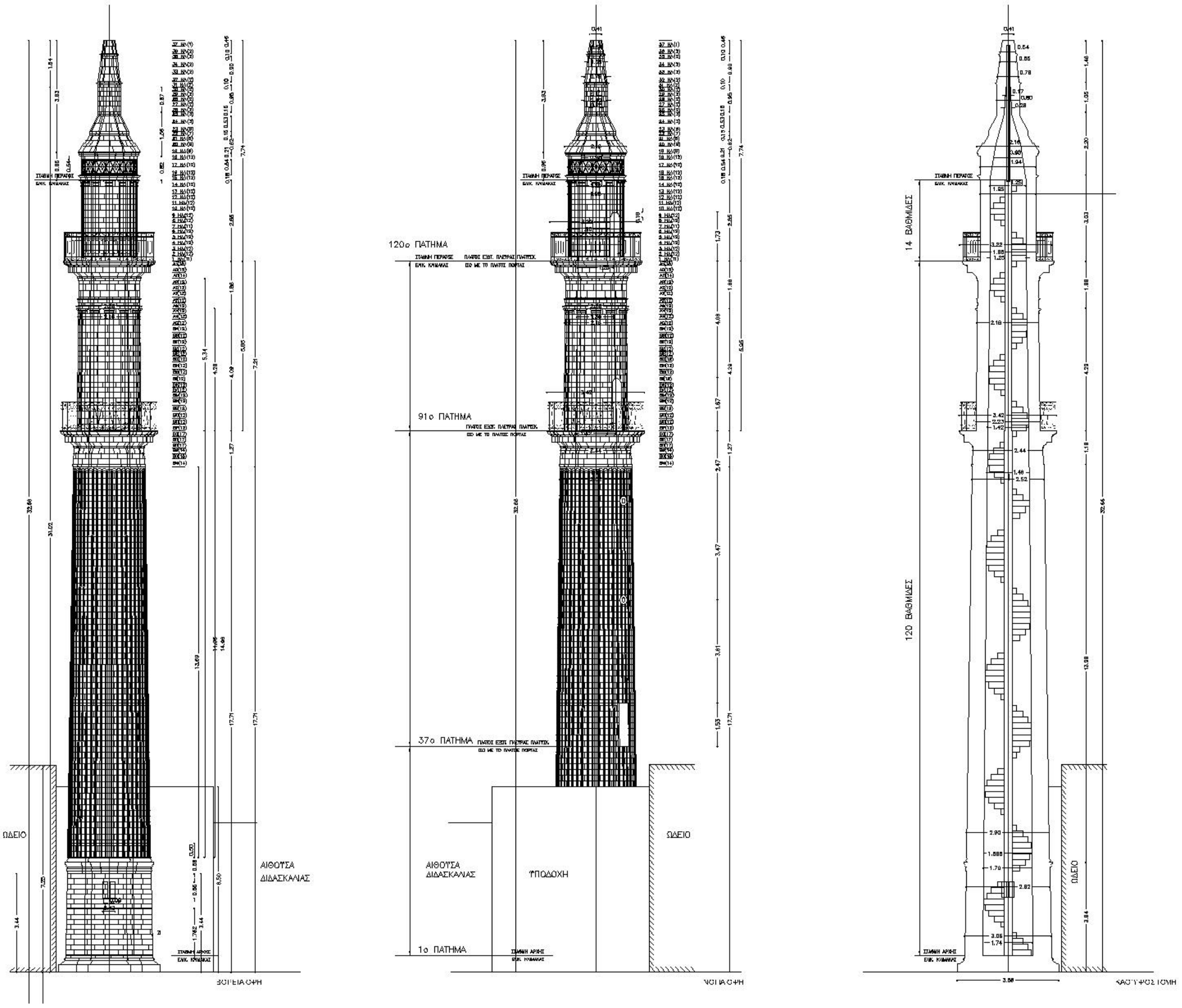
The Neratze minaret belongs to the complex of Gazi Deli Hussein Pasha and is located in the old town of Rethymno, next to the neighboring mosque of the same name. The minaret, with a total height of 32.66 m, was built in the year 1890/91. The load-bearing system of the minaret has been constructed from stones that are cut at the visible faces, using a thin layer of mortar between the successive height levels. Its cylindrical section, which rests on an octagonal base 3.84 m high, consists of vertical rows of concentric rings, with the exception of the 1.64 m high upper part, which has a solid section. The thickness of the ring masonry ranges from 0.65 m at the base to 0.50 m at the top. The minaret has two balconies supported on a extended base by two semicircular corbels, surrounded by a steel railing. On the south side of the base, a small arched doorway leads to the spiral staircase, which is constructed of solid stone steps of triangular cross-section.

The construction is included in category C due to its significant height in comparison to its other dimensions.

The diameter of the minaret at the base, 3.05 m, is 10 times the height of the structure. The thickness of the stone masonry of the bearing system is 0.5-0.65 m, giving the minaret great slenderness. The structure is expected to behave like an inverted cantilever under seismic load, with an expected flexural failure mode. Additionally, due to its circular cross-section, the minaret shows sensitivity to torsional deformations during its seismic excitation.

Overview of Neratze minaret (Southwest view)

North side of Neratze minaret



North, south view and vertical section of the Neratze minaret

Source: Structural Analysis. Civil Engineering Consultants Aris X. SMPC, (2018).

3.3.4 Subcategory C.4: LIGHTHOUSES

CHARACTERISTIC PROJECTS OF SUBCATEGORY C.4

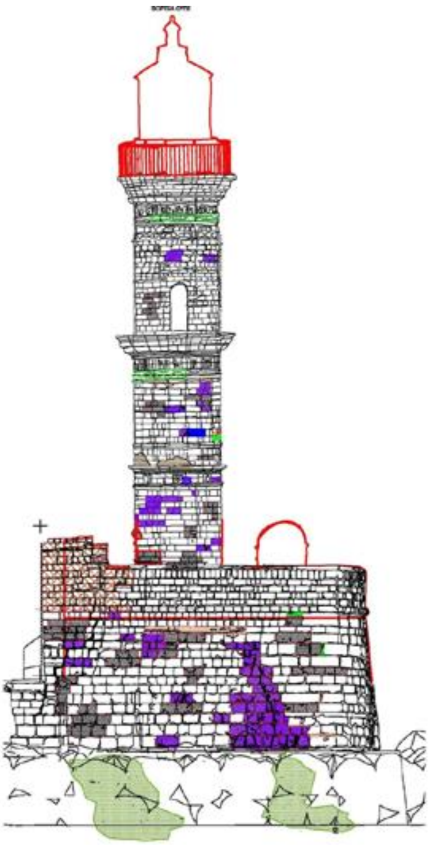
1. Chania Lighthouse

The Chania Lighthouse, was erected on the Venetian built base, during the period of Egyptian rule in Crete, in 1838. In 1853, a reflector (mirror) was placed on the Lighthouse. The lighthouse consists of three cylinders with different cross-sections and rises 16m above the base, without taking into account the glass top. The base section is octagonal in plan, the middle section is hexagonal, while the third one is circular.

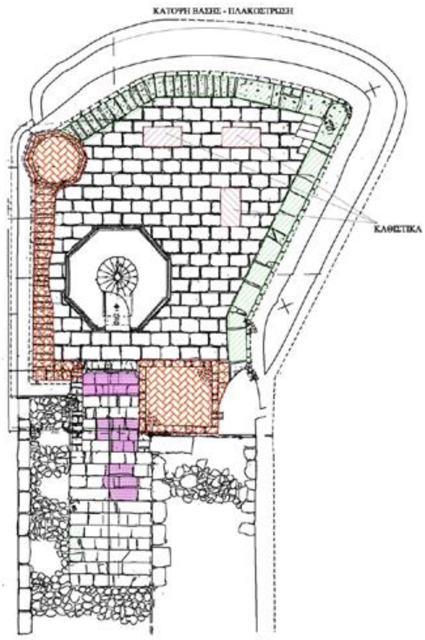
The tower (main section) of the lighthouse is made entirely of cut stones, specifically sandstone limestone. The thickness of the stone masonry of the main section is approximately 0.60m for the entire the height of the tower.

The structure is classified as category C due to its great height, which is significantly greater than the cross-sectional diameter of the lighthouse. The structure is expected to exhibit flexural behavior during its seismic excitation.

Overview of the Lighthouse (South view)



South view (imprinting)



Base plan (imprinting)

Source: A. Chatzidakis, (2015). The restoration of the Lighthouse at the Venetian Harbour of the old town of Chania, 4th National Conference of Restoration, Thessaloniki

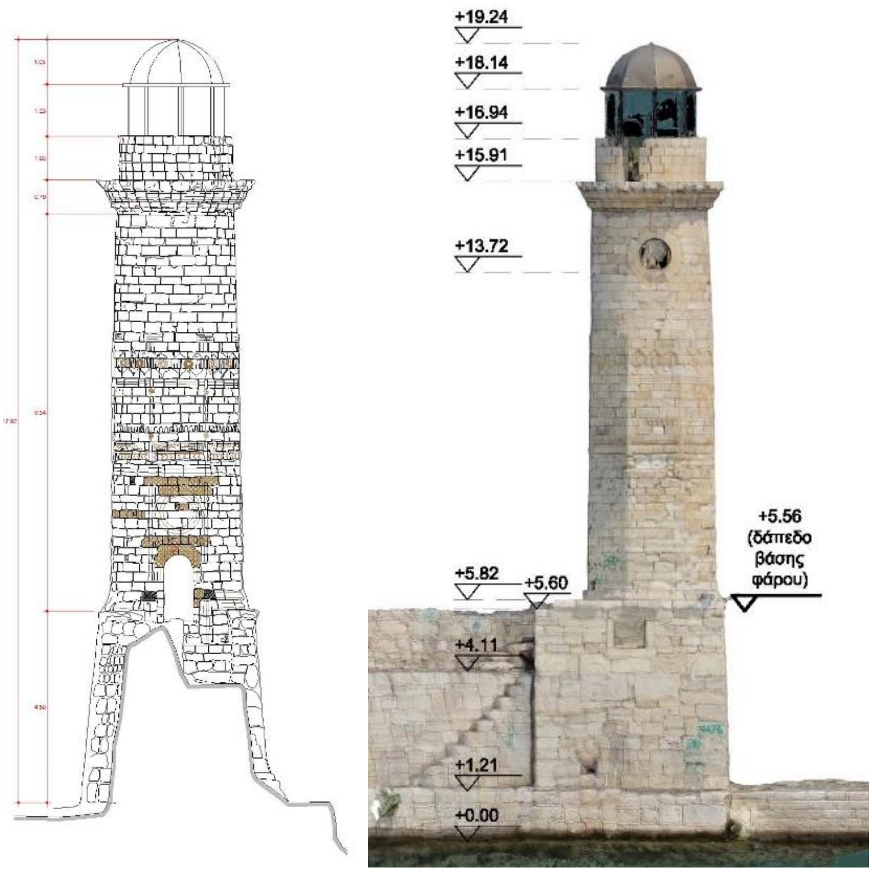
2. Rethymno lighthouse

The lighthouse in its current form is the historical result of the interventions that took place after its construction in 1838 during the period of the Egyptian rule in Crete under Mohammed Ali. It was built at the same period as the Chania lighthouse, with which it has an obvious morphological resemblance. In the period of the Venetian and the Ottoman rule, there does not seem to be any construction of a tower-shaped lighthouse on the windward mole. In 1962, its operation as a lighthouse stopped after a new lighthouse was placed on the windward mole of the new port.

The base of the lighthouse is located at the end of the windward mole which is located on a rocky outcrop in the area. In the area of its base, caving had been observed under the quay of the mole's platform, which, however, was dealt with by an intervention made by the Municipality of Rethymno. The floor of the platform leading to the lighthouse is at an elevation of 1.20m above sea level. The floor of the base, at the height of the entrance to the lighthouse, is + 5.55 meters. The cross-section of the lighthouse up to the height of +12.30 is octagonal on the outside and circular on the inside, while it becomes cylindrical above that height. The balcony floor is at + 15.90, the end of the stone masonry part of the lighthouse is at + 16.95, while from there the steel cage starts and reaches up to + 19.25. The stone spiral staircase reaches the balcony level with an average step height of 0.22 m and an average maximum tread of 0.35 on the perimeter. The thickness of the stone masonry decreases along its height and is equal to 84 cm for the octagonal part at the base and 47-60 cm for the circular part at the top. The sufficient thickness of the structure resulted in the absence of serious damages in it despite the age of the monument.

The construction is classified in category C due to its significant height, which gives a slenderness to the structure.

Overview of Rethymno Lighthouse (Northwest view)



North and west side of Rethymno Lighthouse (existing condition)

Source: Structural Analysis. Civil Engineering Consultants Aris X. SMPC, (2022).

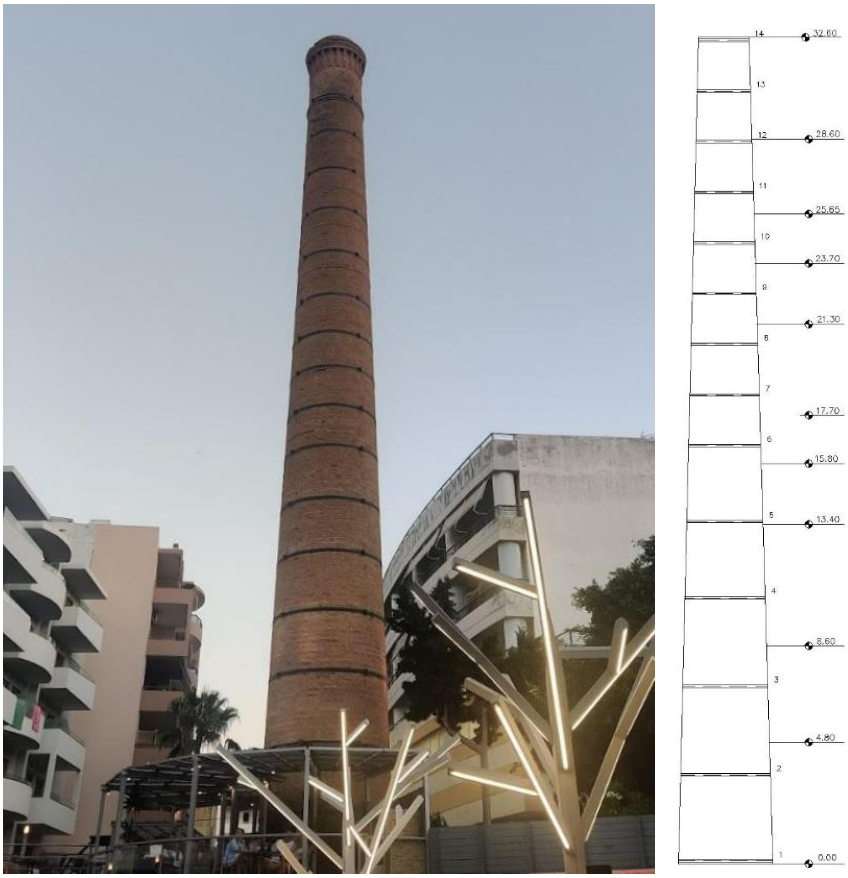
3.3.5 Subcategory C5: CHIMNEYS

CHARACTERISTIC PROJECTS OF SUBCATEGORY C.5

1. BIO Chimney, Rethymno

It was built in 1946-1948 for the needs of the olive mill-soap factory of the company "ETEL AE''. It consists of solid brick masonry and reaches up to 32.60 m height, with a diameter of 3.70 m at the base and 2.00 m at the top.

High-rise construction with expected flexural behavior in case of an earthquake.



Overview of the chimney (North view)

Source: Restoration study. Daidalos (2004)

3.4 Category D

Structures with large length compared to their width and height, with arches and vaults characterized by in-plane failure.

3.4.1 Subcategory D1: APSES (TRIUMPHAL ARCHES)

CHARACTERISTIC PROJECTS OF SUBCATEGORY D.1

1. Arch of Galerius (Kamara)

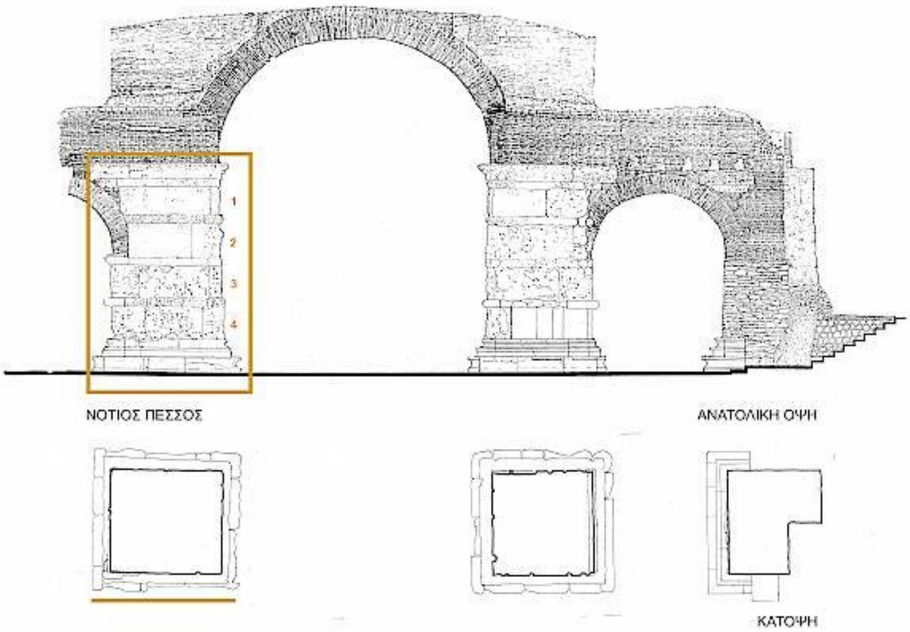
The arch of Galerius is part of the Galerian complex in the southeastern part of the historical center of Thessaloniki. One of the best-known monuments of Thessaloniki and one of the most characteristic of late antiquity, when Thessaloniki became the capital of Caesar Galerius. The arch was built in 305 AD. after the definitive victory of the emperor Galerius against the Persians. In its original form, it is an octapylon (eight gates) with 4 massive central pillars, 4 secondary ones on the sides, the same number of arches and a low spherical dome. Today, two main pillars and a secondary one are preserved, connected by a brick masonry arch. The construction of the arch was based on two parallel walls, approximately 37 m long and 3.80 m thick (one survives at a length of 29 m). The walls had three arched openings, one large in the center, 9.70 m wide and two smaller ones at the sides, 4.85 m wide. The four central pillars were built of thick marble stones, while the core was coated with other marbles and thick plates. For the construction of the rest of the arch, irregular stones with strong mortar and bricks had been used for an external layer 0.70 m thick. The construction belongs to this category due to its geometry which today lists 2 arches and the considerable thickness of its walls in relation to its height, which increases the vulnerability to in-plane failure.

Source: http://odysseus.culture.gr/h/2/gh251.jsp?obj_id=1425

Overview of the monument

Kamara at the beginning of the 20th century with horse-drawn tram passing under

View of the monument's pillars



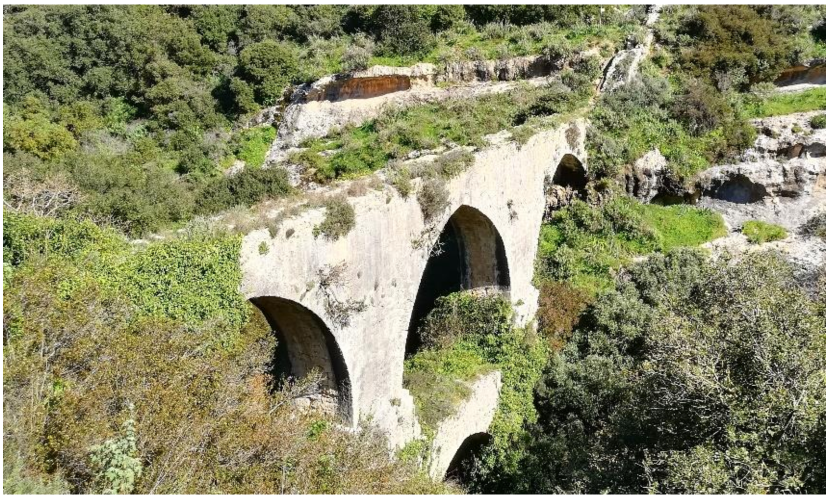
Source: Archive of EFA of Thessaloniki City

3.4.2 Subcategory D.2: AQUEDUCTS

CHARACTERISTIC PROJECTS OF SUBCATEGORY D.2

1. Morosini aqueduct (Karidaki location), Heraklion

The Morosini aqueduct, i.e. the aqueduct that supplied water to the fountain in the central square of Chandaka (old name of Heraklio), was built by the General Governor Francesco Morosini, in 1627-1628. It is a water bridge about 65 meters long, with a double row of three arches. It has a width of 1.50 m and a length of about 36 m. It consists of a double row of arches, with one arch in the narrow row of the base and three arches in the upper part where the gorge widens. The arches are made with cut stone masonry while the rest of the structure is built with semi-regular stones. The work is classified in this category because of its arches.



Overview of the water bridge
(South view)

Upper side of the water bridge

3.4.3 Subcategory D.3: BRIDGES

CHARACTERISTIC PROJECTS OF SUBCATEGORY D.3

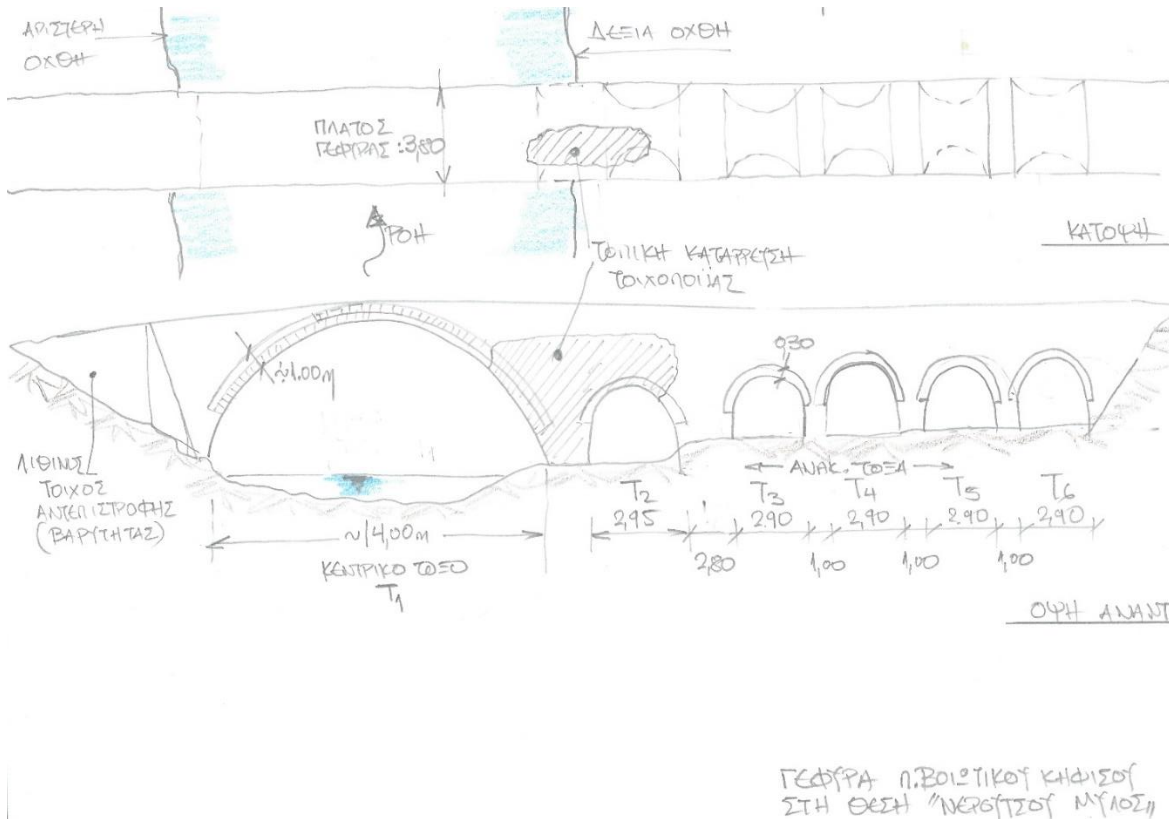
1. Arch bridge at Nerutsu Milos of Viotikos Kifissos

The stone bridge at Neroutsou Mylos site belongs to the Municipality of Amfikleia and was built in the period 1791-1792. It is used for the passage of wheeled vehicles and is now part of the secondary provincial network of the country. It is characterized by a central arch and five smaller relief arches of carved stonework with thin joints. A remarkable interlocking of the stones is observed, which are preserved in good condition. Problems have arisen mainly in the foundation of the pedestals (substructure components of piers). This fact was contributed to by the interventions carried out in the river bed which adversely affect the flow (change in flow characteristics) and which lead to washing away of the mortars of the pedestals at the bearing level of the arch.

It belongs to this particular category because of its geometry which lists 6 arches of stonework.

Overview of the bridge

Pathology of pedestals (base of piers)



Drawing of Façade

Source: First degree Pre-earthquake assessment for masonry Mouments of Structure Categories D3 and F4 (OASP-2019), Research team: I.Psycharis, J.Dourakopoulos, Chr.Giannelos, M.E.Dasiou, E.Toumpakari

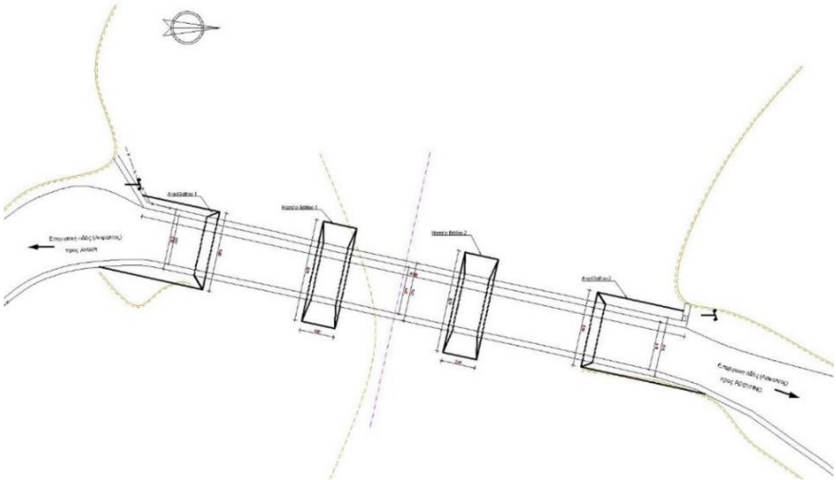
2. Sima bridge, Rethymno

The stone bridge was built in 1910 by the newly established Cretan State. It is an arch bridge with three openings, two piers founded on rocky ground, and two middle piers founded on the rocky bed of the stream. The arched openings reach 9.80 m length and 4.20 m arch height. The piers have a height, from the ground level to the base of the arches, which reaches 21.28m, giving the bridge a total height of 29.08m. The arches of the bridge are made of cut limestones. The piers are constructed in their outer part of irregular stone masonry, consisting of irregular stones with average size of 30-40 cm. The depth of the outer masonry layer was measured to be about 35 cm deep. Mortar with fine-grained aggregates less than 1 cm in diameter and coarse-grained aggregates up to 5 cm in diameter, was found inside the piers. The mortar is of the same composition as the joint mortar of the outer layer and it consists of pozzolanic materials to increase its strength and protect the piers from the water of the stream bed. During its restoration study, no problems were found regarding the bearing system. The only damages observed are related to the bad maintenance of the bridge, which resulted in spalling of the outer layer of joint mortar and the growth of vegetation on the body of the stone masonry.

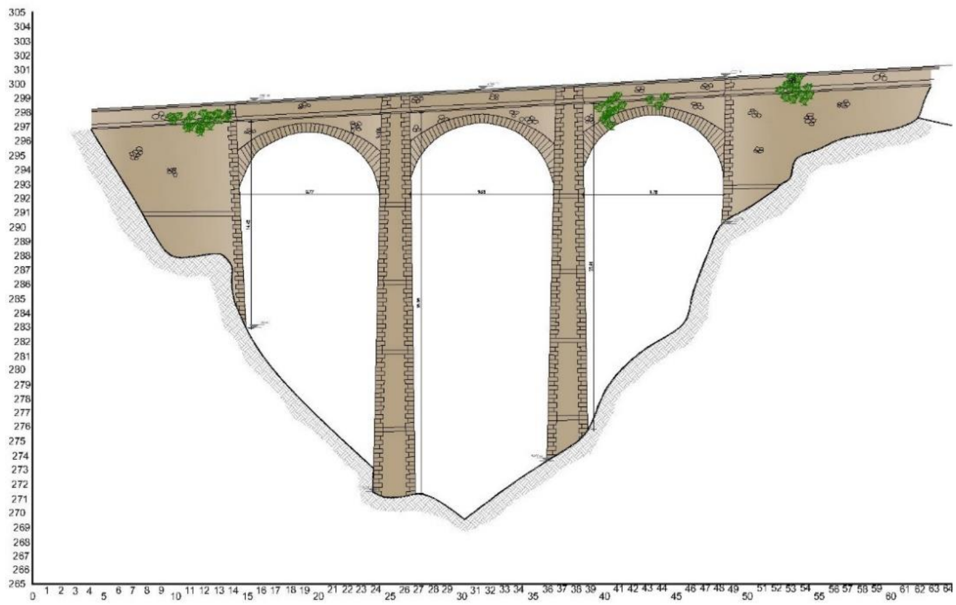
It belongs to construction category D due to its three arches.

Overview of the bridge (east view)

Southeast side of the bridge



Plan of the bridge's bearing system



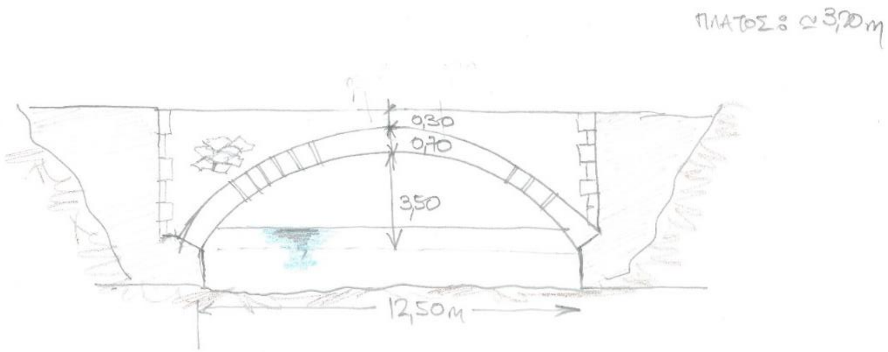
East side of the bridge (present condition)

Source: Structural Analysis. Civil Engineering Consultants Aris X. SMPC, (2019).

3. Arch bridge of the Neoclassical Period of Viotikos Kifissos River in Amfiklia - Elatia

The bridge of the Neoclassical Period of the ancient Boiotikos Kifisos belongs to the Municipality of Amfikleia-Elatia and was built in the 19th century. Today, the bridge is also used by heavy vehicles-trucks. It is a single-arched bridge with an arch lowered to facilitate the passage of wheeled vehicles and made of equal-sized tolite stones with excellent processing. The drums are made according to the polygonal structural system (honeycomb) and the corners of the wing walls are shaped with alternating corner stones. There is considerable interlocking of the good quality stones of the arch and the structural plaster in the interior is kept in good condition. Despite the fact that the main axis of the river flow is perpendicular to the direction of the bridge, no significant structural problems can be discerned.

It belongs to this category because of its arched geometry.



Drawing of Facade

(α)

 (β)

Overview of the bridge: (a) with raised water level, (b) in dry season

Overview of the bridge

Detail of pier and wing wall

Source: First degree Pre-earthquake assessment for masonry Mouments of Structura Categories D3 and F4 (OASP-2019), Research team: I.Psycharis, J.Dourakopoulos, Chr.Giannelos, M.E.Dasiou, E.Toumpakari

3.5 Category E

This category includes massive constructions, in which in which the wide thickness of walls, if compared to other dimensions, doesn't allow the idealization as plane structural element. Local failure occurs as, for example, the detachment of external leaf. Geotechnical aspects play as well important role.

3.5.1 Subcategory E.1: EARTH WALLS

CHARACTERISTIC PROJECTS OF SUBCATEGORY E.1

1. Mocenigo bastion, East Walls of Chania

Part of the Venetian fortifications of the City of Chania. It dates back to the end of the 16th century. During this period, the use of cannons had prevailed, with the result that the fortification walls were built with embankments, so that they could withstand the cannon fire.

The height of the walls reaches up to 10.80 m. The thickness of the masonry is equal to 2.00 m at the top and 5.50 m at the wall s' base.

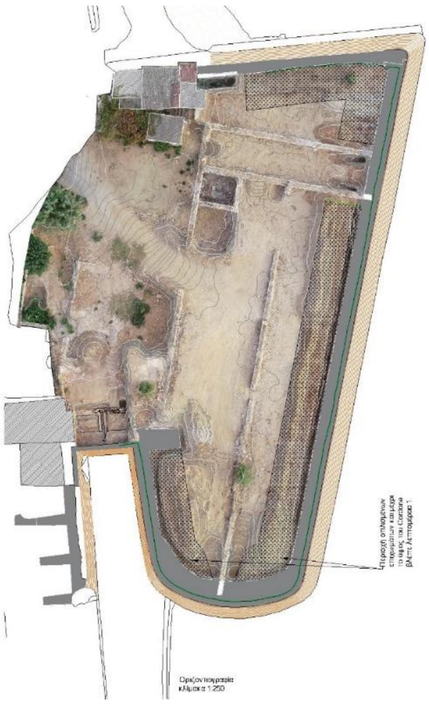
The construction is classified in category E due to its very large thickness, that reaches up to half of its height.

In addition, the cross-section of the walls consists of an outer layer of cut stones and a weaker inner layer of rubble masonry. These two layers are expected to behave differently in the event of an earthquake due to their stiffness difference.

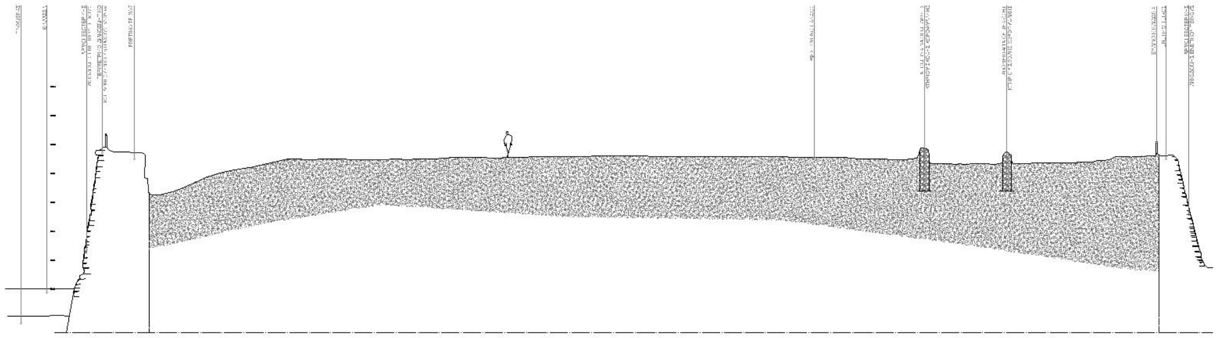
Landscape plan of the walls

Aerial photographs of the walls

South view of the walls



Wall top plan (existing condition)



Walls' section

Source: Structural Analysis. Civil Engineering Consultants Aris X. SMPC, (2021).

3.5.2 Subcategory E.2: WALLS OF LARGE THICKNESS (FREE STANDING WALLS)

CHARACTERISTIC PROJECTS OF SUBCATEGORY E.2

1. Kales castle, Ierapetra

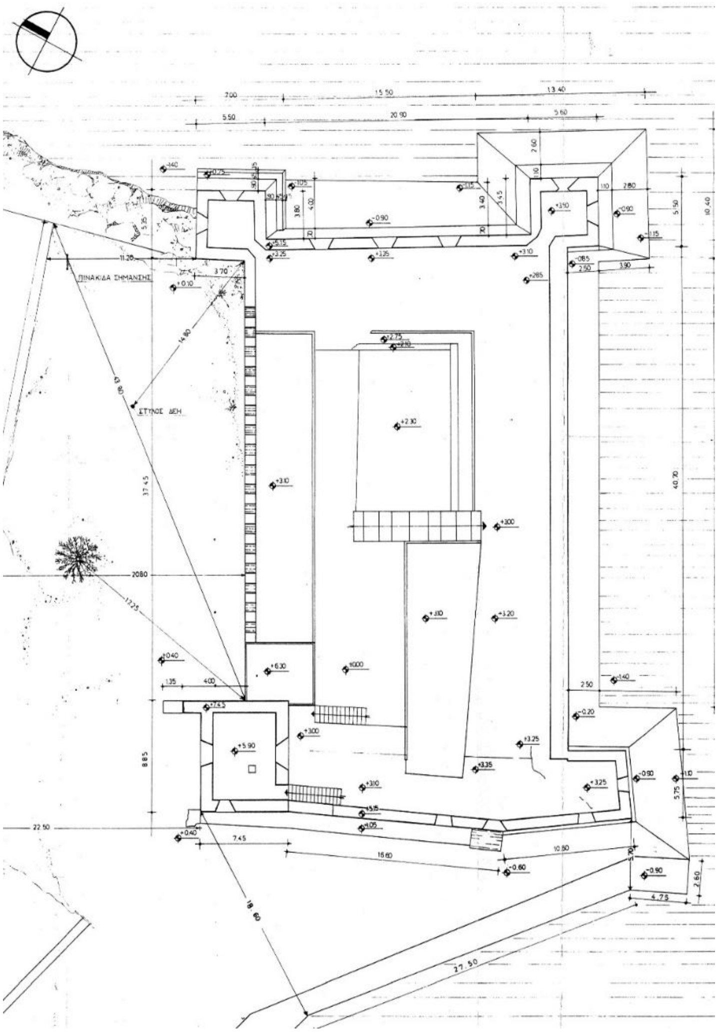
The castle was built by the Venetians and repaired after 1647 by the Ottomans in its current form. It belongs to the category of fortifications that were built prior to the prevalence of the use of cannons, as a result of which the walls are free-standing without having earth backfill.

The walls are made of semi-regular stone masonry.

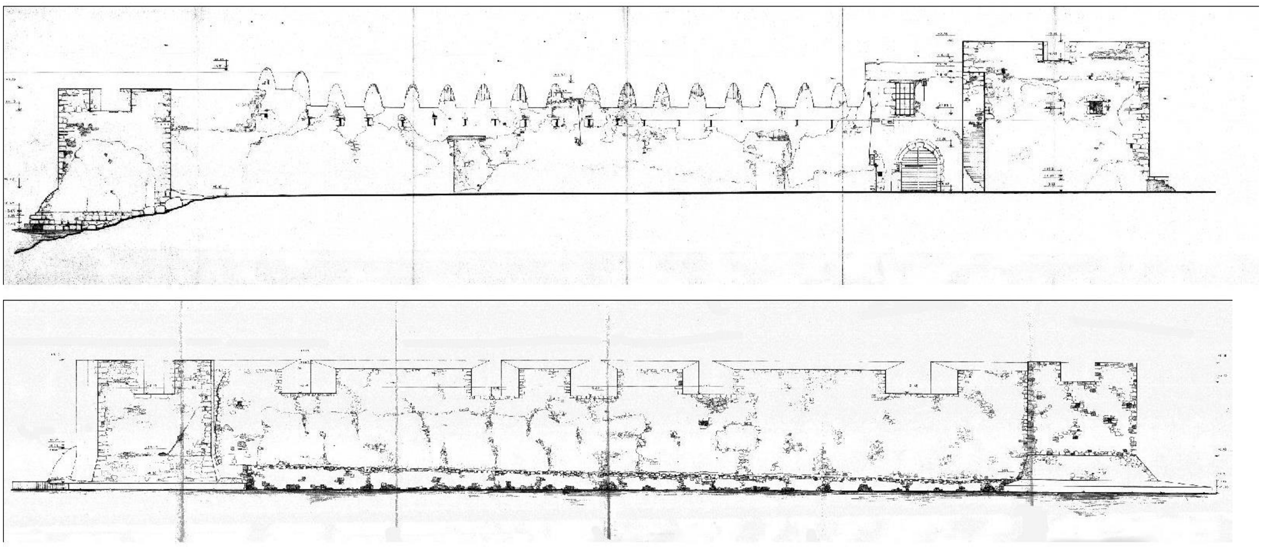
They have a total height of up to 7.40 m and a thickness of 1-1.40 m.

The thickness of the walls is considerable large in relation to the total height of the construction, as a result of which the construction is classified in category E.

Overview of the castle (north view)



Castle's top plan (before interventions)



Castle's views

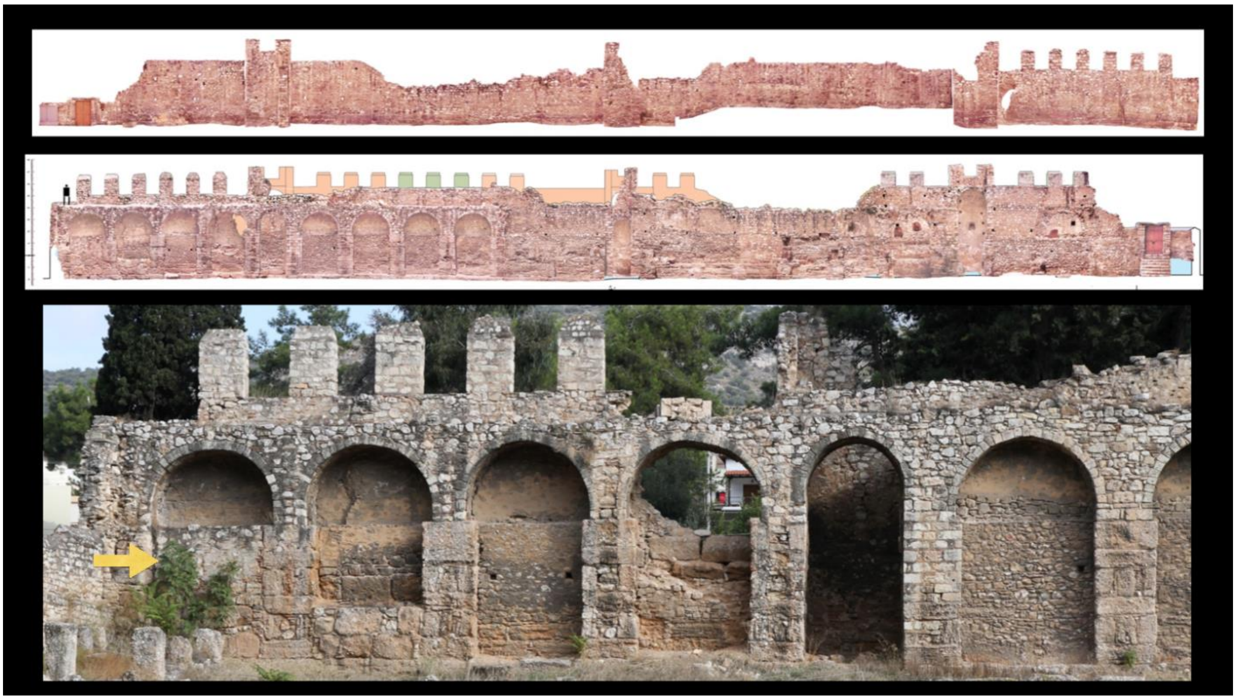
Source: Structural Analysis. A. Chatzidakis, (1992).

3.5.3 Subcategory E.3: WALLS WITH ABUTMENTS

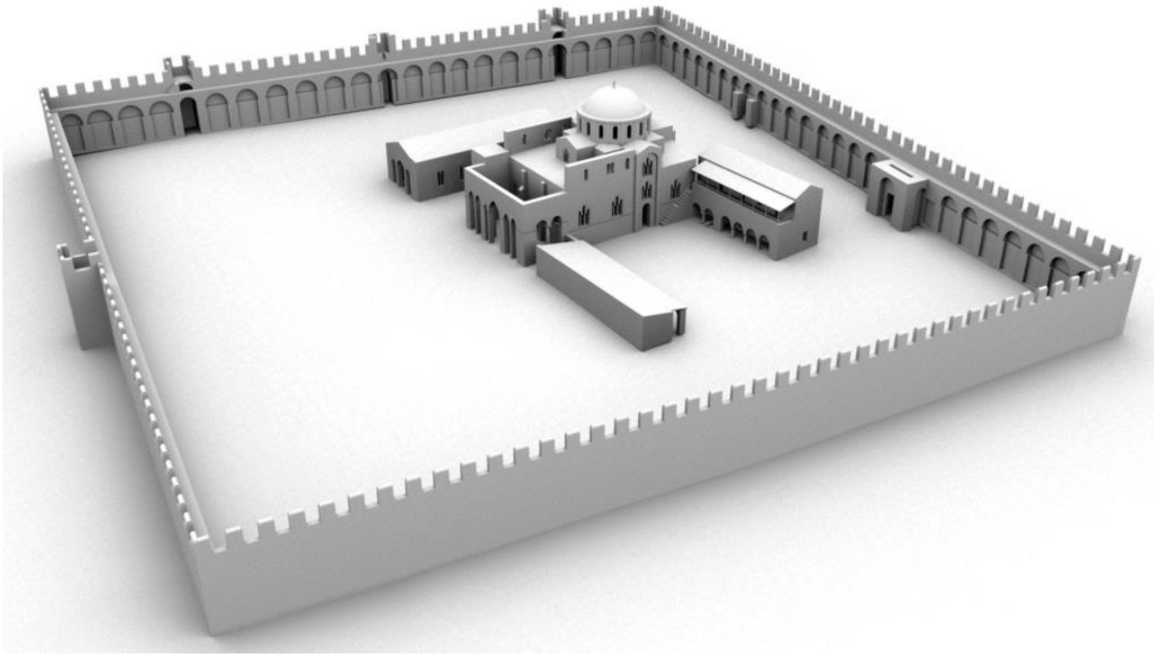
CHARACTERISTIC PROJECTS OF SUBCATEGORY E.3

1. Daphni Monastery's walls

The ruined rhombus-shaped (97.50 x 95.80 m.) Outer or Great Enclosure of the Daphni Monastery, is considered as a building of the 11th century. The strict symmetry of the layout of the two tower-shaped gates with transepts and double pillars and the small eastern gate, the continuous perimeter in blind apses, the limited use of square towers on the north side only, the peculiar original ramparts with semi-cylindrical crowning rather than pointed, the form of the grouting and the composition of the building mortar, reveal a unified design, particularly strict and with excellent application of the rules of fortification. Up to a certain height, large loose stone bricks were used, coming from a temple of the late Roman times, abundant lime mortar with red aggregates from the breaking of part of the large stone bricks, as well as horizontal and vertical bricks. After the use of the boulders that probably come from a building of pre-Christian centuries, the construction was completed with mud-brick construction with abundant mortar and interspersed bricks. The Great Enclosure, despite its strict geometric form and construction knowledge, was ruined to varying degrees after an earthquake in the 13th century. (as can be seen from the building phases of the Catholic) and it was not followed by a comprehensive and systematic restoration.
It is included in this category due to the presence of blind arches that act as buttresses.



Overview of the monument



In a three-dimensional representation of the great Perivolos and the Byzantine Bank, as it was in the 11th century. The Katholikon and the cell wings of the small enclosure are shown as restored after 2007 to convey the scale of the site. View from the SW.

Source: A.Miltiadou &N.Delinikolas. « The Historical Pathology of the Great Perivolos of the Daphni Monastery, a guide for understanding the damage of 1999 and the way to restore it ».

2. Acropolis Walls

The current form of the Acropolis Walls is the result of successive additions, reconstructions, repairs and other interventions.

From the 13th c. BC (Mycenaean period), the top of the Acropolis rock was surrounded by the Pelasgian Walls, which were built according to the cyclopean system and parts of which are still visible today in various places (e.g. southeast of the Propylae). This wall seems to have been preserved until 480 BC. when it suffered serious damage from the Persian raids. Then, and more specifically after the battle of Plataea (479 BC), the northern wall, also known as Themistokleion, was built employing laso parts of the pre-Parthenon and triglyphs, metopes, cornices of the ancient temple of Athena. Three decades later (467 BC) the southern and eastern wall of the Acropolis, also called Kimoneio, was erected. It has a different structure from the northern part, as it is built of rectangular porous stone plinths according to the isodomic system, combined with reused building material. Its external surface has suffered significant changes from the newer repairs that were sometimes investments in the ancient sections and sometimes completions of sections that had collapsed. Today, most of the ancient construction is preserved and only partially it has been supplemented by mudstone constructions during later repairs.

In the 3rd century AD, after the Heroulian raid, an additional fortification and two gates were built to the west of the Acropolis and below the Propylaia, of which the western one is the Beule gate. From that time the Acropolis was once again transformed into a fortress and retained this character until the 19th century. During the medieval period, in the 13th century, its southern wall was repaired and two new towers were built, one to the west of the Propylaea, which does not survive today, and one to the northeast, where the Belvedere is today. The most recent repairs to the wall were carried out after World War II, at its south-eastern corner.

Overview of the east Wall

South east corner of Wall

Source: M. Korres (2013) The walls of Acropolis. Presentation of the existing condition and proposals to deal with it (6th International Meeting on the Restoration of the Acropolis Monuments).

3.6 Category F

Single isolated constructions, which do not delimit an interior space are included here.

3.6.1 Subcategory F.1: FREE STANDING COLUMNS

In terms of geometrical configuration, the immense amount of various columns can be divided in three groups, as follows: a) Free-standing columns in ancient temples b) Free-standing columns in various ancient monuments (galley, gymnasiums, arenas, markets, ancient cities, atriums, fountains, sponsored monuments, etc.) and c) Free-standing columns in early-Christian monuments

It is known that the stability of the above-mentioned columns depends on the following factors:

(1) Their geometrical configuration, mainly in terms of their size and slenderness, the number of the drums and the presence or absence of dowels between them.

(2) Damages in their existing condition, such as drums shifts or breaks, cracks of the construction material, inclination to the vertical, imperfections relating to the contact surfaces between the drums, etc.

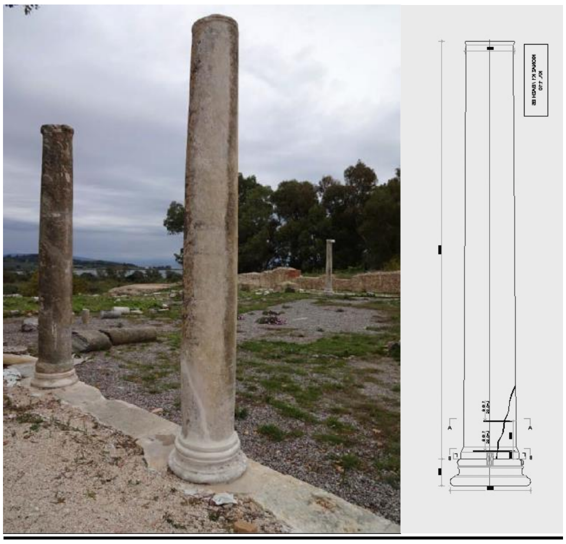
(3) The soil conditions and the general seismotectonic environment of the monument area that affect the characteristics of the ground motion of future earthquakes. It is known that free-standing columns are much more vulnerable to earthquakes containing long period pulses than to high frequency earthquakes. However, earthquakes with large dominant period may occur in locations near faults, or on soft ground.

CHARACTERISTIC PROJECTS OF SUBCATEGORY F.1

1. Peristyle of the domus of the Ekdikos Georgios in Nicopolis

The domus of the Ekdikos Georgios, as the magnificent building west of Basilica A is more rightly called –it was known up until now in the bibliography as the “Vasilospito”, the “Episkopeio” or “Bishop’s Palace” and more recently as the “Palace”– came partly to light during excavations by Alexandros Philadelpheus, carried out under the aegis of the Archaeological Society at Athens early in the second decade of the 20th century. The peristyle itself underwent a number of repairs and alterations. In the first building phase, the porch may have been Doric. In Late Antiquity it acquired an Ionic form, the result of makeshift interventions, repairs, and the collection of heterogeneous architectural members including column capitals and part of a white marble architrave, in addition to monolithic columns of the same material and of green-veined Karystian stone (cipollino verde).

The three restored monolithic Ionic columns have heights of 3.45-3.50m, lower diameters of 0.48-0.50m, slenderness of 6.73-7.20 and material marble. They belong to the specific category as free standing.



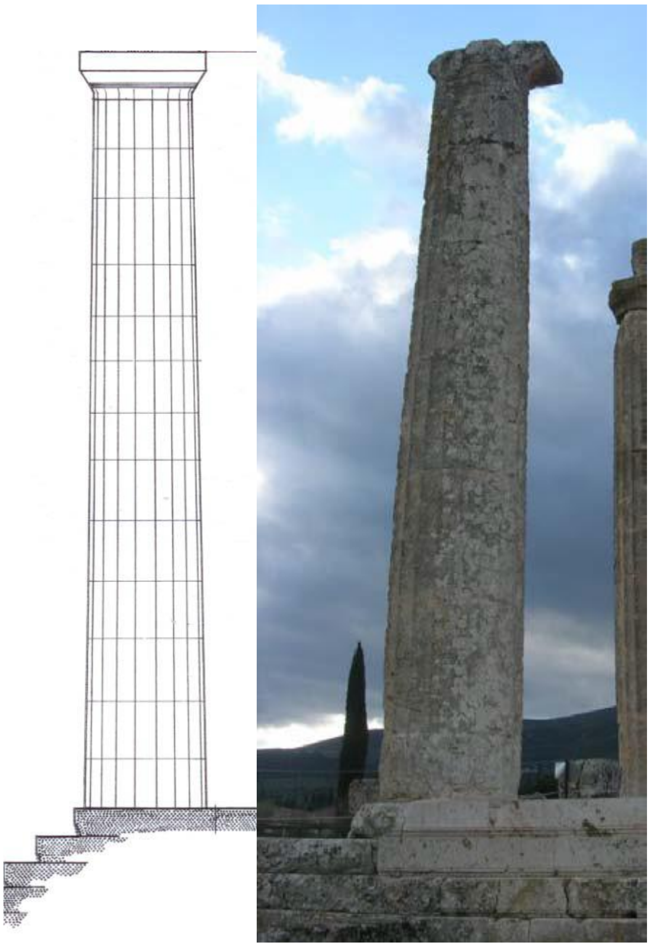
Overview and section drawing of the columns

Sources: Nicopolis. The Domus of the Ekdikos Georgios (2015) Evangelos A.Pavlidis-Ministry of Culture , Source: Pre-earthquake assessment of monuments (OASP-2016), Research group I.Psycharis, E.Delinikola, J.Dourakopoulos, A.Miltiadou, K Papantonopoulos, E.Toumpakari

2. Free standing column of the Sanctuary of Zeus in Nemea

The first temple of Nemean Zeus was built around the 6th century BC, along with the start of the Nemea games. The archaic temple was approximately 10.10X36.30 meters. It did not have a peristyle, while it had two columns on its eastern side, where also its entrance was. It had a two-column facade and a mortar floor, and it had a typical Corinthian roofing system with ceramic flat tiles. After its destruction, in the 4th century BC. it was decided to be rebuild on the foundations of the previous one. Thus, with dimensions of 20.09X42.55 meters, the temple had a pronaos with two columns on the facade, while the pillars were framed by the pilasters, the cella and the adyton. The temple was peripteral with a peristyle of 6X12 Doric style columns and a height of 7.49 meters. On its long sides it had 6 columns, while on its western side it had four.

Each of the large Doric columns of the peristyle consists of 13 cylindrical drums. One of them has an architrave and is free-standing, and its height including its base and capital reaches 10.36m. The diameter of the bearing surface of the lowest drum reaches 1.63m while the upper seat of the highest drum has a diameter of 1.31m. Their material is porolithos.



Overview and section drawing of the columns

Sources: Ministry of Culture and Sports, Pre-earthquake assessment of monuments (OASP-2016), Research group I.Psycharis, E.Delinikola, J.Dourakopoulos, A.Miltiadou, K Papantonopoulos, E.Toumpakari

3.6.2 Subcategory F.2: TRILITHES (MONOLITHIC COLUMNS WITH ARCHITRAVE)

CHARACTERISTIC PROJECTS OF SUBCATEGORY F.2

1. The temple of Aphaia, Aigina

It is the second temple that was built in this specific location and is preserved today, dates back to around 500-490 BC. It is made of tufa, with dimensions of 13.77 m by 28.81 m and has the same orientation as the earliest Doric temple built around 570-560 BC and destroyed by fire around 510 BC. The temple is a Doric peripteral, with a colonnade of 12 columns on the long and 6 on the narrow sides. The columns are monolithic with 20 ribs, except for three on the north side, which is built up of drums. The temple, which stands on a three-stepped crepis, presents the usual arrangement of pronaos, cella and opisthodomos. Both the pronaos and the opisthodomos are distyle in antis, while the cella is divided longitudinally by two rows of five columns each. A ramp of carefully cut stone rises to the crepis on the east side of the temple. The columns, cella walls and entablature were of local porous limestone, which was plastered and painted over. This category includes the two monolithic columns of the western side of the temple connected by an archway.

Overview of the monument

Sources: Ministry of Culture and Sports, Pre-earthquake assessment of monuments (OASP-2016), Research group I.Psycharis, E.Delinikola, J.Dourakopoulos, A.Miltiadou, K Papantonopoulos, E.Toumpakari

3.6.3 Subcategory F.3: FREE STANDING WALLS, OF SUFFICIENT HEIGHT, SURVIVING PARTS OF OLDER STANDING BUILDINGS

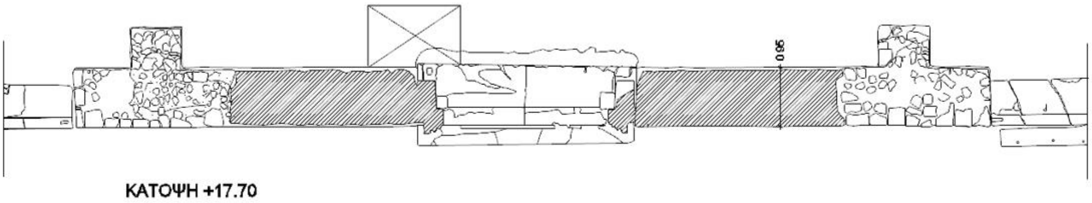
CHARACTERISTIC PROJECTS OF SUBCATEGORY F.3

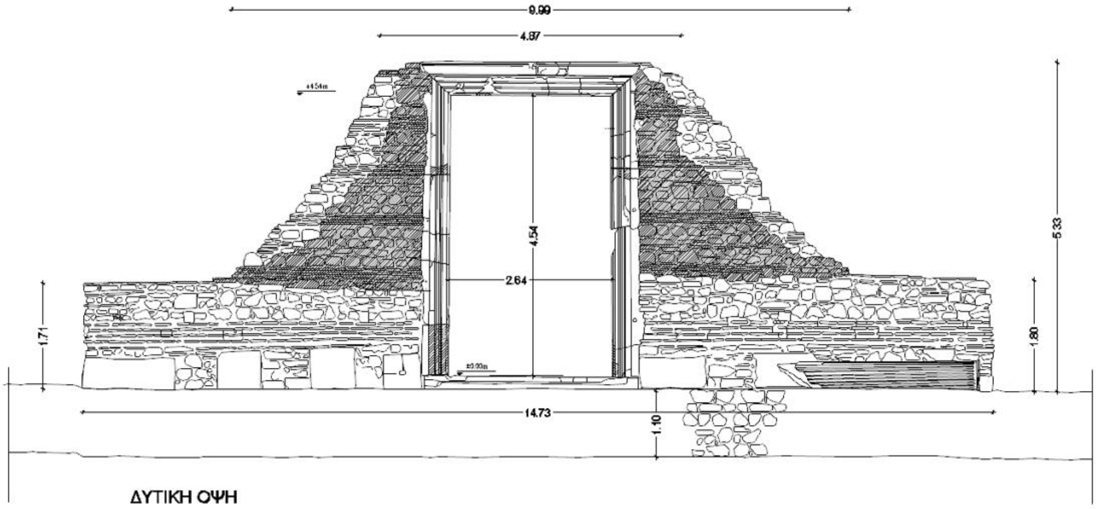
1. Alkisonos Gate, Nikopoli

The structural system of the monument refers to the restoration of Orlandou (1961 – 1964). The marble gate has a free opening of about 2.60 m and a free height of about 4.50 m. The walls on either side are about 0.95 m thick. The total length of the monument under consideration (width of gate and walls on either side) is about 14.70 m. Its total height is about 5.30 m.

The monument is classified as a free-standing wall at risk of out-of-plane flexural failure.

Overview of the monument





Top plan and view

Source: Imergency measures for stabilization– restoration of the Entrance Gate of the Central Aisle of Vasiliki II (Alkisonos) at the archaeological site of Nikopolis P.E. Preveza Region of Epirus (2020). Architectural study: I. Vombiri, Structural analysis: N. Psylla

3.6.4 Subcategory F.4: COLONNADES

CHARACTERISTIC PROJECTS OF SUBCATEGORY F.4

1. Zeus temple, Nemea

The first temple of Nemean Zeus was built around the 6th century BC. with the beginning of the Nemea games. The archaic temple was approximately 10.10X36.30 meters. It did not have a peristyle, while it had two columns on its eastern side, where its entrance was also located. It had a two-column facade, and a mortar floor, with a typical Corinthian roofing system with ceramic flat tiles. After its destruction, in the 4th century BC. it was decided to rebuild it on the foundations of the previous one. Thus, with dimensions of 20.09X42.55 meters, the temple had a pronaos with two columns on the facade, while the pillars were framed by the pilasters, the nave and the adyton. The temple was a pavilion with a peristyle of 6X12 Doric style columns and a height of 7.49 meters. On its long sides it had 6 columns, while on its western side it had four.

Contrary to what was presented in a previous paragraph for one of them, most of them are "connected" to each other due to the epistelium and are therefore classified in the category of columns.

Overview of the monument

Sources: Ministry of Culture and Sports, Pre-earthquake assessment of monuments (OASP-2016), Research group I.Psycharis, E.Delinikola, J.Dourakopoulos, A.Miltiadou, K Papantonopoulos, E.Toumpakari,

3.7 Category G

Historical centers, or other clusters of buildings made of ordinary historical and traditional buildings' aggregates. The seismic response of each building is affected by its connection with neighboring buildings and depends on whether or not the building has a common wall with them and whether or not it is connected to the other walls of the building.

3.7.1 Subcategory G.1: BUILDINGS WITH COMMON ADJACENT WALLS

CHARACTERISTIC PROJECTS OF SUBCATEGORY G.1

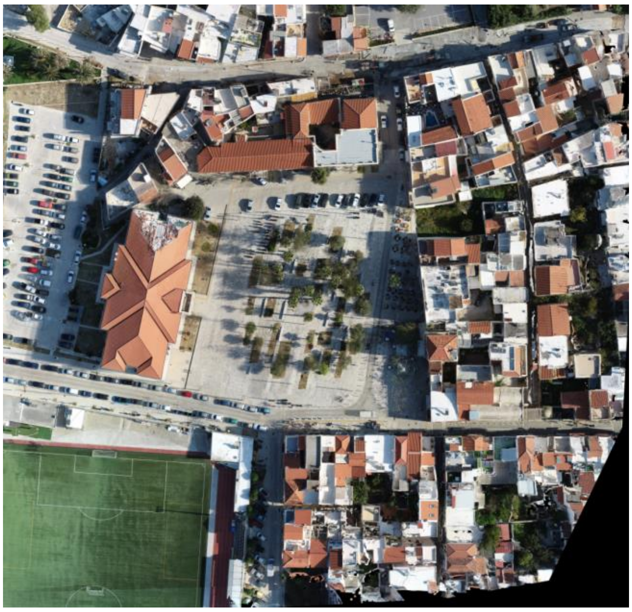
1. Rethymno Old Town

The Old Town of Rethymno dates back to the period of the Venetian rule, 13th-17th century. During the period of the Turkish occupation and the first years of liberation (early 20th century) modifications were made to the existing buildings and limited construction of new buildings. The buildings are, in the majority, constructed with stone masonry. The dominant building material is the local white limestone. In most buildings, the construction is made with irregular stones, while in the most important buildings (public buildings, churches, mansions), construction with cut stones is observed. During the period of the Turkish occupation, small interventions were made, mainly the addition of extensions to the buildings made of timber frames, the so-called sachnisi. During the 20th century, modifications were made to a series of buildings, with the addition of reinforced concrete slabs and balconies.

In terms of their urban planning, the buildings of the historic center are mainly blocks, in which each property has wall dividing it with the neighboring one. The existence of a partition wall, is due to the initial construction of each property in contact and connected with its neighbor one.

Aerial photograph of the Old Town of Rethymno

Plan of the city of Rethymno with the boundaries of the Old Town highlighted within the yellow border. Within the red circle is the Hrwwn Politechniou Square



Plan of the Hrwwn Politechniou Square. Individual building blocks can be distinguished, which in some cases form internal courtyards

Western view of buildings in the north-eastern part Hrwwn Politechniou Square. Four buildings can be distinguished as a continuous construction with partition walls.

Source: Establishing the ADRISEISMIC methodology for the reduction of seismic vulnerability, ADRISEISMIC Project

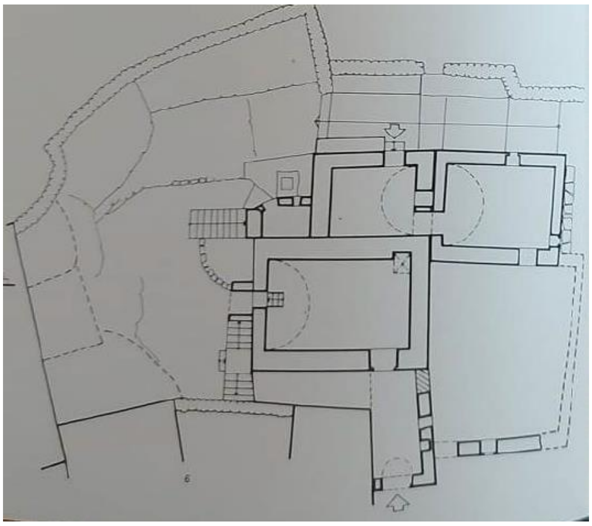
3.7.2 Subcategory G.2: STATICALLY INDEPENDENT BUILDINGS IN CONTACT

CHARACTERISTIC PROJECTS OF SUBCATEGORY G.2

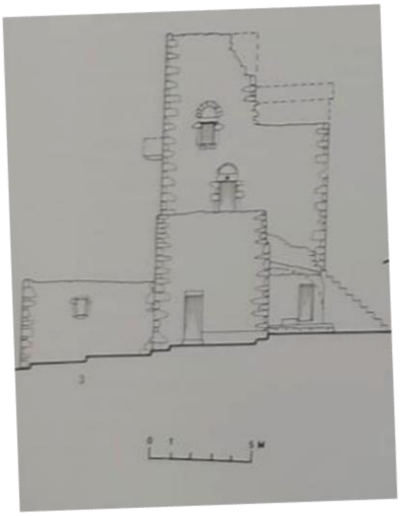
1. Four-storey tower house of Exarhakos with its secondary structures in Vathia Mani

The Vathia settlement in Mani is one of the most impressive tower cities in the country. It dates from the 18th century and is a densely structured building complex, where today about 70 tower houses are preserved. The development of the complex of the tower and its neighboring buildings (usually its lower in height **secondary** structures), is done by the construction of statically independent buildings using a double wall, or with Π-shaped buildings with walls not connected to the neighboring building.

Overview of the settlement



Floor plan of Exarhakos tower (in the center of the image) with its secondary structures. East: secondary structure in contact with the north secondary structure and the tower using a double wall, North: secondary structure in contact with the tower with walls not connected to it (Π-shaped)



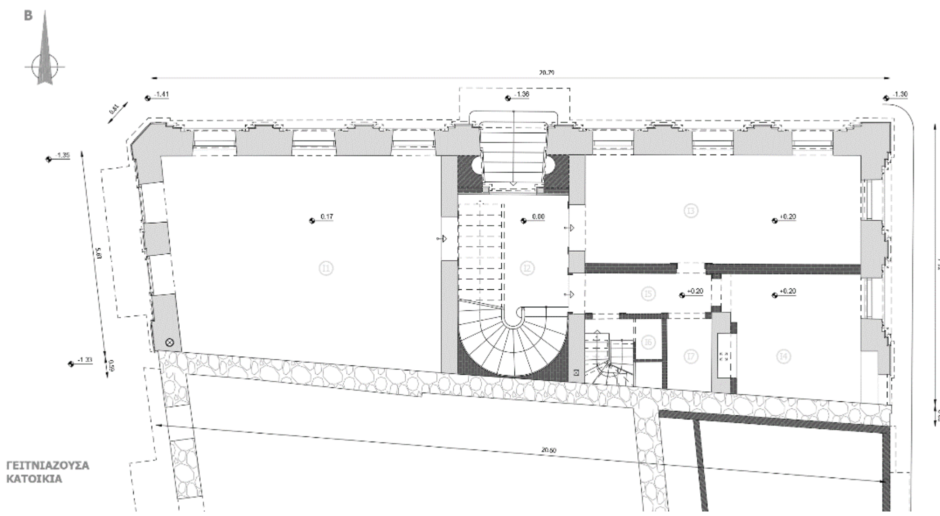
North view

Source: Greek Traditional Architecture, volume 5, p.182, ed. Melissa

2. Dokimaki residency, Samos

It is a two-storey house, neoclassical type, with a semi-basement, with the shape of a regular rectangular prism in plan and general dimensions of 11.7m. x (6.5 to 8.5 m). The residence was built in 1902 and adjoins to the south (intermediate wall), with a traditional building, prior to this one (1890). The load-bearing system of the building consists of a perimeter load-bearing stone masonry approximately 63 cm thick, as well as two 44 cm thick stone walls placed transversely, around the middle of the floor plan. It has timber floors and ceiling. The load-bearing walls of the north, east and west sides are well "tied" together (connection of masonry & steel ties), while the transverse load-bearing walls show little to no engagement with the south wall of the building. Thus, the "tied" Π-shaped circumferential load-bearing body appears to simply touch the intermediate wall.

Overview of the residency



Ground fool plan

Source: Design of the house of Dokimaki in Vathy Samos. Consultunt: Or. Kaklamanis

3.8 Category H

Archaeological sites consisting of ordinary masonry remains of small height which are mainly vulnerable to environmental threats other than earthquakes.

CHARACTERISTIC PROJECTS OF CATEGORY H

1. The Temple of Apollo Zoster in Vouliagmeni Attica

The first excavation in the area of ancient Zoster took place in Laimos in 1925-1927. This research led by K. Kourouniotis revealed a sanctuary with a small peripteral temple, altar and propylon. Based on the inscriptions found, the sanctuary was identified to the one of Apollon Zostiras. The monument of Apollo Zostiras consists of the Cella (main indoor space), which is a rectangular room with dimensions of 10.80mx6.00m, the Peristasis, which consists of 16 individual and statically independent columns as well as the Altar, which is located to the east of the temple. The cella is characterized by masonry, with an average thickness of 0.45m, which has a height of about 1.40m on the north side and 1.60 on the south.

It consists for the most part of rubble and semi regular porous limestone of Piraeus (Aktitis Lithos), bound together with lime mortar. An exception is the lower part, about 0.80m high (height of 2 layers of stones) of the northern surviving wall which corresponds to the polygonal building system, representative of the 5th-6th centenary. The masonry of the cella consists of two sides, of which the inner one is repaired for the most part with stones of various sizes, semi regular and enough lime mortar as a binding material. On this particular side, sporadic parts are observed, where the stones of the original construction are preserved without binding mortar around them. Today, from the 16 columns of the peristasis, drums and fragments of drums are preserved which can restore almost fully the fifteen columns. The columns lay on bases consisting of a plinth and lower layers of flattened stones combined with amounts of sand and gravel, that have formed into clumps over the years.

Overview of the monument

Source: I. Ntourakopoulos (2021). Structural Analysis of the Temple of Apollon Zostira

3.9 Category I

Underground structures, often constructed with the cut-and-cover procedure, or structures carved in soft bedrock or caves. In these particular structures the geotechnical aspect is of main importance.

3.9.1 Subcategory I.1: CAVE STRUCTURES

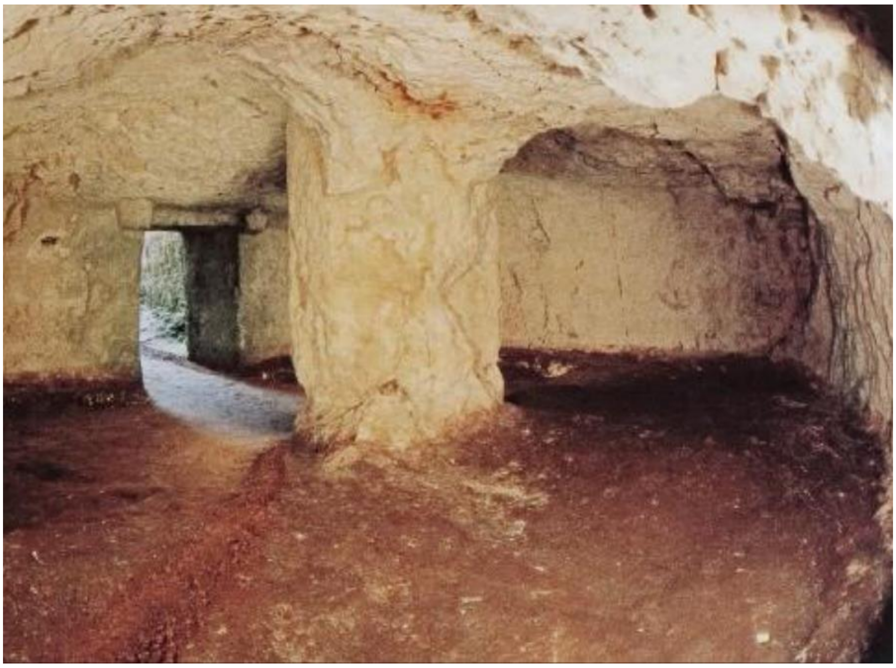
CHARACTERISTIC PROJECTS OF SUBCATEGORY I.1

1. Necropolis at Armenoi

The burial monument consists of 220 vaulted tombs carved into the soft rock in an east-west orientation. The tombs are accessed by a narrow corridor, also carved into the soft rock. The monument dates from the Late Minoan Period (14th - 12th century BC).

Overview of the tombs

Source http://odysseus.culture.gr/h/3/gh3562.jsp?obj_id=2570&mm_id=7778



Overview of tomb 24

Source: Fovakis, P. Th. Ganetsos, and N. Daskalakis. "Study and analyses of pigments in minoan larnax from the peripheral unit of Rethymnon (Crete) applying non-destructive techniques."

3.9.2 Subcategory I.2: CATACOMBS

CHARACTERISTIC PROJECTS OF SUBCATEGORY I.2

1. Catacombs of Milos

It is a complex of spacious halls and corridors carved into the soft porous volcanic rock (tuff). All of the graves were covered with slabs of different sizes. The catacombs of Milos were a community cemetery which, based on excavation findings carried out in 2007-2009, was in use from the 1st to the 7th century AD.

Overview of the monument

Overview of the entrance of the monument

Source: Marina Vogli (2017). "The catacombs of Milos: latest excavation data (2008-2009)". Archaeological Project in the Aegean Islands (Mytilini) B.: 497-508.

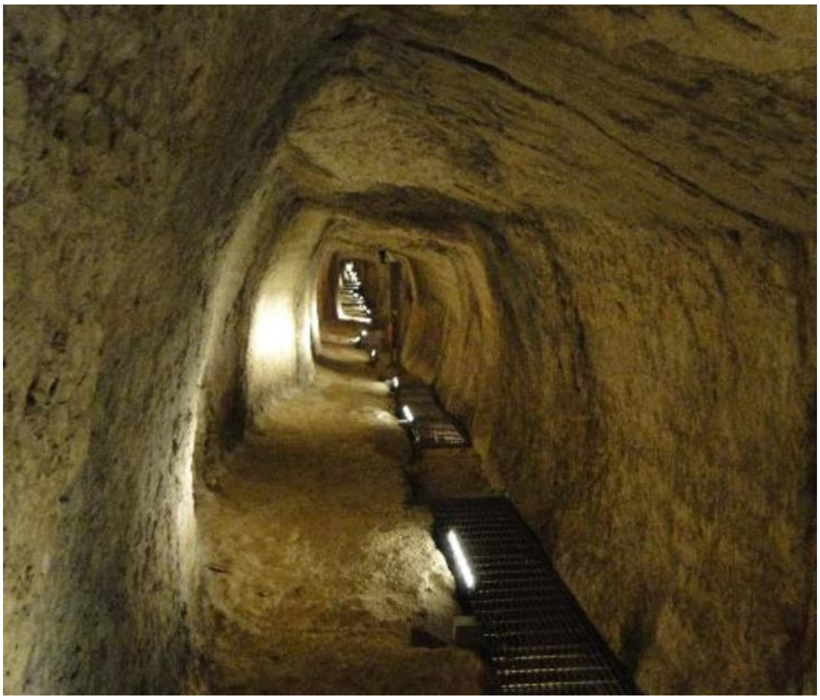
3.9.3 Subcategory I.3: TUNNELS

CHARACTERISTIC PROJECTS OF SUBCATEGORY I.3

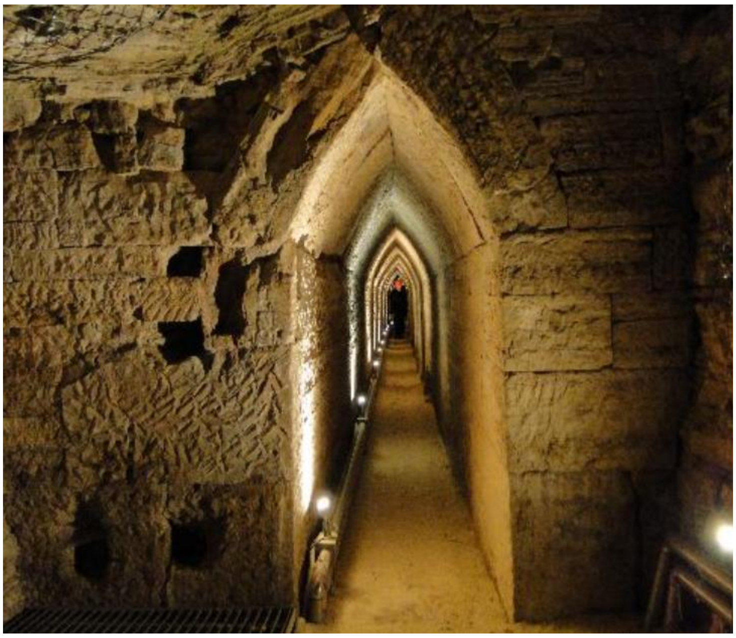
1. Eupalinian tunnel (aqueduct)

It is a water transport tunnel, which was opened in the hard limestone rock of the hill by carving, has a length of 1,036 m and average dimensions of 1.80 X 1.80 m. The walls of the tunnel were reinforced locally with stone masonry. The maximum depth from the top of the mountain is 180 m and the elevation from sea level is 55 m. It consists of a corridor and a trench, the depth of which varies from 3.80 m at the northern end, to 8,90 m at the southern end, with a slope of 0.6%, to facilitate the natural flow of water through earthen channels placed on its bottom. The water reached the reservoirs and fountains of the ancient city of Samos (present-day Pythagorion) through an underground urban aqueduct, which has been traced along the modern road, leading from the Eupalinian aqueduct to Pythagorion.

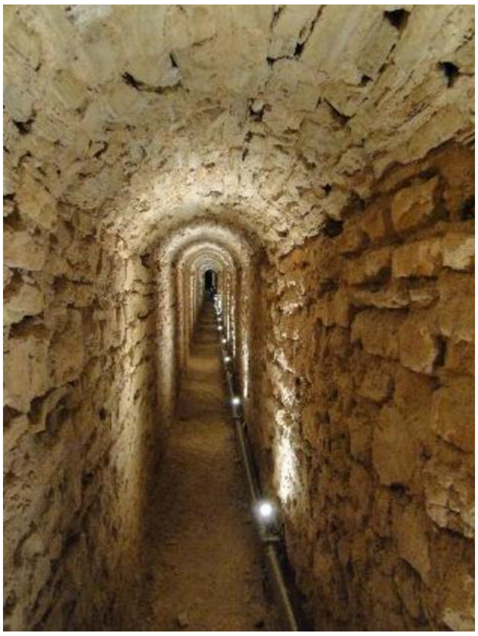
The work began around 550 BC. and took 8-10 years to complete. The excavation was done simultaneously from both faces of the hill, north and south, and the two construction crews met approximately in the middle of the tunnel with a slight deviation from the straight line. The aqueduct worked for 1100 years.



Indoor view of the trench

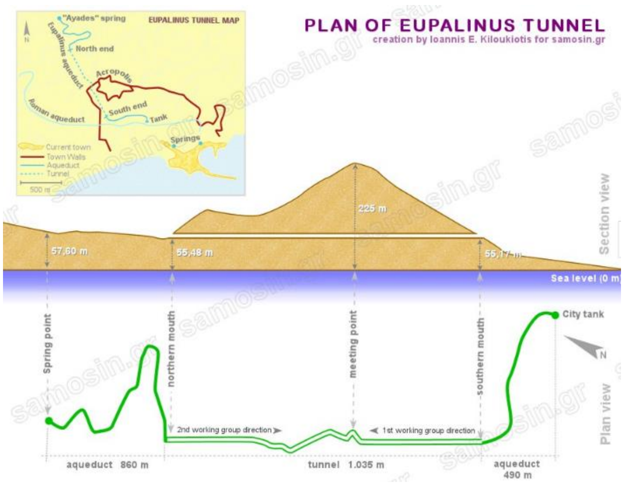


Archaic coating inside the trench

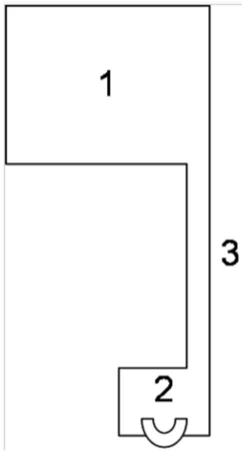


Roman period coating inside the trench

Source: http://odysseus.culture.gr/h/2/gh251.jsp?obj_id=818



Topographic representation of Eupalinian tunnel



Tunnel section: (1) Corridor, (2) Trench with earthen water pipes at its bottom and (3) Vertical trench
https://el.wikipedia.org/wiki/Ευπαλίνειο_όρυγμα

3.9.4 Subcategory I.4: TOMBS IN TUMULUS

CHARACTERISTIC PROJECTS OF SUBCATEGORY I.4

1. Kasta tomb

A burial monument dating back to the Hellenistic period. It includes a vaulted tomb made of cut stones.

Entrance of the burial monument

4 *Conclusions-Future research*

Within this study, the categorization of historical constructions was attempted based on the characteristics of their structural system, and primarily the geometry of their bearing system. The structures were categorized taking into account the common characteristics of their structural system, characteristics that determine their vulnerability and seismic behavior and, consequently, their expected **dominant** failure mode. It was attempted to present, as complete as possible, the usual construction systems of the historical constructions found in the Greek area.

It was found that future research is required that will concentrate in two main goals: a) to extent to all the proposed categories, the determination of the appropriate parameters that should be examined for a construction, with the aim of composing a reliable first-degree pre-earthquake assessment report according to the category in which belongs, and b) to prepare instructions and recommendations, as the necessary guidance to engineers for the selection of the appropriate methodology for the simulation and analysis of a construction, depending on the category in which it has been classified, in the next, more detailed, phase of the secondary, post-earthquake assessment.