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Study for the Restoration of the Walls of the Castle of Kalamata

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ABSTRACT

The presentation concerns the study for the strengthening and restoration of a part of the walls of the Castle of Kalamata, Greece. The castle of Kalamata, despite the continuous destruction and repairs it has undergone, still retains a typical medieval form, with the donjon and the cistern at its steepest point. The succession of the Franks, Byzantines, Turks, Venetians, Turks, Greeks, etc, makes it problematic to follow its structural phases. The object of this study is the investigation of the mechanical properties of building materials and the completion of the existing geotechnical investigation, a structural study to ensure the structural safety of the walls as well as measures for their strengthening, restoration and protection. The main intervention was the proposal for reinforced embankments replacing the existing ones behind the walls to diminish the actual earth pressure so that the existing thin walls can reach an adequate safety level.
Keywords: Fortification, retaining walls, reuse of fortifications

HISTORICAL BACKGROUND

The castle of Kalamata, despite the continuous destruction and repairs it undergone, still retains a typical medieval form, with the donjon and the cistern at its steepest point. The succession of the Franks, Byzantines, Turks, Venetians, Turks, Greeks, the partial destruction by Ibrahim Pasha of Egypt and finally the Italians make it problematic to follow the structural phases and especially the expediencies imposed. From a depiction of the Flemish D' Voornaamste we have the following image of the castle.

Figure 1.*Illustration of the Castle, D'Voornaamste, Amsterdam,1640*

Here the castle is designed with four corner towers and battlements of Ottoman typology. Obviously, the depiction is imaginary.

The thickness and cross-sections of the walls that we find do not suggest that they were designed to be filled in with soil until their coronation as they are today. During the reconquest of Kalamata by the

Venetians under Morosini in 1685, a representation of the battle was drawn by Coronelli in 1686. As is well known, Coronelli was named cosmographer of the Most Serene Republic of Venice and was commissioned to paint the victorious battles for Venice of the Venetian-Turkish War of 1684-1687. Since then, these paintings have undergone many re-editions on maps and travel chronicles.

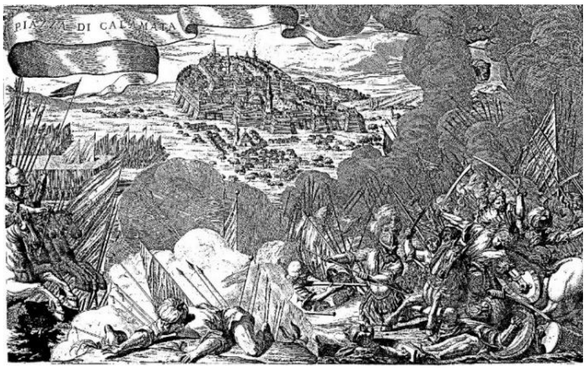

Figure 2. *Battle of Kalamata.The Castle at the backround, Coronelli, Venice,1686*

As we can see, Coronelli designed the castle full of buildings, with the walls not fully filled and with a multitude of external and internal buttresses. Of course, it is a serious question whether the illustration is true, even approximately, since the exaggeration is evident in it.

It is known that the Turks, while retreating from the castle, blew up the gunpowder warehouses, causing extensive damage to the fortifications. When the Venetians entered the castle, they demolished what was still standing so that it could not be used again by the Turks. Later, however, the Venetians repaired and expanded it by building the second tier, without neglecting to place the Lion of the Most Serene Republic at the gate. The reconstruction of the gate on the east side dates back to the second phase of the Venetian rule. It is known that the Venetians had a number of famous specialized military engineers and were the first to write Treatises on modern fortifications. They had understood the unique role of earth embankments in absorbing the energy of artillery bombs. They were aware of the earth pressure acting on the walls but they had no analytical calculations or scientific approach. They designed by experience and the rules of art. We have to wait almost one century for the famous Memoir of Coulomb.

The Dutchman Dapper, apparently copying Coronelli, publishes in 1688 the left illustration. Coronelli himself published in 1708 the right image.

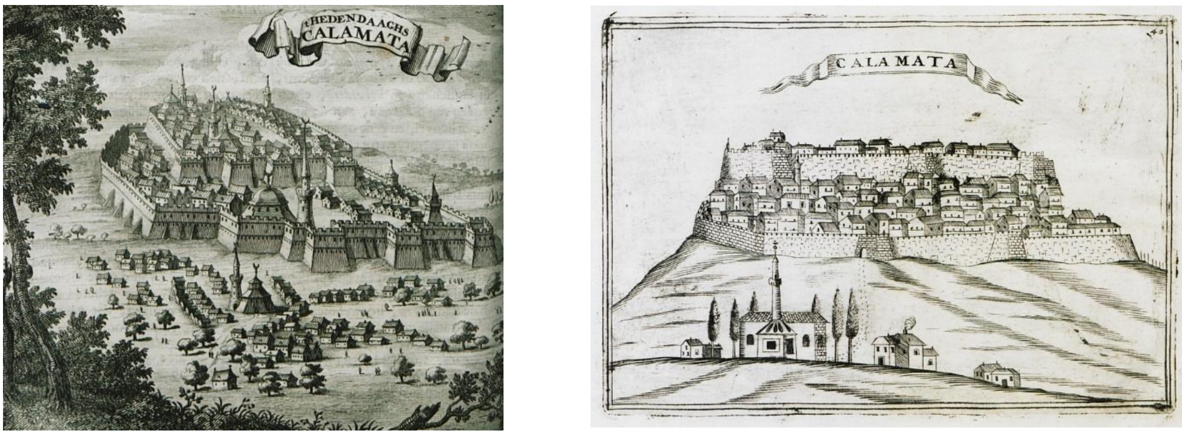

Figure 3. *Castle of Kalamata. Left drawing Dapper,1688. Right drawing* ***Coronelli****,1708.*

By this short review it becomes clear how little credibility can be given to the various depictions of the castle.

EXISTING STRUCTURE

The Castle of Kalamata consists of a fortified area of approximately 1.300m^2. The walls' height varies from 6 to 9 meters tall, while their thickness is approximately 1.6 meters. The walls do have a soil backfill for their entire length. The castle has several masonry Towers mainly on the south side.
The castle's walls, after many modifications and reconstructions, consist of the remains of medieval fortress architecture, probably at a height lower than they once had.
On the contrary, the maintenance of the perimeter in several places indicates that the height of the courtyard was lower. What we see today may have emerged during the period of the second Venetian occupation with hasty embankments in order to shield the walls against Turkish artillery.

The basic structure of the walls consists of an internal layer of rubble masonry from river rocks with a thickness of about 1.30 meters and a visible part of 0.30 m thick, initially perhaps of carved porous stone in many places, but after subsequent reconstructions, this layer may also be made of crude stones. As far as masonry's mortars are concerned, we have distinguished lime mortars in places, but it is possible that we originally had Pozzolan mortars during the Latin occupation. From the image we have of part of the base of the low wall that collapsed, it seems that a coherent mortar is preserved.
The general thickness of the walls is therefore 1.60 and the quality of the building due to rounded rubble stones is relatively poor. A greater thickness of around 2.0 meters was only seen in a part of the upper wall just after the buttress and just before the donjon. Only around the gates do we see a better quality of construction with large cornerstones, which is natural since the main effort of the attackers was focused on them.

Figure 4. *Site plan of the Castle*

PATHOLOGY

The thickness of the walls is generally insufficient for the current height of embankments, as it is concluded by the findings of this study. It is possible that in an earlier phase the levels of the fills were lower, since the initial construction was Byzantine-medieval. Therefore, cracking of the castle's walls is observed. Besides smaller cracks and partial collapses, there is extensive cracking and partial collapse at the base of the southeast low wallpart A). The walls appear extremely weak in this area, which is problematic since this area bears the small amphitheater of the castle, and is adjacent to the settlement at the base of the wall. This area is perhaps the most prone to collapse part of the castle. Even while the castle rests on a rocky background, the heights of fills made of loose materials make this section precarious.

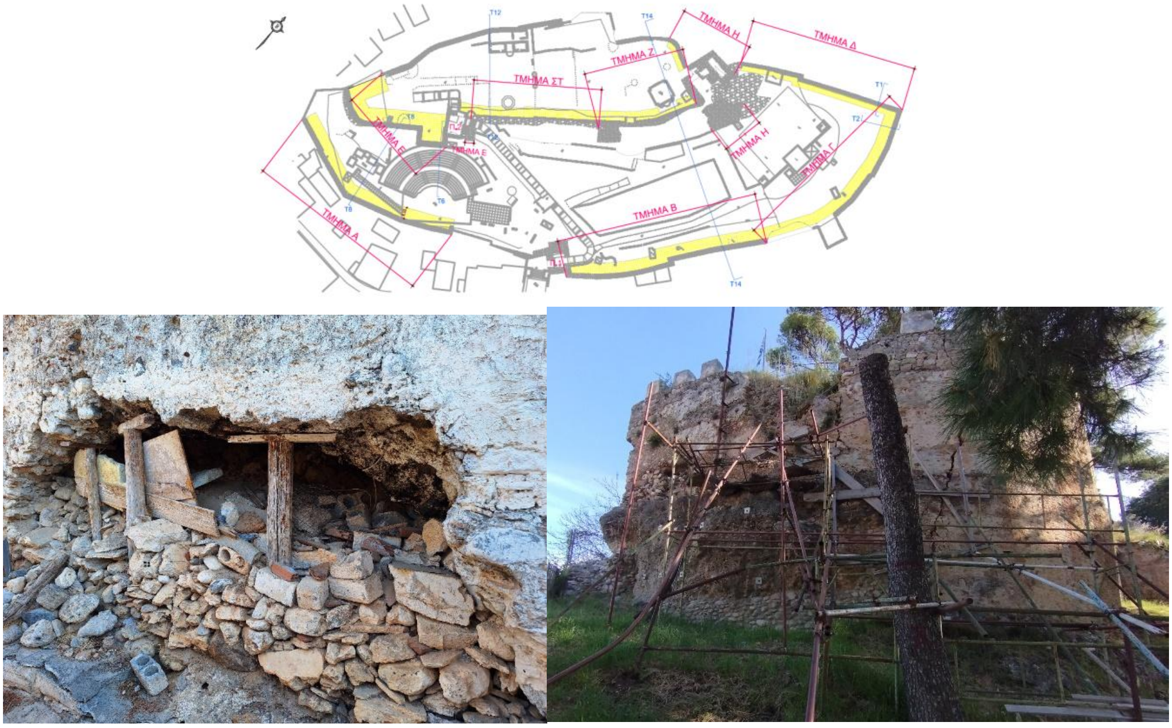

Figure 5. *Discretization of the Castle into parts. Partial collapse in part A and cracking in part E.*

The next major failure is the disorganization of the area in the southwest curved area of the upper wall (Part E), which has also received a retaining scaffold as a direct measure to avoid collapse.

MATERIALS RESEARCH

As far as the on-site research is concerned, rebound hammer test was carried out on characteristic types of stones from which we found two categories of strength level. The river rocks gave measurements between 40 and 50 and lime sandstone of the outer lining, which gave measurements between 25 and 30. As far as the lime sandstones of the external carved lining of the walls are concerned, samples were taken from stone elements that were on the ground and were not detached from the masonry.

Sampling for the mortar was done in a position where the calcium mortar was visible. A grain size analysis of the lime mortar was conducted. The results showed a poorly graded mortar with few fine grains (binder) and coarse aggregate. That indicates the mortar's low strength and poor quality. It was not possible to create laboratory specimen for the masonry mortar, due to its aforementioned low strength. Therefore, the mortar strength was taken by the values proposed by the Code for the Assessment and Structural Interventions of Masonry Structures (KADET 2022). The code proposes a value of 0.30 MPa for poor-quality lime mortars.
Regarding the stones, the average compressive strength of the two stone specimens taken is equal to 15.63 MPa.

This compressive strength is estimated by the equation proposed by KADET 2022:

$$f_{wc} = \xi \left[\left\{ \frac{2}{3} \sqrt{f_{bc}} - f_0 \right\} + \lambda f_{mc} \right]$$

The final value equals to:
Compressive strength fwc=1.71 MPa,
Modulus of Elasticity Ewc = 1000 fwc = 1.71 Gpa ,
Tensile strength fwt=fwc/10 = 0.17 MPa
The aforementioned strength was calculated for the wall masonry as a homogenous material. No distinction was made between the external layer and the rubble infill. The external layer’s thickness is very low compared to the rest of the masonry wall. Therefore, its contribution was considered, resulting in a conservative, relatively low, masonry strength.

GEOTECHNICAL PARAMETERS

A research program was carried out by the University of Patras in 2002: "Geotechnical investigation of the stability conditions of the slopes and the foundation of the walls of historical monuments and formulation of measures for the strengthening of their background, with application to the castle of Kalamata", (G.Koukis et al 2002.). Additional observations and measurements taken by G. Poutios, Associate Engineer, MSc and K. Provia, Geologist, associates of EDAFOS E.P.E. After these studies an extended program of stabilization interventions were undertaken to the founding rock of the Castle. The soil characteristics, derived from the experimental study cited before, is presented below.

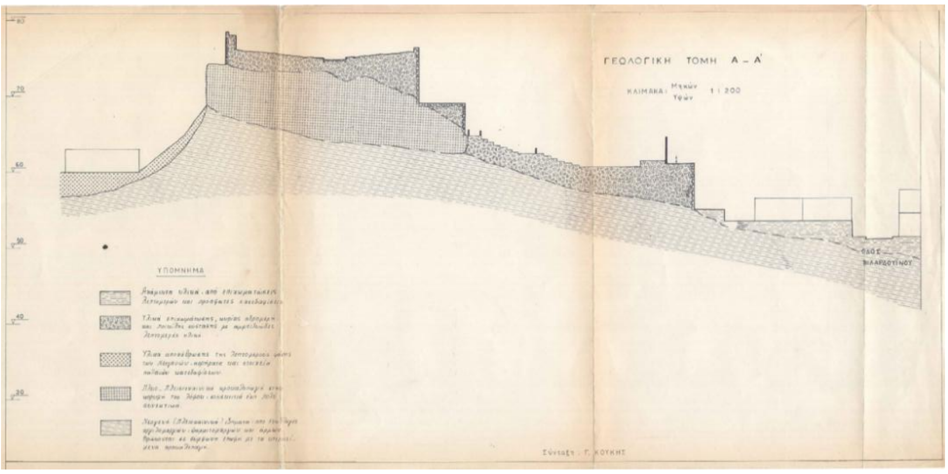

***Figure 6**. Geological section A-A' (G. Koukis et al 2002)*

The backfill soil of the walls, , consists of materials found on the area, mainly coarse and of varying composition, with sandy-silt material, detailed material (*G. Koukis et al 2002)*). The base of the walls, it is mainly consisted of semi-rocky background of Neogene sediments (Pliocene), with alternations between clay and sandstones, which are in contact with the overlying conglomerates. For this layer, due to lack of data, a maximum allowed soil bearing capacity value of 410 kPa was conservatively considered.

The following table presents the geotechnical parameters taken into account in the geotechnical analyses (*G. Koukis et al 2002)*:

***Table 1.** Geotechnical parameters of geotechnical analyses*

LAYER	Description	Apparent Weight (kN/m3)	Active coherence c (kPa)	Internal Friction Angle (O)
1	Existing-New backfill	18,50	3	30
2	Neogenous sediments	19,50	150	33

Regarding the loading conditions, due to the proposed placement of a waterproofing layer over the reinforced embankments, which will drain rainwater and lead it to perforated pipes, the analysis was carried out under drained conditions.

2D ANALYSIS

The analysis of the wall, using a two-dimensional model was carried out with FINE's GEO5 'MSE WALL' and 'Wall of Gravity' software. The geometry of the walls is analyzed according to DA-2 variant (Reduction of actions and resistances), Eurocode 7. Active pressure is calculated using the Coulomb method, while passive pressure is calculated using the Caquot-Kerisel method. The seismic loading was calculated according to the Mononobe-Okabe formula. Several cross-sections were chosen to be solved, with the most critical being the upper section of the wall of the T8 cross-section, where the highest height of supported ground is observed, approximately 7.50 meters.

The verifications (checks) carried out are (In this analysis the wall was considered as a solid body):

1. Overturning-Slip
2. Ground-bearing capacity of foundation and eccentricity
3. Geoenhancement strength and slip
4. Internal stability
5. Overall stability

The analysis of total stability was performed with the Limit Equilibrium Method using the Bishop strip method. The software calculates the failure cycle surface with the lowest safety factor. The total stability analyses were carried out using FINE's GEO 5 software and specifically the 'GEO 5-Slope Stability' program. The permanent design state follows Design Approach 3 (DA-3) and the seismic state follows Design Approach 2 of Eurocode 7.

Below, the results of a typical section of the walls is presented.

Table 2. *Results for section T8*

	Type of loads.	Overturning	Slipping	Eccentricity	Ground-bearing capacity	Reinf. slipping	Reinf. capacity	Pull-out resistance	Overall stability
Existing.	Stat.	161,8%	89,3%	177,7%	3414,6%	-	-	-	46,2%x 1,10=50,82%
	Earth.	217,8%	113,0%	362,5%	2439,0%	-	-	-	47,6%x 1,10=52,36%
After Interventions.	Stat.	18,3%	33,8%	13,5%	66,2%	25,3%	78,2%	48,2%	46,2%x 1,10=50,82%
	Earth.	37,9%	63,1%	51,7%	45,8%	25,8%	47,8%	64,9%	47,6%x 1,10=52,36%

The analysis highlights the weakness of the walls before the proposed interventions with reinforced embankments, since they do not meet the safety standards against tipping and slipping, as well as the restrictions of eccentricity and load-bearing capacity of the ground. After the strengthening proposals (presented in detail below), the stability of the walls is guaranteed.

3D ANALYSIS

A supplementary 3d analysis was carried out to ensure the wall's structural integrity. The simulation of the load-bearing system was carried out using SOFISTIK's SSD finite element software,. The walls are 1.60 m thick, while the tower is 1-1.50 m thick. Because of these, the simulation was executed using 6 node-solid (brick) elements. In terms of boundary conditions, the base was considered a hinge due to the bearing of the wall and towers in rocky subsoil.

The simulated section is section E, which includes a wall section and one tower. The geometry simulated is the one after the reconstruction-completion of the missing parts of the wall. Only section E was studied, as this was the most sensitive area based on geotechnical analyses. At the edges of the FE model, where the modeling of the wall was interrupted, a joint was installed to limit the movements parallel to the wall..

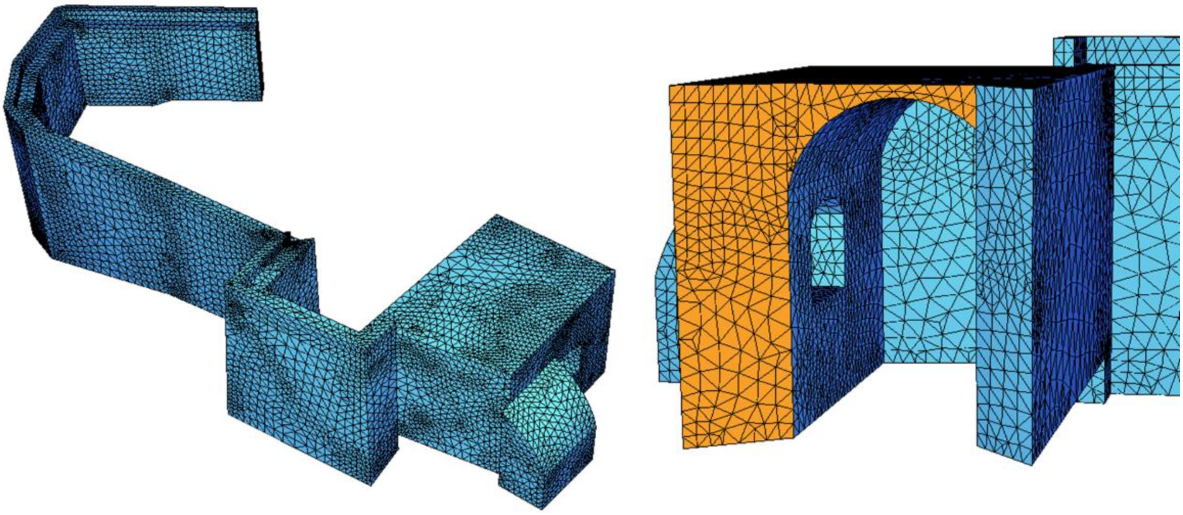

***Figure 7**. Finite element model of Part E*

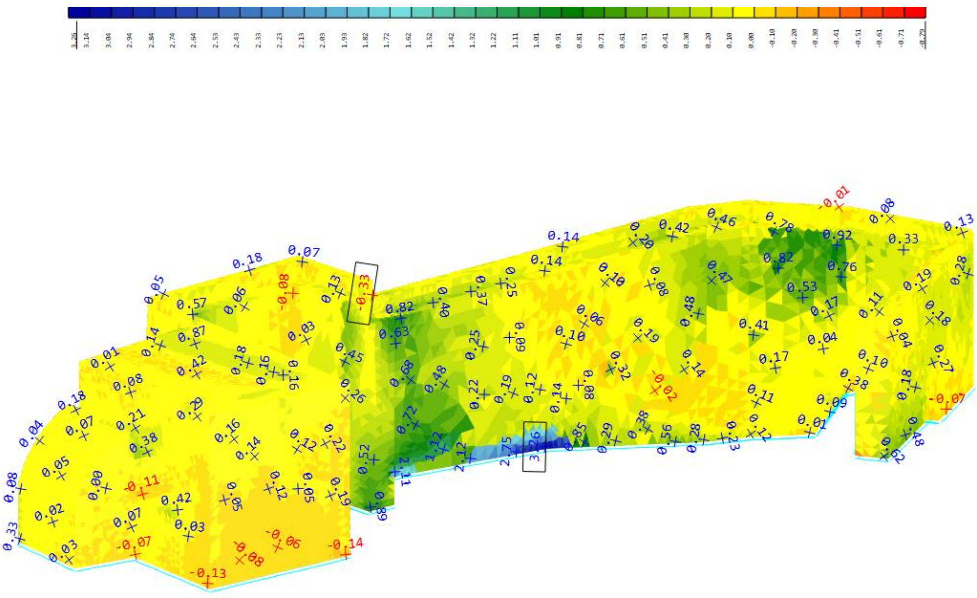

***Figure 8**. Principal stress σ_I for earthquake* -0.3Ex-Ey in MPa

In Figure 8 tensile stresses greater than the tensile strength of masonry (0.17 MPa) are observed. Therefore, it is expected for the walls to sustain damage and cracking during the earthquake. Due to the limited area where stresses exceed 0.17 MPa, it is concluded that the structure is going to undergo damage, without risking overall collapse though.

Strengthening proposals

The proposed intervention for the walls of the castle so that they become structurally safe, is the construction of reinforced embankments, replacing part of the wall's infill. The material of the excavations for the creation of the reinforced embankments will be checked for compliance with the specifications of at least category E2, so that it can be reused. Otherwise, the material of the embankments will be mixed with quarry material which will be of category E2 or better. The geogrid that was chosen to reinforce the embankments has a characteristic strength in the main direction of 301 KN/m. A geogrid of relatively high strength was chosen in order to have the smallest possible volume of excavations due to the difficulty of access to several parts of the castle. The selection of the aforementioned reinforcements was taken after the findings of the wall's 2D analysis. The embankments will be constructed in accordance with ELOT TS 1501-02-07-04-00:2009 and ETEP 02-07-01-00. For the process of construction-condensation of the embankments, the following are briefly mentioned:

To achieve the required degree of compaction, the laying should be done in continuous layers of equal thickness. The granulometric gradation specified by the materials mentioned above should be applied, and any oversized grains should be removed before compaction. Appropriate equipment should be selected and, based on its specifications the number of passages required, the desired condensation should be determined.

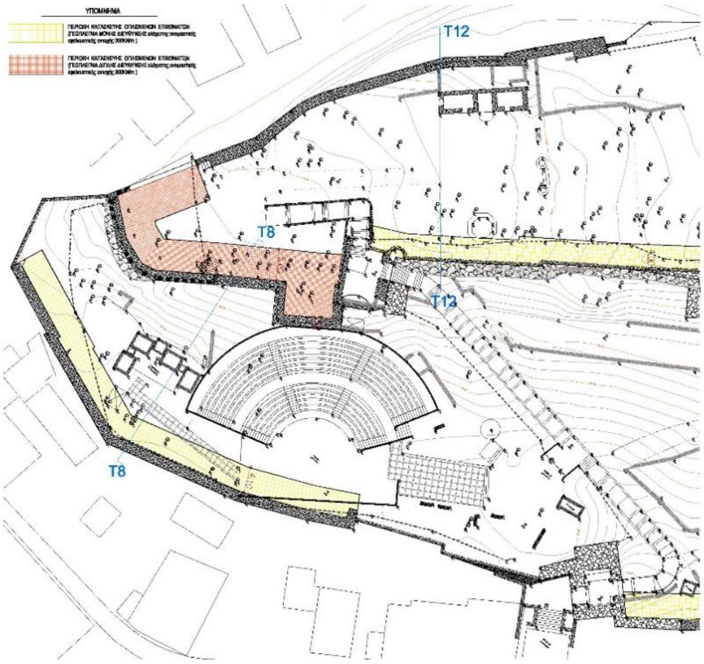

***Figure 8**. Zones of reinforced embankments*

The required compaction of the embankments must ensure a minimum dry apparent density of at least equal to 90% of the maximum density achieved at the modified Proctor compaction test.

The tensile strength of the geogrids (indicatively mentioned for Tult = 301kN/m) was taken in accordance with the American Regulations and refers to a type of Maccaferri Paralink 300 geogrid.

For the complete application of geogrid systems, waterproofing membrane (PVC-P or HDPE) is also required, the installation and specifications of which will be in accordance with ELOT TS 1501-08-05-03-04:2009 and geotextiles weighing at least 200gr/m2, according to ELOT TS 1501-08-03-03-00:2009.

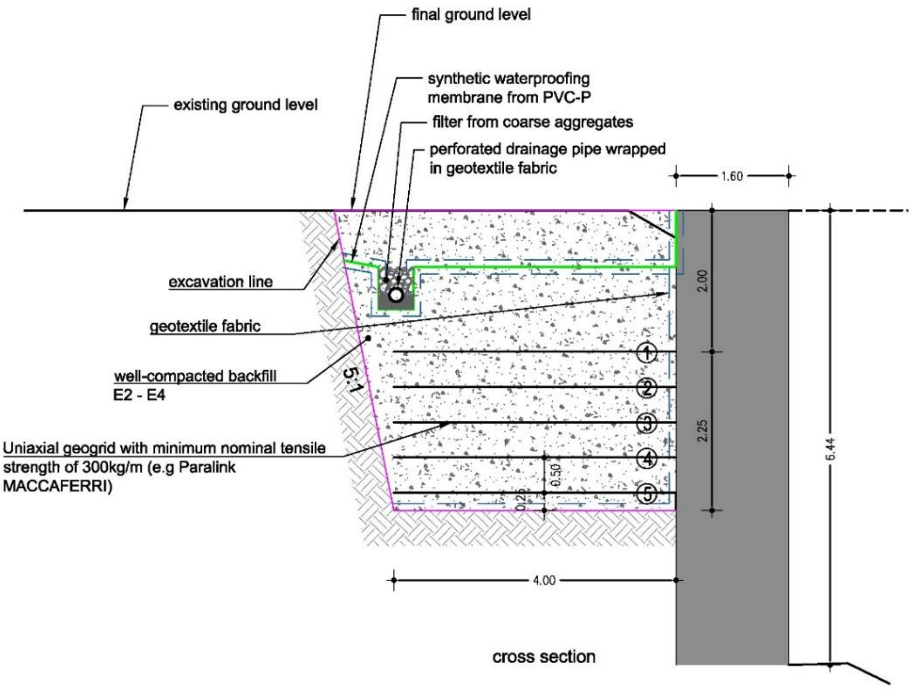

Figure 9*. Typical wall section including the proposed interventions*

CONCLUSIONS

The evolution of artillery made the Medieval fortifications unable to resist the power of new canons. This was the main reason for the development of Bastioned system with large earth embankments to resist the bombardment. In such a case, the Castle of Kalamata underwent a series of interventions through the centuries, increasing the lateral loading of the walls and, thus resulting into extensive cracking and partial collapsing of segments of the wall. An analytical survey was conducted in order to verify the level of the existing structural safety. Afterwards the design of a series of interventions was done, in order to ensure the safety level required by the Regulation.

REFERENCES

Geotechnical investigation of the stability conditions of the slopes and the foundation of the walls of historical monuments and formulation of measures for the strengthening of their background, with application to the castle of Kalamata, G. Koukis et al.

Additional observations and measurements taken by G. Poutios, Associate Engineer, MSc and K. Provia, Geologist, associates of EDAFOS E.P.E.

Code for the Assessment and Structural Interventions of Masonry Structures (KADET 2022).

ACKNOWLEDGEMENTS

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