# Finite Element Analysis of the Seismic Performance of a Historical Masonary Cistern

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**SUMMARY:**
This paper presents the results of numerical study carried out to assess the seismic performance of the Pantokrator Cistern in Istanbul and proposes a strategy for its structural retrofit. Detailed structural and architectural site investigations were performed in order to determine the structural weaknesses of the cistern. Inspection of the existing structure revealed two main problems, which were the missing wooden ties that connected the buttresses and the excessive roof loads from irregular infill. Afterwards, a retrofit strategy was developed based on the existing structural problems. Seismic response of the cistern was assessed using a refined linear, 3D structural model of the structure developed with ANSYS. An additional numerical analysis has been conducted in order to evaluate the effects of a mosque, which was indicated by architectural historians to be supported on the vaults of the cistern since recent years, to be possibly reconstructed on the roof of the cistern.

*Keywords: Masonry Structures, Finite Element Analysis*

## 1. INTRODUCTION

In recent years, a great amount of work has been carried out on the structural rehabilitation of ancient cultural heritage structures in Turkey [1]. The ancient cisterns of Istanbul are a part of the prestigious heritage structures which constituted a major part of the hydraulic works to supply the old metropolis. The Pantokrator Cistern, one of the several hundred ancient cisterns that lie beneath the city of Istanbul, is located in the Molla Zeyrek District in the immediate vicinity of Golden Horn on the steep slope towards the Zeyrek Mosque (The Pantokrator Church). The cistern was built in the 12th Century by Ioannes Komnemos the 2nd, the Byzantine Emperor.

Its structural system consists of unreinforced masonry (URM) walls. The roof system consists of cross masonry vaults which are supported by URM buttresses. These buttresses are connected to each other by timber ties. Material used in the masonry walls and buttresses consists of shallow solid bricks, stone and lime mortar for joints, representing the construction technique used in that century.

During the structural and architectural site investigations of the Pantokrator Cistern within the scope of a restoration according to the Turkish Cultural and Natural Heritage Protection Act 2863, some structural weaknesses such as material flaws, cracking, and inappropriate interventions have been observed. In the following sections, structural issues encountered during current repair and retrofit works of the Pantokrator Cistern are presented.

## 2. STRUCTURAL SYSTEM OF THE PANTOKRATOR CISTERN

The Pantokrator Cistern is a single story, multi-bay (in both directions) masonry structure. The dimensions of the cistern in plan are approximately 60.70 m by 25.29 m, and its height varies from 9.85 m to 10.14 m (Figure 2). Thickness of the outer walls of the cistern facing east (Unkapani Street) and west varies between 3.95 m and 4.50 m, whereas the thickness of the outer wall facing north and south varies from 2.80 m to 3.25 m. Although the thickness of the outer walls facing east and west is nearly constant, there are buttresses outside the outer walls facing east and inside the outer walls facing west. Buttress spacing is approximately 4.50 m and the depths of the buttresses vary between 1.20 m and 1.35 m.

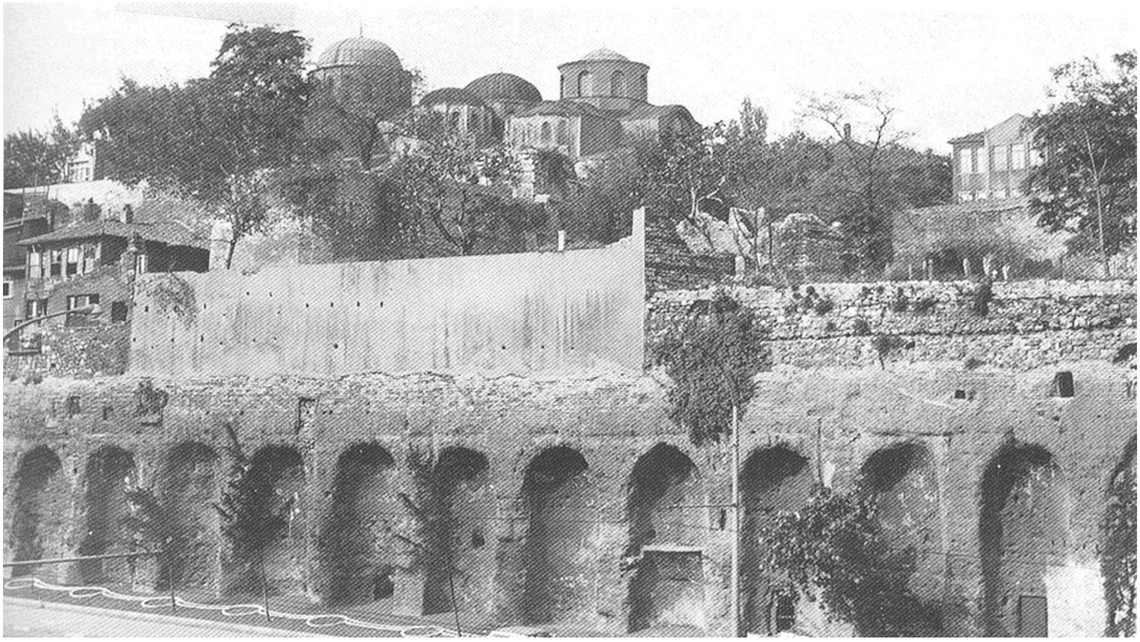

**Figure 1**. View of the cistern from Unkapani street

The perimeter walls are made of bricks, which are 34 ~ 35 cm long and 3.8 ~ 4 cm thick, with 3.5 ~ 6 cm thick joints. Of particular interest is the arrangement of the niches applied in order to save material: The east wall is relieved with niches, but the sole is bricked in full width, so that in an empty and not vaulted reservoir, the ground under the wall foundations at the outer side is subjected to a lower pressure through the wall weight than on the inside. In this way, the effect of water pressure and arch thrust, which exert a great pressure on the ground under the outer side, was partially compensated.

Vertical structural members at the inner section of the cistern are aligned to a regular grid system, which consists of 2 gridlines parallel to the outer walls facing east and west and 12 gridlines which are parallel to the outer walls facing south and north. Grid spacing parallel to the outer walls facing east and west are 5.00 m, 6.25 m and 4.50 m, whereas the grid spacing parallel to the outer walls facing north and south are 3.35 m, 4.30 m, 4.30 m, 4.50 m, 4.30 m, 4.50 m, 4.00 m, 4.30 m, 4.50 m, 4.50 m, 4.30 m, 3.75 m and 2.00 m.

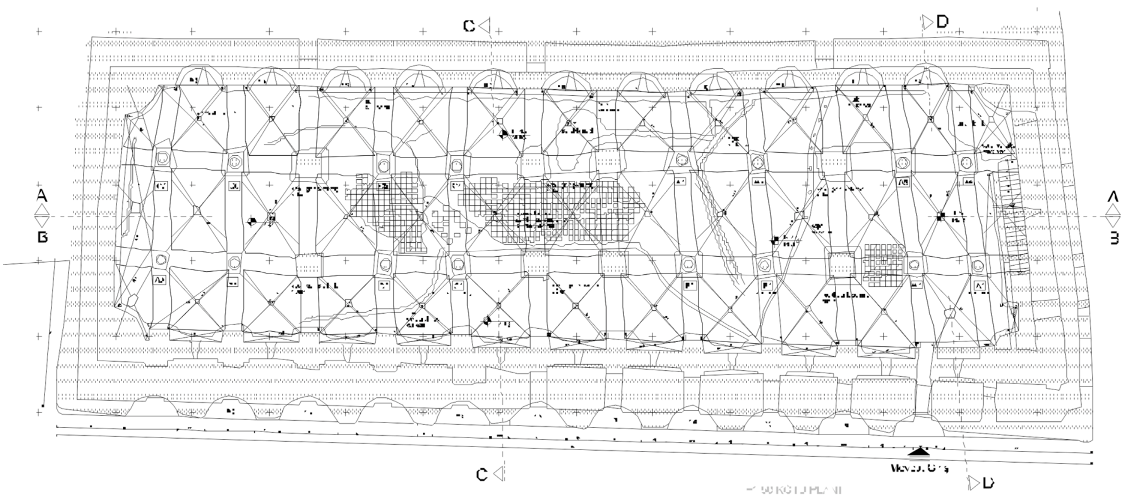

**Figure 2**. Plan layout of the cistern (at elevation +1.5 m)

Sixteen of the vertical structural members are circular columns having a diameter of 50 cm. Sections of the other eight masonry columns were later enlarged to have the dimensions of 1.45 m x 1.45 m. Height of the columns (up to the elevation of the tension rods) are in the order of 6.80 m to 6.90 m. Roof cover of the cistern has the plan dimensions of 4.50 m ~ 6.25 m by 2.00 m ~ 4.50 m and the thickness of the groin vault roof is 40 cm. There are galleries which surround the structure at the elevation of +7.87 m ~ +8.13 m (Figure 3).

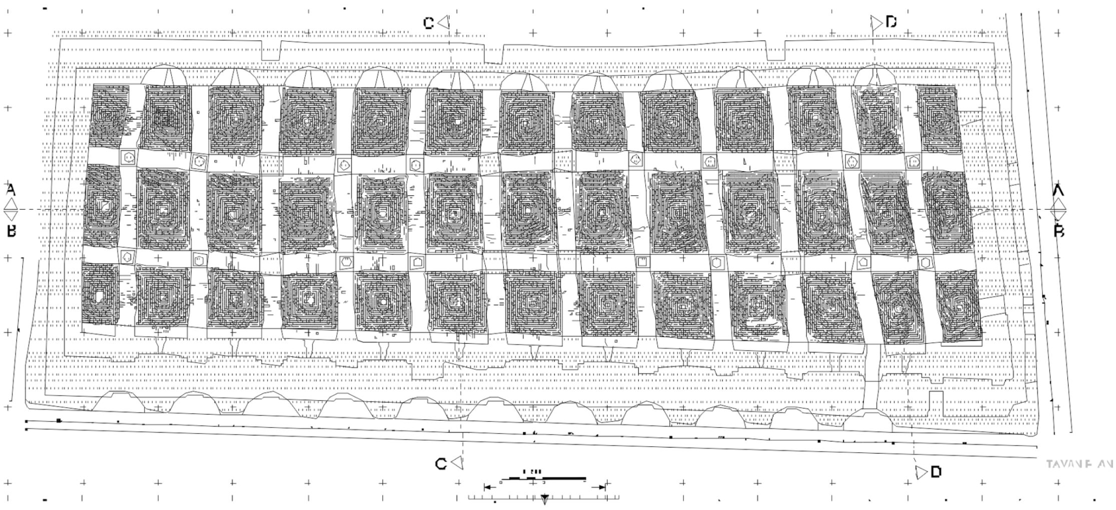

**Figure 3**. Plan layout of the cistern (at elevation +7.83 m)

## 3. REPAIR AND RETROFIT WORKS OF THE CISTERN

Within the scope of the restoration of the Pantokrator Cistern, detailed structural and architectural site investigations have been performed. During these investigations, the following structural issues were encountered: Intense pollution and vegetation were observed both on the internal and external surfaces of the side walls of the cistern. There was also a surface degradation of the outer surfaces of the side walls due to loss of some of the stones. In some parts of the side walls, holes of different sizes were formed by local people probably to use the cistern unauthorized. In the region of the northeast side walls, a noticeable distortion of the cross vaults forming the roof upholstery was observed. The irregular infill over the cross vaults with heights ranging from 0.80 to 2.80 m is clearly a sign of excessive roof loads (Figure 4). Although there was not a significant deterioration in the columns, the wooden tension members connecting the columns to each other and to the side walls were completely missing.

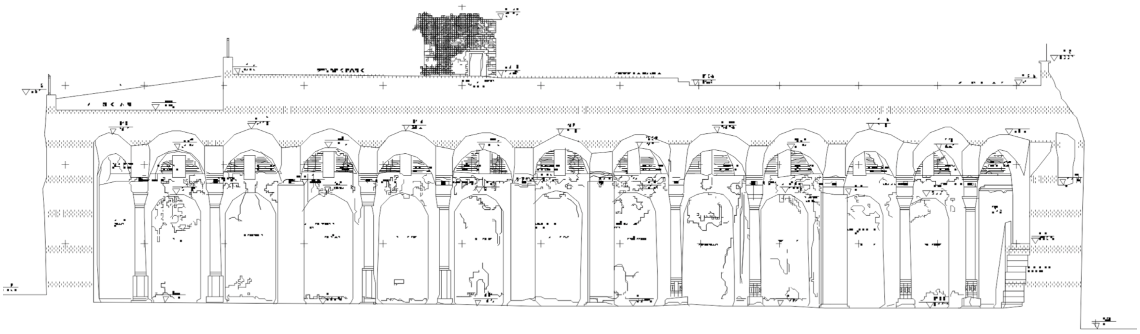

**Figure 4**. Section A-A in long direction

Subsequent to the site investigations, all missing stones in the side walls with surface degradation are completed. The cracks, which were observed during to the cleaning of the surfaces with intense pollution and vegetation were repaired. In addition, all holes in the side walls except the main entrance were closed using stone/brick and mortar with similar properties of that of the original material of the cistern. In order to provide a circulation of the gallery floor around the whole structure, the rubble and mud on the gallery floor have been cleaned.

The irregular infill over the cross vaults is resulting in a distributed load ranging approximately from 1.50 to 5.00 t/m$^2$. To decrease these partly excessive loads over the cross vaults, the infill is reduced to a reasonable height of 1.40 m. As known from former numerical investigations [2], [3] wooden ties have a significant influence on the seismic behaviour of masonry stone vaults. In some cases stresses as well as deformations can be reduced up to 50% by replacing the old ties with the new wooden ties [4]. Thus, in order to ensure an appropriate level of safety, all missing wooden ties connecting the columns to each other and to the side walls are reconstructed.

Architectural historians have indicated that a mosque was supported by the Pantokrator Cistern's vaults since recent years. The Piri Mehmet Pasa Masjid, only the traces of its foundations of which can be seen nowadays above the Pantokrator Cistern, can be identified on the historical maps of Istanbul prepared by Jacques Pervitich. The Piri Mehmet Pasa Masjid was a masonry structure with plan dimensions of approximately 11.65 m x 12.75 m. The Masjid was supported by six columns and the vaults between these columns as well as the outer wall facing the back side of the Pantokrator Cistern (Figure 5).

**Figure 5**. Restitution of the Piri Mehmet Pasa Masjid

## 4. MODELING ISSUES AND NUMERICAL ANALYSIS

In order to evaluate the effects of the Piri Mehmet Paşa Masjid on the Pantokrator Cistern in terms of bearing capacity of the structural system, a realistic three-dimensional (3D) model of the cistern was developed (Figure 6) and finite element (FEM) calculations have been conducted. Heights of the infill on the cross vaults vary depending on the form of the vaults approximately between 1.30 m and 1.95 m.

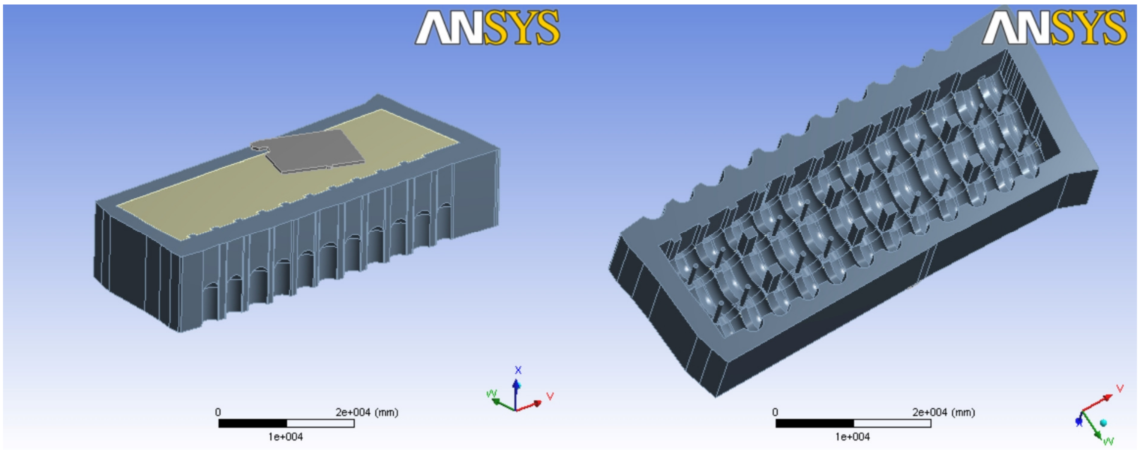


**Figure 6**. Three-Dimensional (3D) model of the cistern

For the numerical analysis under vertical loads, the dead load acting on the structure is calculated as g = 2.88t/m$^2$, considering an infill height of approximately 1.60 m, the unit weight of soil 1.8t/m$^3$. Live loads acting on top of the cistern was assumed as q = 0.75t/m$^2$. The sum of the dead and live loads due to a possible reconstruction of the Piri Mehmet Pasa Masjid was assumed as approximately p = 2.5t/m$^2$. The numerical analysis under vertical loads resulted in a maximum equivalent Von Mises stress of $\sigma$ = 11.585 MPa, the maximum shear stress of $\sigma$ = 5.995 MPa and the maximum normal compressive stress of $\sigma$ = 10.652 MPa in the vertical direction (Figure 7).

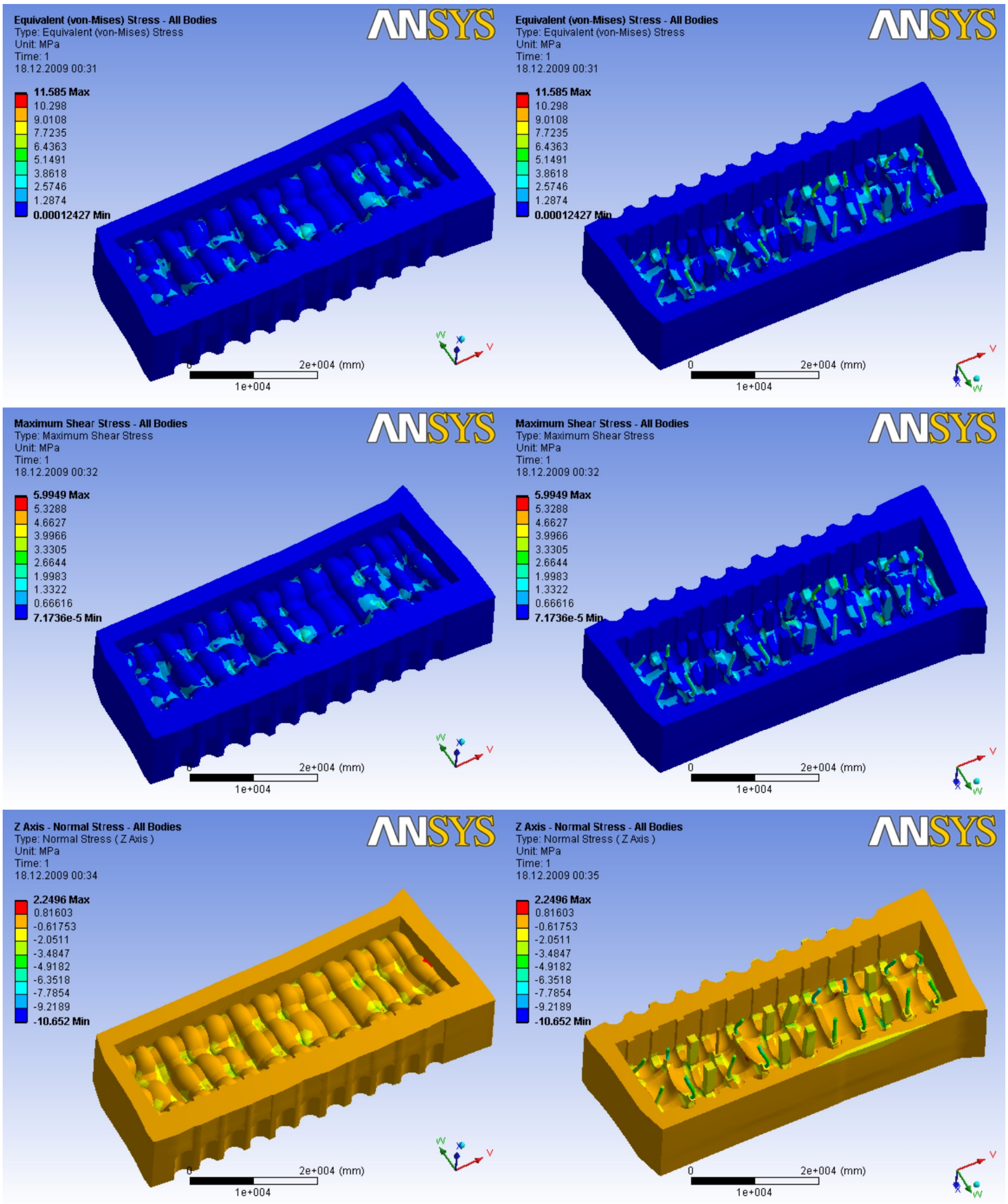


**Figure 7**. Results of the numerical analysis

Although the calculated maximum stress values are local values, in the entire structure, the calculated normal compression stresses in the vertical direction range from 2.00 to 5.00 MPa, shear stresses range from 2.00 to 3.00 MPa. All of these values (especially the shear stresses) are clearly on the unsafe side considering the allowable stresses for stone / brick masonry structures.

## 5. CONCLUSIONS

Within the scope of the restoration of the Pantokrator Cistern according to the Turkish Cultural and Natural Heritage Protection Act 2863, detailed architectural and structural site investigations have been carried out. Structural weaknesses observed during these investigations have been remedied by appropriate repair and retrofit techniques. In order to evaluate the effects of the Piri Mehmet Paşa Masjid to be possibly reconstructed on the Pantokrator Cistern, numerical analysis under vertical load have been carried out. The analysis results showed that even if the Piri Mehmet Paşa Masjid is not reconstructed, under current loads due to infill soil the structural system of the cistern does not possess an adequate level of safety. Thus, it is decided to remove the excessive soil from the top of the cross vaults and not to reconstruct the Piri Mehmet Pasa Masjid.

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