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STRUCTURAL AND EARTHQUAKE RESPONSE ANALYSIS OF THE LITTLE HAGIA SOFHIA MOSQUE

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SUMMARY

In this study, the structural and earthquake response of the Little Hagia Sophia Mosque (Kucuk Ayasofya Camii) of Istanbul is investigated. The building has lived several earthquakes, various parts of the building were damaged, plasters fell and cracks appeared in the walls and in the main dome. Recently, a large scale restoration has been started by the Great Municipality of Istanbul. Within this activity, the building is investigated in detail and soil testing is been carried out to identify the properties of the soil. This paper presents the primary results of the structural and earthquake response analysis of the historical building within the development of appropriate methods and techniques for repair and strengthening of the Little Hagia Sophia Mosque. A brief discussion is presented for possible strengthening of the foundation and the structure of the historical building.

INTRODUCTION

The Little Hagia Sophia Mosque (Kucuk Ayasofya Camii) is one of the oldest historical buildings in Istanbul. In fact the building is also known as Sergius and Bacchus Church which was converted to a Mosque following the Ottoman conquest of the city. It remains the oldest surviving Byzantine monument in Istanbul. Due to numerous internal and external alterations as well as natural disasters that have occurred since its construction, severe cracks, especially in its dome and vaults have developed. The building has been subjected to a number of earthquakes of different level of intensities. The side walls, the vaults and the main dome of the building were damaged partly by cracks appeared at the periphery walls of the domes. In course of time the cracks worsen, they threaten the structural integrity of this monument, although various restorations had been carried out in the past. Following these unfavorable conditions, in order to prevent further damages, the Ministry of Cultural Affairs of Turkey has restricted all new constructions in the area of the Mosque until the structure has been stabilized. Furthermore the Great Municipality of Istanbul has launched a large scale of repair and restoration work to rehabilitate the building for further use and maintain its historical value.

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Development of an effective methodology for repair and strengthening of important historical constructions require an integration of knowledge at least in the area of seismology, geotechnics, structural engineering, material science, architecture, art as well as social, cultural and economic aspects. Deterioration of these structures occurs mainly as a result of environmental effects and change in soil conditions in long run.

Presently, 1500 years old building is located between Cankurtaran and Kadirga districts, inside the Old Istanbul City Walls. The Mosque had been restored and strengthened many times in past. Old restoration works generally concentrated on the northeast part of the structure that is also damaged today. Causes and magnitudes of existing damages have been investigated in 2003. During these investigations, it was observed that there is a differential settlement in the Mosque towards west. Recently, the Great Municipality of Istanbul has decided to repair and retrofit the structure due to its cultural importance. Restoration projects of the Mosque have been carried out under the supervision of Alper [1]. The authors participated to the project in developing geotechnical and civil engineering analysis and supplying technical support.

This paper presents the preliminary results of the structural and earthquake response analysis of this historical building carried out within this process. The results are presented in corporation with the existing damages in the structural elements of the building. Moreover, the soil testing studies have been given to identify the properties of the soil and the participation of the soil to the damages in the building. Furthermore, a brief discussion is presented for the method to be use in the repair and strengthening of the structural system and the foundations of the Little Hagia Sophia Mosque.

ARCHITECTURAL DESCRIPTION

The structure is one of the typical samples of central planned, first period Byzantine Churches in Istanbul. Narthex lies at the west and semi-hexagonal shaped apsis lies at the east side of the irregular, rectangular planned niches at the corners. The eight piers of the octagon have a pair of columns in between, forming a peristylar circular ambulatory with an upper gallery. The arrangement of piers and columns is repeated on the gallery, with the only difference that the 16 columns on the ground-level carry a trabeated entablature, whereas the 18 columns of the gallery carry triple arcades crowned by half-domes. Eight pendentives at the angles of the octagon and the arches of the half-domes support the central pumpkin dome. The view of the structure, layouts of the ground and gallery floors are given in Figure 1, Figure 2 and Figure 3, respectively. The church was built using an ancient masonry technique of slanted bricks combined with later structural forms of Roman Imperial decoration such as the gored dome and complex corner vault. Curved elements are executed in both late classical and specifically Byzantine styles.

Following its conversion to a Mosque in 1504, a half-century after the Ottomans came to power in Istanbul, the interior decoration of the sanctuary was modified. Many windows at various dimensions were opened with the Ottoman architectural characteristics and some of the existing windows were closed. An independent minaret was established to the south-west corner of the building. The characteristic of the first minaret is not being known. It is being stated in the sources that a new minaret with Baroque style was made in 18th century [2]. The body of the Baroque style minaret was placed on an octagonal pulpit; the body climbs on the Baroque profile arches and joined to a minaret balcony with a bracelet part. Furthermore, a Turkish portal was added on the west. In 1870-1871, the main rail line of the city was laid between the Mosque and the adjacent sea wall (Figure 1). Construction of the railroad immediately next to the building has been a source of concern ever since, but the rumbling of trains seems to be only one of many threats to the building.

BUILDING MATERIAL

The building material used is stone, brick and plaster. Except the restored parts, the walls on northern, western and eastern fronts are made by reinforcement of bricks with stones arranged in wide intervals. The bricks of $70cm \times 35cm \times 5cm$ are adhered together with plaster of $4{\sim}5cm$. On the southern front of building which is a 19th century structure there are irregular laid stone and bricks. Various lime types have been used for stone lines made for reinforcement of bricks. In the building, for the pillars, shelled limestone adhered with *4cm* plaster was used on the ground floor and brick was used on the gallery floor. Bricks were used as material for the vaults of the corridors and the gallery floor and for the central dome, and the bricks are laid in a manner to form radial pointing united at the center of the vault. The columns between the pillars are made of red and green serpentine; the head of columns and the architrave at the gallery floor level are made of Mediterranean marble. The physical and mechanical properties of building material are investigated by Aköz and Yüzer [3] by using the non-destructive technique.

SUBSOIL CONDITIONS

For site investigation three boreholes and six test pits were executed in order to obtain detailed information about the soil profile and the foundations. The locations of boreholes and test pits are shown in Figure 4. Preliminary study revealed that the soil profile at the site has some anomalies [4]. No compressible soil was found in the borehole SK1 that was drilled at the north-west corner of the Mosque. Observations have revealed that there is an artificial fill consisting of remains of some old structures and limestone blocks between the bedrock and the existing ground. Compressible soft silty clay and loose sand layers were encountered in the borehole SK3 that was drilled at the south of the building. By using the findings an idealized soil profile is given in Figure 5. Two test pits were excavated outside of the building, next to the main wall of the Mosque whereas four test pits were excavated inside the Mosque. During excavation of test pits, cut-stones were found beneath the main walls. Cut-stones were also found under the slab and pillars. In other words, it seems that probably the entire structure rests on cut-stones that were placed regularly.

DAMAGE PATTERNS

According to the sources, the first damage and thus the first restoration in the building has been done after the Iconoclasm movements in the 9th century [5]. After the Latin invasion, the inner ornament needed to be restored [6]. As it is mentioned above, various restoration and repair interventions have been applied to the structure until today. Özşen and all [7-9] studied the damages and the structural system of the building. At the site observations, it is noticed that some parts of the walls had been damaged heavily by the time and later they were repaired (Figure 2). The minaret having a lead coated classical spire was destroyed up to its pulpit in 1936 due to unknown reasons. The minaret, which remained ruined for a few years, was rebuilt in 1955. Structural problems were become more significant by the 1999 earthquake. The fracture in the northeast angle now extends from the dome, through the exedra, breaking the gallery arches, into the lower cornice, with a maximum separation of *4-6 cm*. The damages available on the structural system can be seen in the photographs given Figure 6-9. The south-east part of the exterior brick wall was damaged and later it is rebuilt with that of stones as shown in Figure 6. Observations at the site and inspection of the soil profile have shown that a moderate level of soil settlement is also responsible for the damages in the structure. It is generally believed that the train traffic is not source for the development of the existing damages although only limited studies exist. Accelerations due to the train traffic are measured by Yüzügüllü and Durukal [10] as $6.47\ cm/s^2$, $8.63\ cm/s^2$ and $7.65\ cm/s^2$ in X, Y and Z (vertical) directions, respectively. Maximum velocity is also measured to be *0.66mm/s*, which is quite below the acceptable limits (over *2mm/s* for plaster damages and *5mm/s* for structural damages in accordance with accelerations between $6\ cm/s^2$ and $9\ cm/s^2$) given in the related guidelines.

STRUCTURAL MODEL

Elastic analysis and under vertical earthquake loading is generally considered as a reasonable tool for structural investigation for basic understanding of response of ancient masonry building formed by complex components. In the analysis particular importance is given to develop an appropriate mathematical modeling of the structure. Within the restoration studies, architectural plans and elevations (sections) are prepared by Alper [1] using the ACAD package. They are directly used for computational model of the structure. The structural system of the building mainly consists of masonry walls, piers and masonry dome. Due to the complexity and the sophisticated geometry of the building, its modeling has been a complex task. Preserving the main body of the building, various minor simplifications are made, to keep the number of the finite elements, consequently, numerical analysis reasonable. In the modeling the opening of windows and doors are excluded. However, it is believed that the number of the elements assumed is quite enough to identify the structural response of the building subjected to its own weight and the earthquake load. The non-linear version of the SAP 2000 software is used. Three dimensional of solids, two dimensional shells and frame elements are used for modeling the thick masonry walls, dome and piers (columns), respectively (Figure 10). The structural walls of the building are composed of at least three major materials, i.e., stone, brick and mortar (plaster). However, in the construction of the model the building is assumed to be of a single material regarding its modulus of elasticity and specific density. The success of the modeling is measured whether the location of the high tensile stresses can be matched with the actual cracks or damages in the building. According to the knowledge of the authors no test results are available regarding properties of the materials in the building. In the numerical analysis those of the Hagia Sophia, one of the most famous churches of the Byzantine architecture, are adopted. In the modeling of the structure, the part of the pulpit that is added later is not considered.

NUMERICAL ANALYSIS

The analysis of the building is carried out by considering self weight and earthquake loading and aimed to find out essential information about overall stress distribution within the building and to provide insight to the response of the structure to vertical and lateral loads. The building is assumed to be supported by the elastic springs in order to include the soil settlement in the analysis and to find its effect in the structural damage results are adopted for the value and the variation of the sub grade modulus of the soil the geotechnical inspection results are adopted as much as possible. Assuming the structure is subjected to its own weight and earthquake load, a linear analysis is carried out by using the material properties of the soil and the structure. The results of the analysis are inspected thoroughly and the locations of the tensile stresses are identified. In order to include the stress redistribution and the local disintegration in a limited degree within the structure, the elastic modulus of the material at these locations is reduced before repeating the analysis once more. In fact, this type of the analysis is carried out several times iteratively to find the most realistic stress distribution. Although the model is linear one, in this way the material non-linearity is taken into account in a limited extent. Figures and presented to show variations of the stresses in the building subjected to self-weight and earthquake loading. Furthermore the free vibration mode frequencies and shapes are given.

The masonry structural system of the Mosque consists of stone, brick and mortar. All the arches and domes are made of brick and mortar. The parameters used in the structural analysis are as follows:

Mass density:	$ro = 1700\ kg/m^3$
Elastic modulus:	$E = 1000\ MPa$
Poisson ratio:	$\nu = 0.17$
Sub grade modulus of soil:	$K = 15\ 000\ kN/m^3 \sim 40\ 000\ kN/m^3$
Earthquake zone factor:	$A_o = 0.3$
Importance factor:	$I = 1.0$
Spectrum coefficient:	$S = 2.5$
Ductility factor:	$R_a = 2.5$

In the numerical solutions, two types of the soil condition are assumed. In the first solution, it is assumed that the structure is supported fixed at the base. In the second solution, following the findings of the geotechnical investigation, it is assumed that the *2/3* part of the foundation area located at south-east has an elastic sub-grade modulus of $40000\ kN/m^3$ and *1/3* part of the area located at the north-west an elastic sub-grade modulus of $15000\ kN/m^3$.

The analysis of the building is carried out to find out the static and dynamic responses as follows:

a. analysis under the self weight
b. free vibration analysis
c. spectral analysis in the E-W direction according to the specifications given in Turkish Seismic Code [11]
d. spectral analysis in the N-S direction according to the specifications given in Turkish Seismic Code

The first analysis corresponds to the building under the sustained loads. As it is expected, the vertical normal stresses increase from top to down of the walls and it reaches its maximum value at the bottom. Its magnitude approximately is $200kN/m^2$. However, at the various local geometrical discontinuities, such as corners of the windows and doors and piers, stress concentrations can be noticed, where its magnitude is greater than $200kN/m^2$. The soil reactions under the internal walls are lower than those under the sidewalls, because the weight of dome and other structural elements are transferred mainly to the sidewalls. However, stress concentrations under the piers located at the middle part of the structure comes into being due to the concentrated supporting. The vertical displacement of the dome at the top is evaluated as *3.65mm*, at the support level *1.85mm* and at the periphery wall of the dome *0.63mm*. The first seven modal periods are given in Table 1 for the cases of the fixed support and the elastic support ($K = 15000 – 40000\ kN/m^3$) on the soil. As it is known, in the case of elastic support, the system softens and the vibration mode periods increase.

Table 1 Free vibration modal periods (T1: fixed support at base; T2: elastic foundation)

Mode	*1*	*2*	*3*	*4*	*5*	*6*	*7*
T1 (s)	*0.218*	*0.196*	*0.131*	*0.128*	*0.117*	*0.099*	*0.090*
T2 (s)	*0.364*	*0.324*	*0.207*	*0.170*	*0.163*	*0.152*	*0.150*

The first, second, forth and fifth mode shapes are given in Figure 11. As it is seen, the first two modes correspond mainly to horizontal translation (mode 1 and 2) and torsional rotation (mode 4 and 5) of the entire primary structure system.

The historical monuments are constructed of brittle materials with large cross-sections of the structural elements. It should be recognized that their earthquake response would be limited to the elastic range of structural behavior. The analysis and the observations of the structure yields transversal earthquake motion are more effective than the longitudinal one (Figure 12). Probably the main reason is the length of the building in the corresponding direction, i.e., the lateral structural behavior of the masonry building to a specific direction depends mainly on its length. The stress distribution shows an increase and a quite different variation at the lower level of the walls, especially around the re-entrant corners of the structure. The maximum normal stress is approximately $200\ kN/m^2$ for self-weight of the building and it is $\pm 150\ kN/m^2$ for the lateral loading (earthquake). In the combination of the vertical and the lateral loading cases, the maximum normal stresses reach to $200\ kN/m^2 \pm 150\ kN/m^2 = 350\ kN/m^2$. These results are obtained under the assumption that the building is supported elastically (Figure 13).

RETROFITTING OF THE FOUNDATIONS

The foundations of the building were constructed over soil layers that exhibit different soil compressibility. West side of the Mosque constructed on loose-compressible soil layers when compared with the east side. As a result, the building has made a differential settlement towards the west. The symmetry of the structure was disturbed by the strengthening works and the functional interferences to the structure done in the past. In return, this has caused uneven loading, eventually lead to an increase in differential settlements. One other observation is tilting of the minaret towards east, to the direction of the Mosque.

The strengthening of the foundations of old buildings has been carried out according to different techniques such as underpinning, micro piles and soil reinforcement by jet grouting, conventional piles, etc. Micro piles were conceived in Italy in the early 1950s, in response to the demand for innovative techniques for underpinning historic buildings and monuments that had sustained damage with time and especially during World War II. A reliable underpinning system was required to support structural loads with minimal movement and for installation in access-restrictive environments with minimal disturbance to the existing structure. The pali radice (root piles) is a small diameter, drilled, cast-in-place, lightly reinforced, grouted pile. The underpinning of existing structures may be performed for many purposes as given below:

- To arrest and prevent structural movement.
- To upgrade load-bearing capacity of existing structures.
- To repair/replace deteriorating or inadequate foundations.
- To add scour protection for erosion-sensitive foundations.
- To raise settled foundations to their original elevation.
- To transfer loads to a deeper strata.

Observations show that the main causes of the structural damages in the present building originate mainly due to poor soil conditions and uneven load distribution. State-of-art reports about retrofitting of historical buildings in literature have been searched and the widely used underpinning method with micro piles has been chosen. Consequently, it is recommended that, in restoration works, a priority should be given to retrofitting of foundations by utilizing widely used underpinning method with micro piles, broadly known as Pali Radices. A typical cross section of retrofitting of main walls is given by Sağlamer [12] in Figure 14. Main points of foundation retrofitting can be summarized as follows:

- Main walls and pillars are to be supported with inclined micro piles with a diameter of *165mm.*
- Micro piles are to be connected by a continuous beam on top.

- The beam top elevation shall be below Roman time slab.
- Steel pipe shall be utilized as reinforcement.
- Cement grouting shall be carried out between micro piles as a soil improvement.

REPAIR AND STRENGTHENING OF THE STRUCTURAL SYSTEM

The building has been investigated thoroughly having in mind that the structural system of the historic building has already resisted a number of earthquakes, the building should be respected. Any new material and structural element used for repair and strengthening should be compatible and durable. The repair and strengthening intervention should be minimized. Structural resistance of the historic building depends primarily on the geometrical configuration of the structure, strength and stiffness of the material used. As it is stated above, probable due to the differential settlements, the damages are occurred especiall on the main dome, on the small domes at its surrounding, on the peripheral walls and on the main side walls of the building. These damages indicate that the differential settlement seems to come into being around the axis, which passes through North-East and South-West. Larger crack openings are observed at the North-East corner of the building. Observations indicate that an urgent strengthening intervention is required to prevent the collapse of the main dome and to secure its structural stability. Güler and Celep [13] have recommended carrying out the strengthening by using fiber reinforced polymer (FRP) or steel plates for providing confinement to the ring beam of the dome along the circumferential belt. After securing the stability of the dome, the next step will be the soil improvement for preventing the differential settlement, which is the main cause of the damages. The final step will be repair and strengthening of the damaged walls and other structural elements including the damages that are not caused by seismic effects.

CONCLUSIONS

In present paper, observations of the damages in the Little Hagia Sophia Mosque reported. The analytical approach carried for the study of the structural condition of the building is explained. The dynamic response of the structure is evaluated by using the three-dimensional modeling of SAP 2000 finite element package. Free vibration response and modal parameters of the building are obtained by assuming the fixed and elastically supported. The parameters of the elastic foundation are evaluated by using the soil test data. The stresses in the building subjected to gravitational and earthquake loads are obtained. The zones of maximum tensile stresses are determined in the various part of the building. The existing crack patterns and damage variation are compared to the stress variation of the numerical analysis to identify the possible agreement between the observations and the numerical results. The paper includes preliminary recommendations of the authors related to repair and strengthening of the Little Hagia Sophia Mosque.

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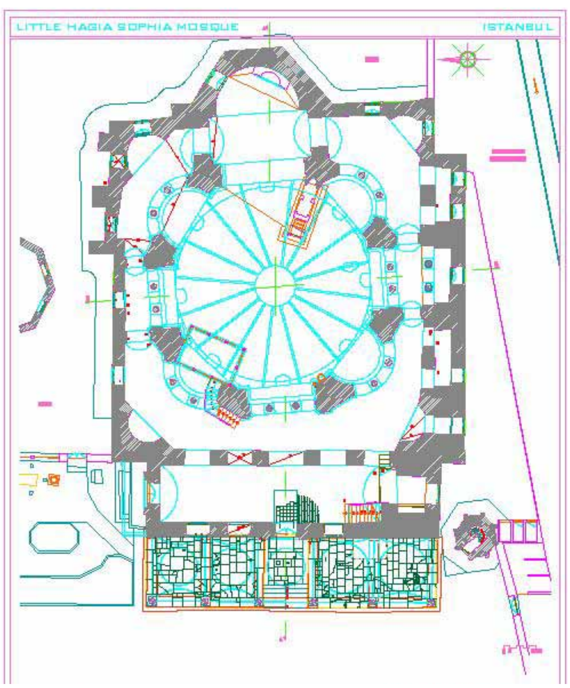
Figure 1 a) General view of the Little Hagia Sophia Mosque and the rail way between the building and the sea.

Figure 1 b) General view and the main dome of the Little Hagia Sophia Mosque



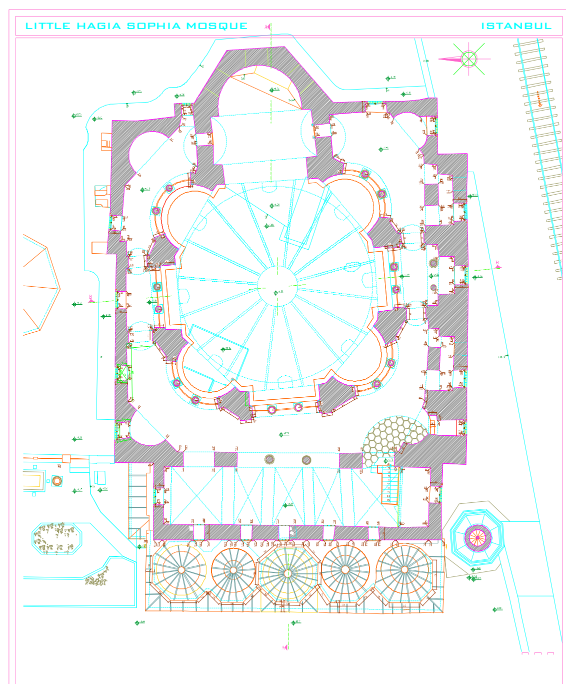


Figure 2 Layout of the ground floor

Figure 3 Layout of the gallery floor

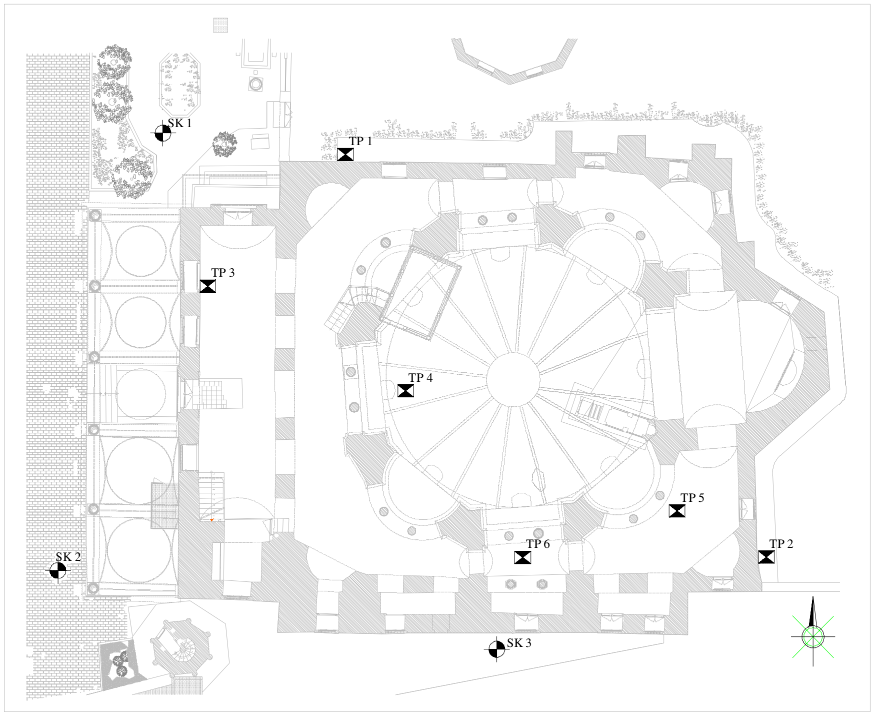


Figure 4 Locations of boreholes and test pits around and inside of the building (plan)

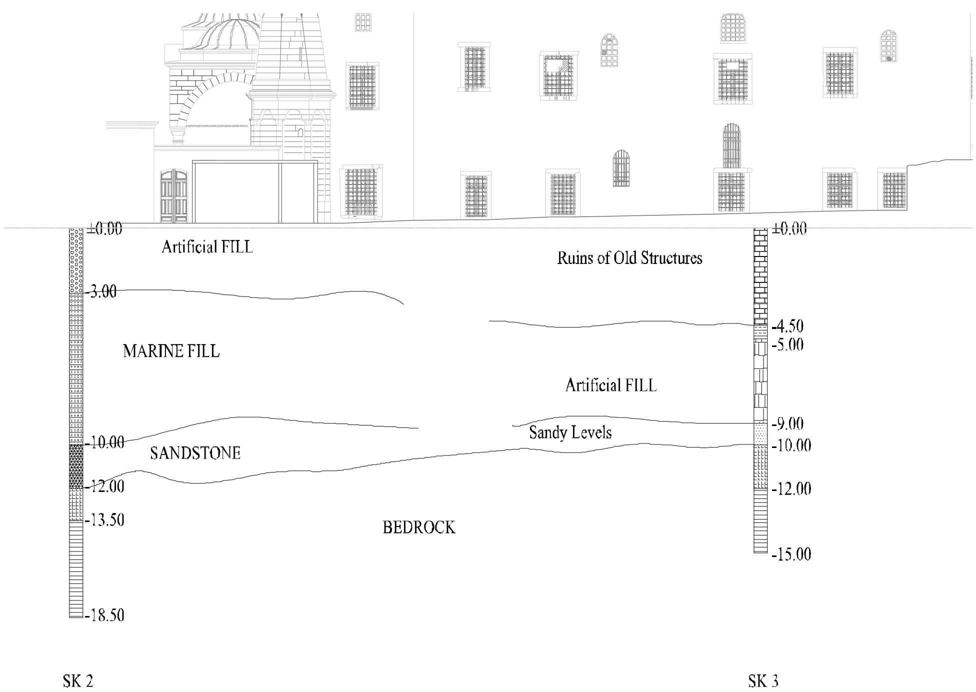


Figure 5 Soil profiles of the foundations of the building underlying

Figure 6 Damaged, rebuilt and strengthened wall parts of the north-east view

Figure 7 Interior damages one of the small domes next to the main dome

Figure 8 Crack patterns of the periphery wall of the main dome

Figure 9 Interior cracks of the main dome

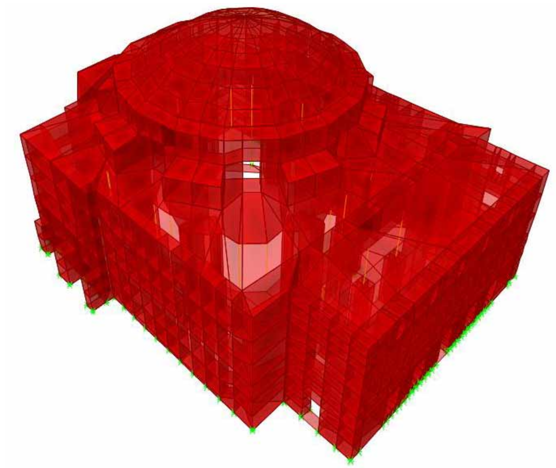


Figure 10 a 3D-Structural Model of the Little Hagia Sophia (North-West)

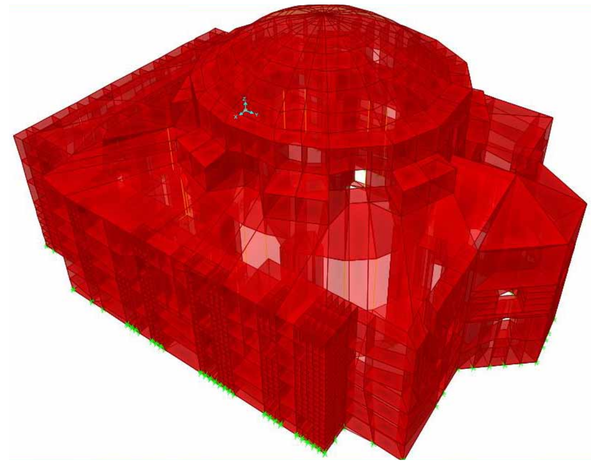


Figure 10 b 3D-Structural Model of the Little Hagia Sophia (South-East)

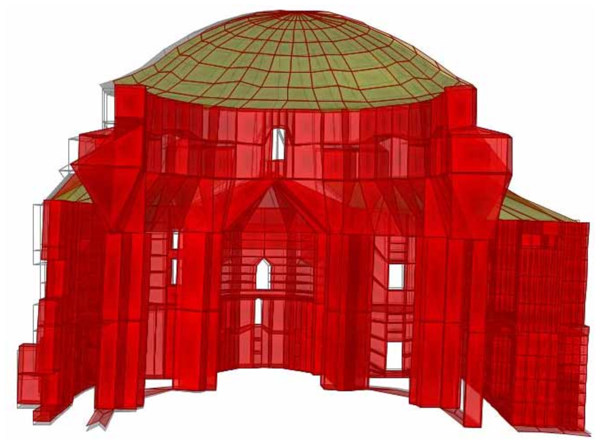


Figure 11 a First mode shape

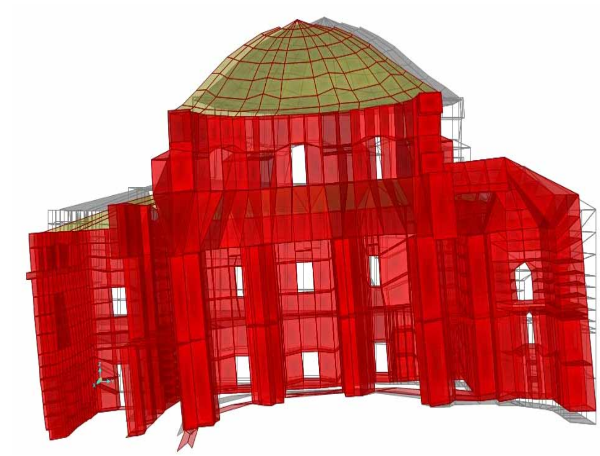


Figure 11 b Second mode shape

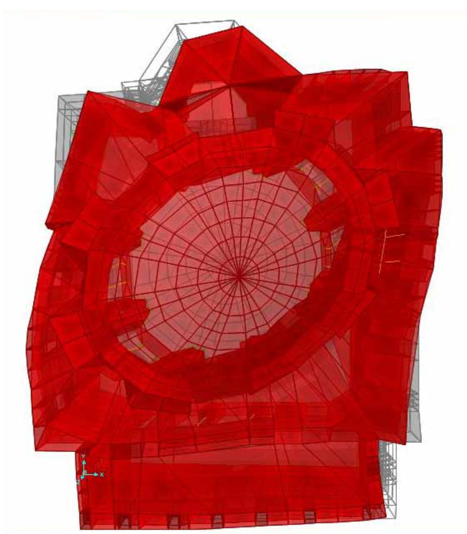


Figure 11c Fourth mode shape

Figure 11 d Fifth mode shape

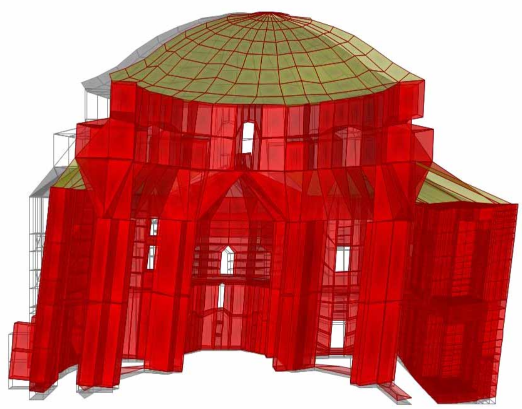


Figure 12 a Spectral displacement response to the east-west earthquake

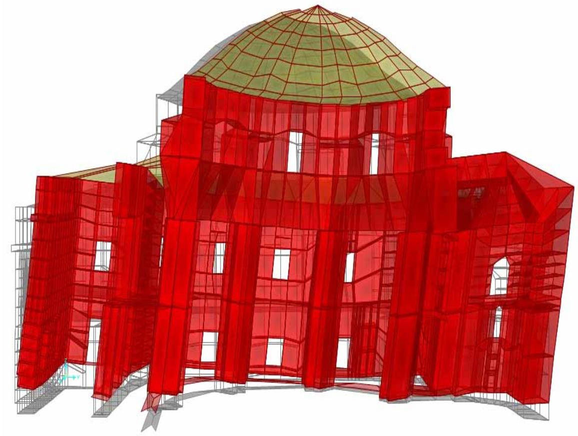


Figure 12 b Spectral displacement response to the north-south earthquake

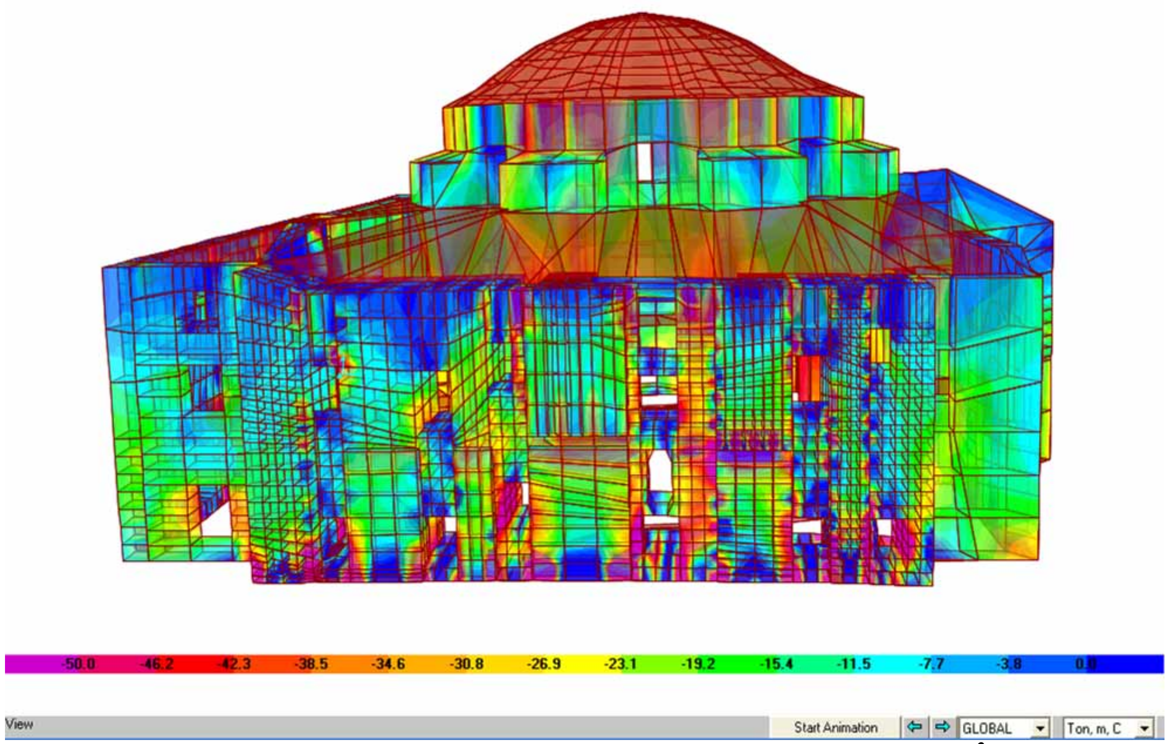


Figure 13 a Axial stress variation (south) of the structure (in t/m^2)

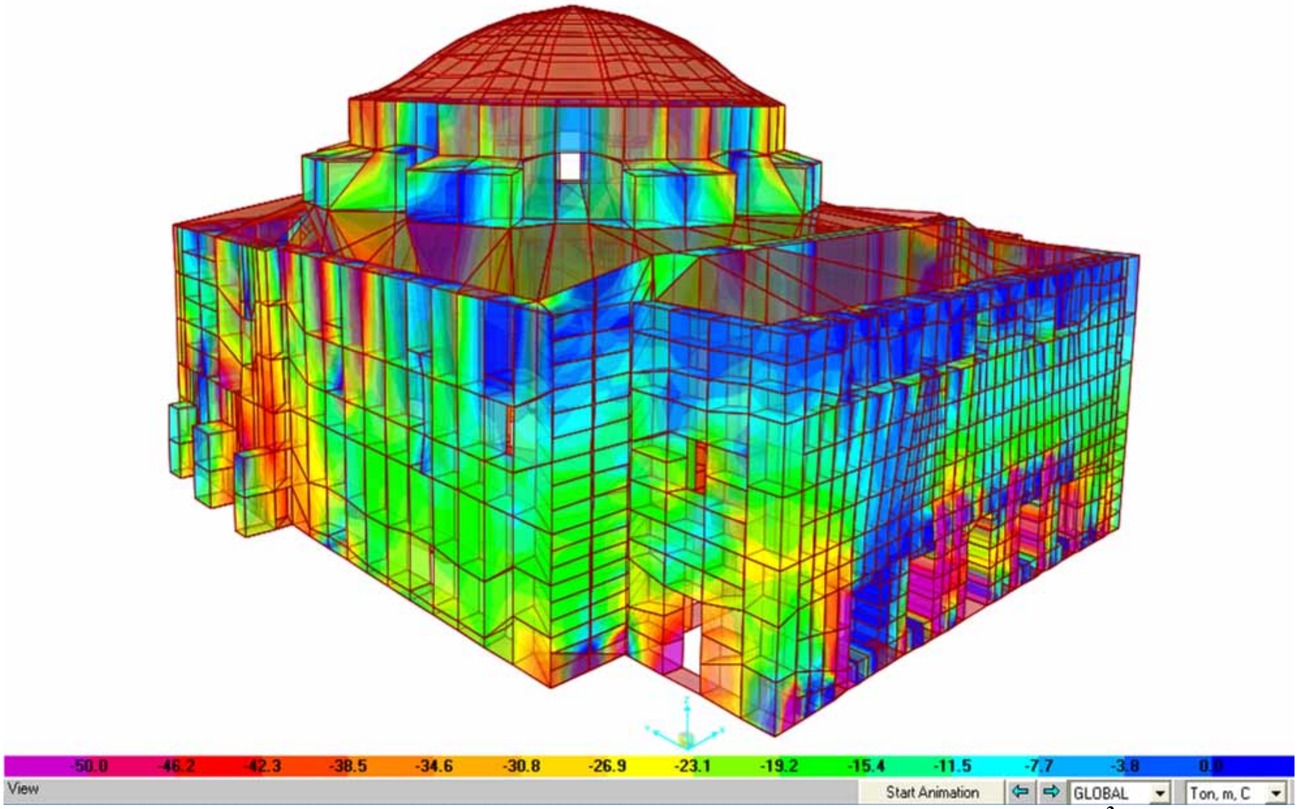


Figure 13b Axial stress variation (north-west) of the structure (in t/m^2)

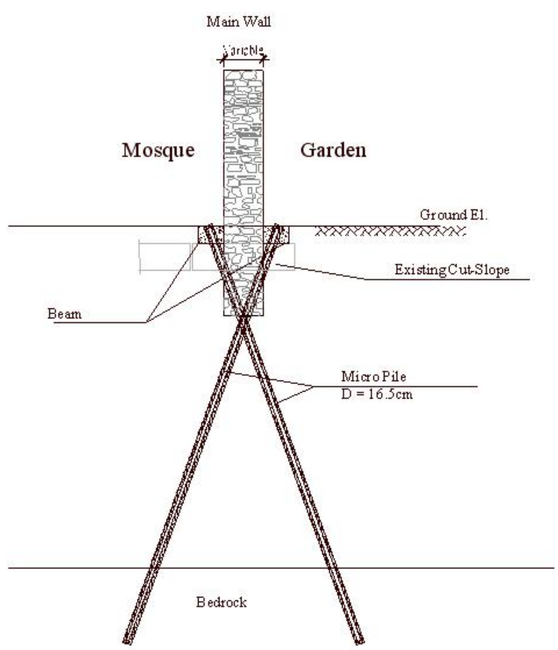


Figure 14 Strengthening of the foundation of the building by micro piles (section)