STRUCTURAL AND EARTHQUAKE RESPONSE ANALYSIS OF THE MURADIYE MOSQUE IN BULGARIA

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ABSTRACT :

Recently, a large scale restoration has been started by the Great Municipality of Istanbul for the Muradiye Mosque of Filibe (Plovdiv), Bulgaria. Within this activity, the building is investigated in detail, damages of the building have been documented and soil testing has been carried out to identify properties of the soil and the foundation configuration. In this study, structural and earthquake responses of the Muradiye (Djumaya) Mosque of Filibe, Bulgaria, are investigated and by using these information a detailed repair and strengthening project is developed. The paper presents a summary of the results of the structural response analysis including seismicity of the building. Main principles of the recommended repair and strengthening interventions for the building are given as well. The authors participated to the project in developing geotechnical and civil engineering analysis and supplying technical support for its evaluation and strengthening.

KEYWORDS: Historical buildings, earthquake response, strengthening

1. ARCHITECTURAL DESCRIPTION

The Muradiye Mosque also known as Ulu Mosque and Djumaya Mosque is a precious architectural monument in the center of Filibe (Plovdiv). It is one of the biggest and oldest mosques that is one of the numerous Ottomans historical buildings in Bulgaria which stood against environmental conditions and human damaging effects. Although numerous monuments, such as schools, hospitals, mosques and commercial buildings, had been constructed by the Ottoman Sultans, it is said that this mosque is one of the three examples of the oldest type of the Ottoman Mosques still standing against various conscious and unconscious human destruction on the entire Balkan Peninsula.

The mosque is believed to be built in 1425 as an imperial mosque by Shihabedin Pasha, son of the patron of Filibe and Ruler of Balkan Peninsula during the reign of Murad II (1359 - 1385). The Mosque has been restored twice in 1787 by Sultan Abdulhamid I and again in 1818 after being damaged in earthquakes. The writings on the walls of the mosque give brief information on these restorations. The interior architecture of the building seems to be monumental. Inside of the building there is rich painting decoration with plant and geometrical motifs, medallions and texts from the Koran. Its minaret has been attached to the north-east part of the mosque.

2. THE BUILDING

The mosque is an extremely solid building with thick stone walls having a thickness of *1.80m* and is covered by three domes having a diameter of *8.50m* and six interior vaults having a span of *6.5m*. The main structural system of the building consists of the thick external walls having door and window openings. There are four square pillars which support domes and vaults. Its minaret of height *23m* is located at the northeastern corner of the mosque. It is a three-nave building with approximate measurements *30m×40m*. The central nave is with three spherical domes and the two side ones – with three bed-shaped arches, supported by columns. The building material used is stone, brick and plaster. The domes and arches are covered with lead sheets. The structure consists of stones alternated with bricks. At the beginning of the 19th century, a wooden annex was constructed to the north and the ground floor of the annex was turned into a café (*Figure 1*).

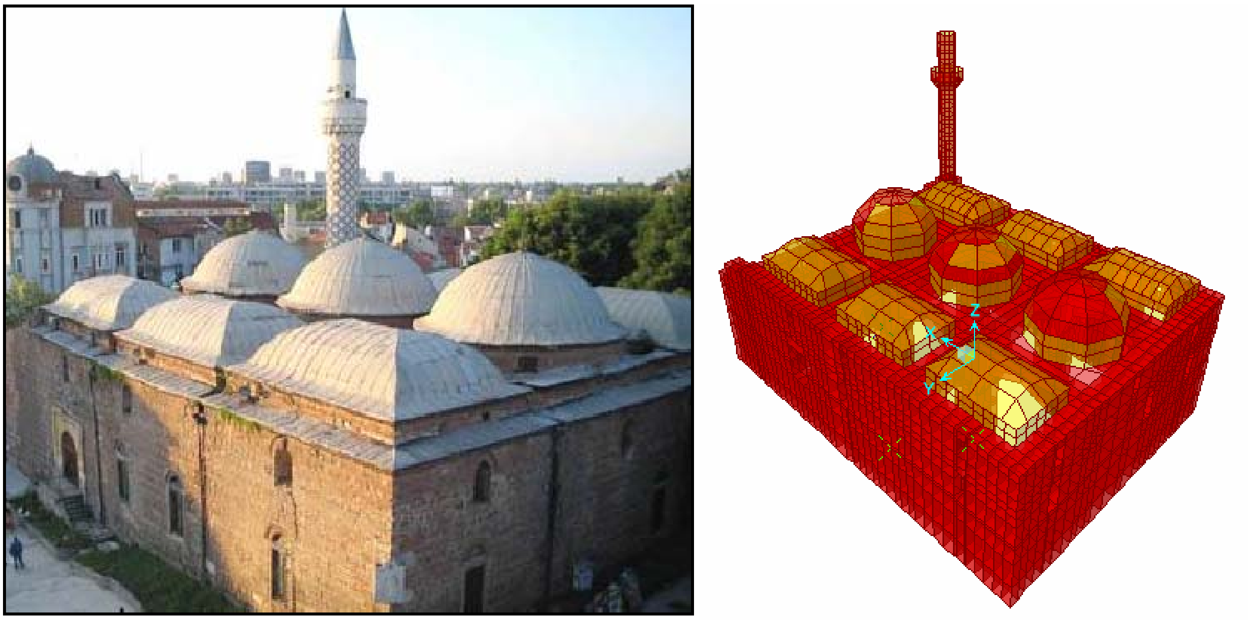

Figure 1 Muradiye Mosque of Filibe and its structural finite element model

3. DAMAGE PATTERNS

The building has lived several earthquakes, various parts of the building had been damaged, plasters fell and cracks appeared in the walls due to lack of proper maintenance. The building has undergone various structural modifications as well, due to produce commercial rooms facing to outside. The city of Filibe is located in a relatively active seismic zone experiencing by large scale earthquakes in the long period of existence of the building. According to the sources, the last large earthquake was in 1928 of a Richter magnitude of 7.0, which caused a number of cracks in the walls, domes and vaults and leakage from the roof. At the site observations, it is noticed that some parts of the walls as well those of domes and vaults had been damaged heavily due to environmental conditions as well. However, it is reported that severe cracks appeared after excavation for a minor Roman historical side next to the mosque. Although the recent damages threaten the integrity of the building significantly, almost no repair has been under taken. It is the first time that a comprehensive repair, strengthening and restoration procedures are planned (*Figure 2*).

Structural problems were become more significant after change done in the ground level as a result of the excavation. Since these historical remnants are very close to the mosque and probably the excavation was carried out without taking necessary precautions, the soil level was lowered down to the level of the foundation of the mosque. *Figure 2* shows various damages observed in the structural walls. Further damages came into being to the leakage in the sewage system. Deterioration of the building occurred mainly as a result of the environmental effects and change in the soil surface. In course of time the cracks and damages worsen, they threaten the structural integrity of the building. Following these unfavorable conditions, in order to prevent further damages, 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. To develop an effective methodology for repair and strengthening of the mosque, an integration of knowledge of seismology, geotechnical and structural engineering and architecture are carried out.

Figure 2 Cracks and damages in the walls of the mosque

4. GEOTECHNICAL INVESTIGATION

Geotechnical investigation has been carried out by Water and Canal Project of Bulgaria. For sub-soil investigation, five exploratory boreholes, with a total depth of *37.75m*, and two exploratory pits have been dug around the building. In this way the depth of the mosque foundation is tried to determine and undisturbed soil samples are taken to determine the physical-mechanical properties of the building soil. The site of the mosque is located in the centre of the city of Filibe. The ground surface has a slope to the north and northwest. The soil consists of sandy clays to clayey sand with building waste, old walls and pieces of rock. Its thickness varies from *2.60m* in the north-east part of the building to *3.40m* in the south-west one. The thickness can relatively be regarded as almost even. This soil has a special gravity of $\gamma = 19 \sim 20kN/m^3$, a cohesion of $c = 60kN/m^2$ and shear friction angle of $\phi = 25 \sim 29^\circ$. In the southern part, it is overlaid by a thin layer of refilled soil for grass. The second layer of soil is **c**lay – silty, sandy to clayey sand, light brown to reddish brown in between depth from *2.60m* to *10.50m* showing a large variation. The undisturbed earth samples showed that it has a specific gravity $\gamma = 18 \sim 21kN/m^3$, a cohesion of c = $30 \sim 60kN/m^2$ and shear friction angle of $\phi = 19 \sim 35^\circ$. Under this layer, syenites lay most shallowly in the south-east part of the mosque site; at *10.5m* in the north part of the site and at

6.0m in the south-west part. The rocks which make up the hills of Filibe belong to the granitoid type of rocks. Syenites are quartz-free rocks or rocks deficient in quartz. No ground water is detected in the soil examination. According to the macro-seismic division of the region, the coefficient of seismicity of the site is *0.27*.

5. STRUCTURAL MODEL AND ANALYSIS

The load carrying structural system of the building consists of masonry periphery walls, piers and domes and vaults. Due to relatively brittle behavior of masonry, elastic finite element analysis is adopted to gain an insight to its structural behavior under vertical gravitational and lateral earthquake loadings. Various minor simplifications are made in modeling to keep the number of the finite elements minimum to avoid the complexity of the geometry of the building. However, reasonable attention is given to capture the behavior of the building and to identify its structural response.

For this purpose, the SAP 2000 software is used for finite element modeling [2]. The building is modeled by using three dimensional solid elements for the external walls, the piers and the minaret and two dimensional shell elements for the domes and the vaults and one dimensional frame elements for steel elements used for strengthening of the vaults (*Figure 1* and *Figure 3*).. Since an overall behavior of the building is of interest, in the model the building is assumed to be of a single material defined with modulus of elasticity, Poisson ratio and specific density. The structural analysis is carried out twice. First analysis is carried out to determine the stress level in the existing building and the second analysis of the building by including strengthening interventions to check their effectiveness. As it is given in the drawings the foundation of the building is approximately *5.0m* below of the ground surface. The structural walls of the building are composed of at least three major materials, i.e., stone, brick and mortar (plaster). However, in the structural model of the building is assumed to be of a single material regarding its modulus of elasticity and specific density. The structural system is assumed to be subjected to the following loads:

a. *Gravitational weight*: It is considered by using a unit weight of the material ($\gamma = 17kN/m^3$) a modulus of elasticity ($E=1000MPa$) and a Poisson ratio ($\nu = 0.2$). Corresponding unit mass is assumed to be used in the dynamic seismic analysis.

b. *Spectral seismic analysis:* It is carried out by assuming a constant spectral coefficient of $S(T) = 2.5$ and a seismic area coefficient of $A_o = 0.4$ [1]. In the analysis ten free vibration modes are considered and the complete quadratic combination is adopted. The analysis provides a purely near elastic representation of the structure. Being insensitive to values of modulus of elasticity the non-linear elasto-plastic behavior of masonry comes into being due to cracking and weakening of the masonry at a specific tensile stress level. This behavior is taken into account by using a seismic load reduction factor of $R_a = 2$ for all periods of the structures. The first and second mode shapes corresponds to the vibration of the relatively elastic minaret in two directions (T_1 and $T_2 \cong 1.25s$), and the remaining ones (T_3 and the others $\leq 0.39s$) to the mode shape of the structural system itself, where the higher modes of the minaret can be seen as well.

c. *Seismic time history analysis:* As the acceleration record of ground motion at the side of the building was not available, the records of Ceyhan (Turkey) Earthquake (*27.06.1998*) in the three directions having a magnitude of *5.9ML* are used. Without changing the vertical seismic record, two analyses are carried out, by adopting the horizontal records are in both kibble direction and perpendicular to it and by assuming complete elastic behavior. The records are increased so that the maximum acceleration to be *0.4g*.

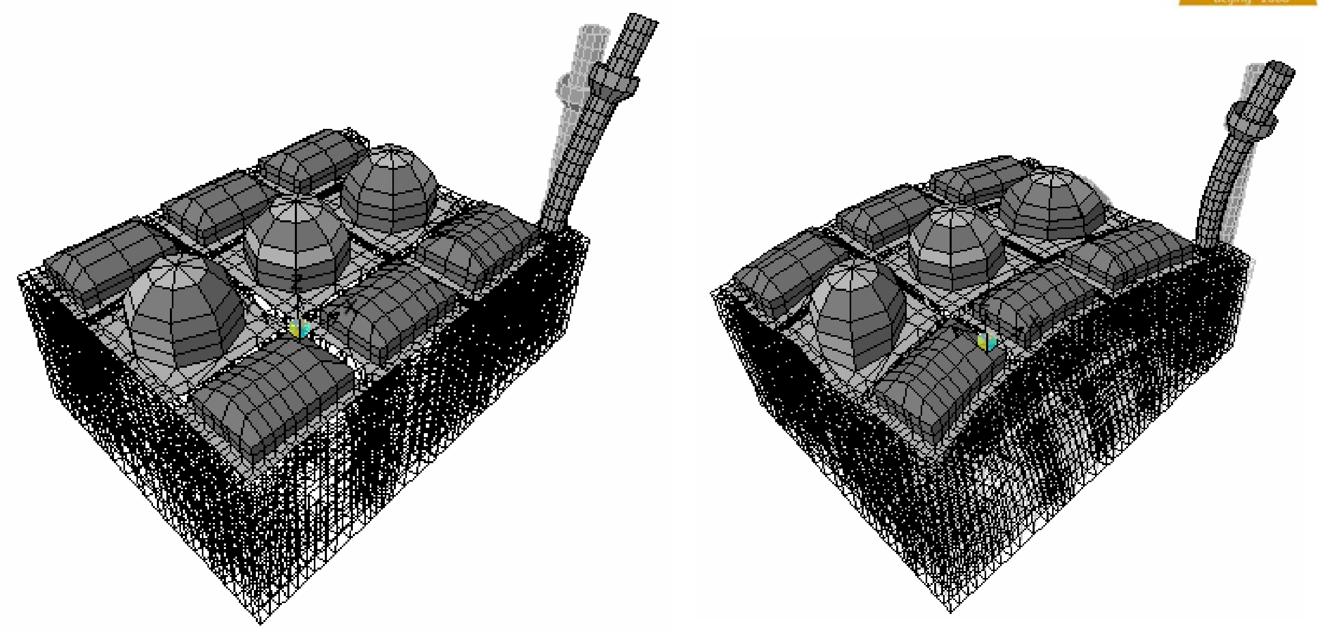

Figure 3 Mode shapes related minaret only and to the walls sat the periphery (T =1.29s and T = 0.39s)

Since the historical building is constructed of brittle materials with large cross-sections of the walls, the seismic response would be limited to stresses in the elastic range. The lateral structural behavior of the masonry building to a specific direction depends mainly on the area of the walls along in the corresponding direction. The stress distribution shows an increase at the lower level of the walls, especially around the re-entrant corners of the structure. 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. However, at the various local geometrical discontinuities, such as corners of the windows and doors, stress concentrations can be noticed. The soil reactions under the sidewalls are relatively large, because the weight of the domes and the vaults are transferred mainly to the walls on the periphery. However, soil stress concentrations under the piers located at the middle part of the structure comes into being due to the concentrated supporting. In these analyses, the maximum compressive and tensile stresses are identified in the structural elements in order to see how far the predictions of the numerical analysis checks with those of the actual observation. The location of the high tensile and compressive stresses may indicate the cracking and crushing of the masonry units.

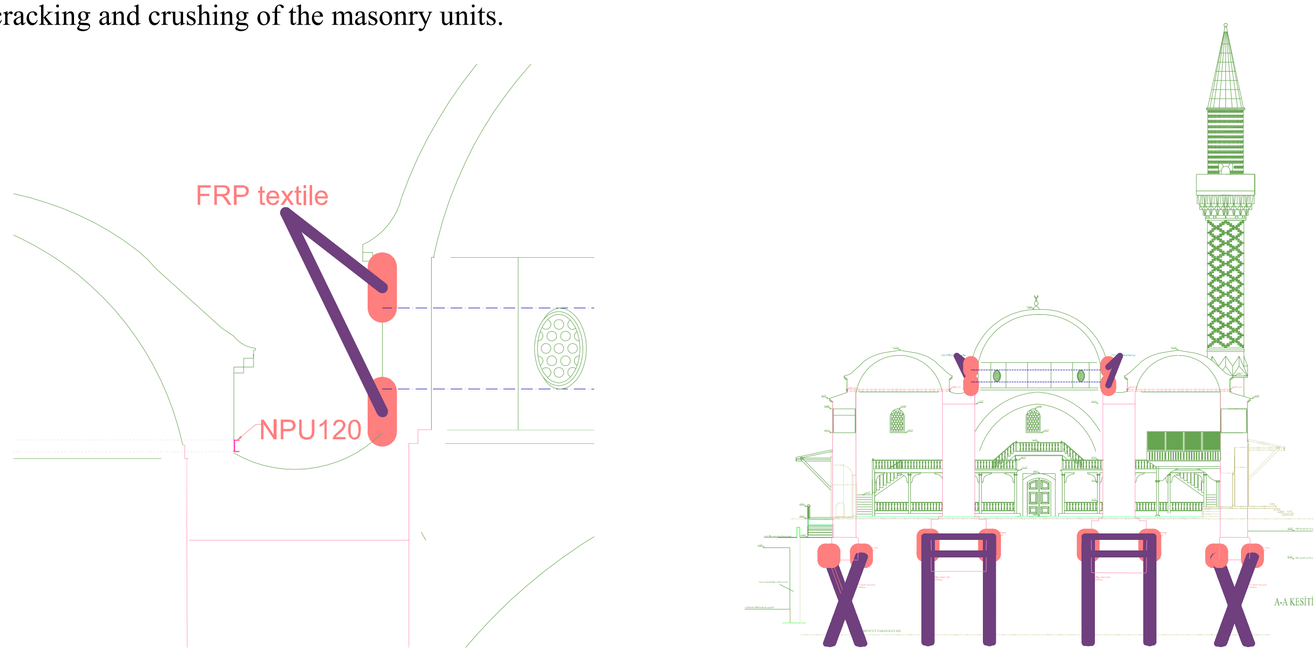

Figure 4. Strengthening of vaults and domes and foundation strengthening of the building

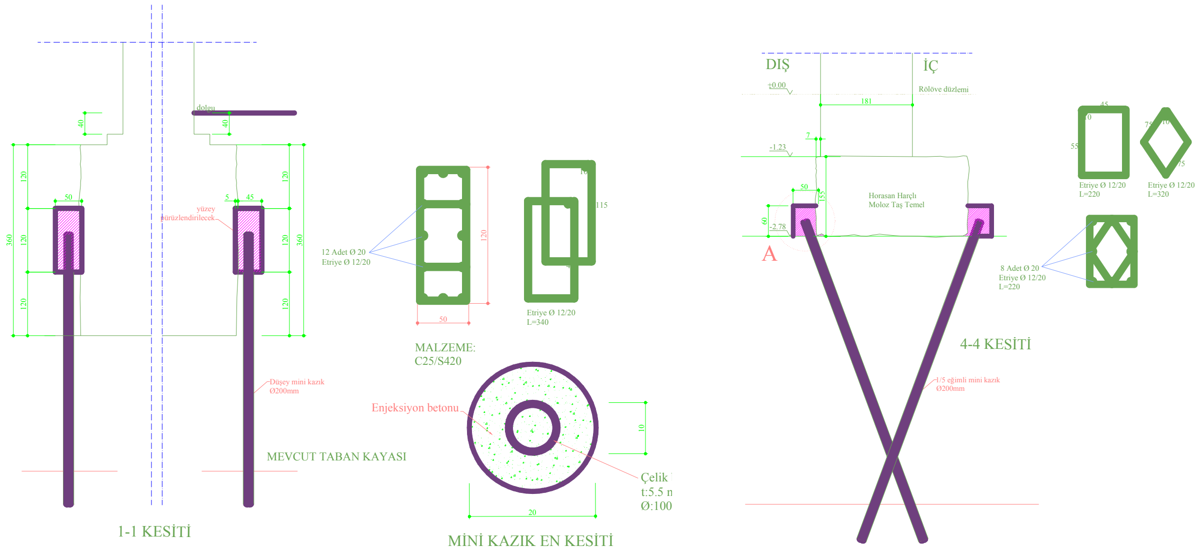

Figure 5. Micro pile application in the foundation strengthening of the building

6. REPAIR AND STRENGTHENING OF THE BUILDING

The walls, domes and vaults of the structure have been investigated thoroughly having in mind that the structural system of the historic building has already resisted a number of earthquakes. The building is damaged the lack of the proper care and due to environmental conditions exposed. However, one of the prime causes of the damage has been lowering the soil surface nearby. It is done during excavating historical remnants. Therefore the purpose strengthening recommendation consists of several parts.

Since observations shows that the major cause of damages in the building is the change in the soil profile originating mainly due to the excavation done close to the building. Consequently, in strengthening procedure priority is given to retrofitting of foundations by utilizing widely used underpinning method with micro piles which are used in various part of the world [3]. Micro piles are recommended under the bearing walls and piers to support structural loads and transfer loads to deeper layers of the soil and to prevent structural settlement. The micro piles recommended have a diameter of *0.20m* and a steel tube of diameter of *100mm* and a thickness of *5.5mm*, they are drilled, cast-in-place (*Figure 4, Figure 5* and *Figure 6*).

To provide the integrity of the domes and to prevent opening of the domes at the support level, FPR strips are applied at the support of the domes to bear to rotationally symmetric support reaction. However, the same procedure can not be recommended for the vaults due to their rectangular configuration. In stead of FRP strips steel elements of NPU120 around the vaults having rectangular configuration are used. Measures are taken to provide integration between these additional strengthening elements and the existing masonry structure. Furthermore, repair and strengthening of the external walls, domes and vaults are recommended by replacing the missing and damaged masonry units and cracks and damages are repaired by using specially design mortar to provide integrity of the structural elements. Furthermore, it is recommend that measures should be taken to carry off surface waters including from the roof further away from the outside walls of the mosque. Another measure is maintaining plumbing and sewage system inside the building of the mosque in the good working conditions.

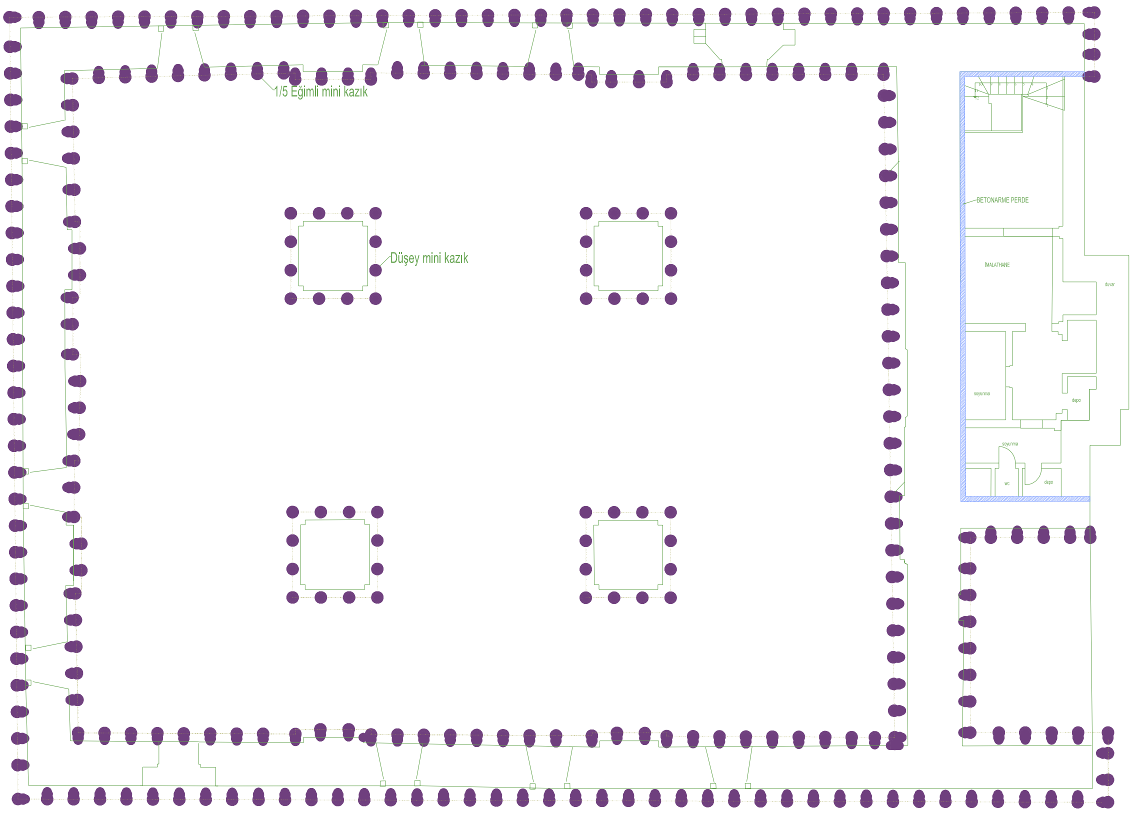

Figure 6 Configuration of micro piles at the foundation

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REFERENCES

Turkish Seismic Code (2007). Ministry of Reconstruction and Resettlement, Turkish Government, Ankara.
SAP2000, Structural Analysis Program (2005). Computers and Structures, Inc.
Güler, K., Sağlamer, A., Celep, Z. and Pakdamar, F. (2004). Structural and earthquake response analysis of The Little Hagia Sophia Mosque Paper no. 2652, 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada. August 1-6, 2004.