ESCUELA DE CONSTRUCCIÓN CIVIL
FACULTAD DE INGENIERÍA

Revista de la Construcción
Journal of Construction

Research Article

Soil-structure interaction analysis of Çelebiağa Mosque, Pertek-Türkiye

Özgür Yıldız[1], **Ebru Doğan**[2]

[1] Faculty of Engineering and Natural Sciences, Civil Engineering Department, Malatya Turgut Özal University, Malatya (Türkiye), ozgur.yildiz@ozal.edu.tr
[2] Faculty of Art, Design and Architecture, Architecture Department, Malatya Turgut Özal University, Malatya (Türkiye), ebru.dogan@ozal.edu.tr
*Correspondence: ozgur.yildiz@ozal.edu.tr

Received: 16.08.2022; **Accepted:** 28.11.2022; **Published:** 29.12.2022

Citation: Yıldız, Ö. and Doğan, E. (2022). Soil-structure interaction analysis of Çelebiağa Mosque, Pertek-Türkiye. Revista de la Construcción. Journal of Construction, 21(3), 749-766. https://doi.org/10.7764/RDLC.21.3.749.

Abstract: After the construction of the Keban Dam, some settlements with historical, cultural, and natural value were flooded. A scientific committee consisting of academicians and public authorities decided to the relocation of the buildings including the historical Çelebiağa Mosque. In this study, the seismic soil-structure interaction analysis of the historical Çelebiağa Mosque, which was dismantled and reconstructed in a separate region due to the construction of the Keban Dam was carried out. The analysis of the masonry mosque was performed with the SAP2000 finite element analysis software. The Winkler foundation model was used to idealize the soil environment on which the historical mosque was built. The effects of soil-structure interaction on historical masonry mosque were examined in terms of transmitted acceleration, response spectra, and lateral displacement at various heights of the structure. Depending on the results of the analysis, the effects of soil-structure interaction of a reconstructed historical masonry building were investigated. PGA was obtained as 0.51g at the flag level of the minaret under the Kocaeli earthquake and 0.94g under the Sivrice earthquake. Again, the maximum horizontal displacements of the minaret at the flag level were obtained as 11 cm and 8.5 cm under the Kocaeli and Sivrice earthquakes. The behavior of historical masonry structures under earthquake loads has been interpreted by considering the geological conditions.

Keywords: Masonry structure, relocation, earthquake, soil-structure interaction, SAP2000.

---

1. Introduction

Based on the changes and developments in technological, intellectual, visual, social, cultural, aesthetic, environmental, and economic conditions, certain performance features of buildings and building parts may remain below target levels. In order to avoid this situation and constitute sustainable environments, recovery options have been appealed for building and building parts that have come to the end of their usage period. One of these recovery options is relocation, which allows the building system to be reused. Relocation contributes to the preservation and sustainability of the building systems and historical and cultural values of historical buildings.

The relocation of buildings takes place in line with social needs such as geological and climatic conditions, natural disasters, public investments (i.e. road and dam construction decisions, etc.), and legal regulations. The relocation process is the dismantling of the building, and construction to a predetermined place. Three different methods are followed during this relocation process of the building system. The first one is the dismantling of building parts and transporting them to a new location. The second one is the partial dismantling of the building and its transportation in blocks. The last one is the transportation of the building as a whole in one piece. Factors such as the distance from the location of the building to the transported area, construction technique, massive weight, plan scheme, and transportation cost are determinative in the selection of the relocation method. Regardless of the applied method, the relationship between soil structure and seismic loads, which will affect the building after the relocation, is crucial for the sustainability and strength of the building. The relationship between soil structure and seismic loads should be examined rigorously by making detailed analyses before transferring the historical buildings that should be protected for future generations and to survive (Yıldız et al., 2021).

In the studies to determine the seismic behavior of buildings, the structure-soil interaction has been neglected for a long time and it is assumed that the building supports behave according to the predefined earthquake motion. Initially, it was assumed that all the supports were connected to the foundation with a single rigid block and it was thought that a single component of the movement acted on this block. Later, it came to the fore to consider earthquake motions in two-and three-dimensional coordinate systems. In this case, the soil modeled as a semi-infinite elastic medium will show different deformations and behave differently under external loads. The soil, modeled as a semi-infinite elastic environment, will show different de-formations under external loads and behave differently. Modeling the structures by considering soil properties ensures that the behavior of the structures under earthquake loads can be reflected with sufficient accuracy.

Strong shaking alone cannot explain the extremely serious damages in the settlements. For this reason, it is essential to investigate the construction characteristics, specific vulnerability factors, and construction properties of unreinforced masonry buildings in the earthquake-damaged region (Sorrentino et al., 2019). Soil-structure interaction analysis is of great importance, especially for structures built on weak soils. In order to accurately simulate the structure and soil behavior under earthquake loads, the structure and soil must be modeled as integral. Therefore, it is required that structural and geotechnical engineers work in coordination for these analyses. Although the earliest known study on soil-structure dynamic interaction dates back to the mid-1960s, many studies have been conducted on this subject until today.

The general solution methods used in these studies can be divided into two as common system approach and the subsystem approach (Fleming et al., 1965). In the common system approach, the soil environment is considered an extension of the super-structure system and is calculated according to the earthquake data determined on the ground, that is the bedrock. The use of the common system approach in solving soil-structure dynamic interaction problems is simultaneous with the subsystem approach. Many structural engineers use this method due to the geometric discontinuities in the soil, the change of mechanical properties, and the fact that the foundation is buried in the ground which can easily be taken into account in this method (Aydemir, 2010). The first study using the common systems approach was conducted by Wilson (1969) and many other studies were performed later (Lysmer and Kuhlemeyer, 1969; Waas, 1972; Borja et al., 1998). The subsystem approach is based on considering the soil environment as a discrete or continuous subsystem within the whole system. Soil dynamic stiffness matrix and effective load vector developed in terms of degrees of freedom at the structure-soil inter-section by examining the soil environment as an independent system.

A significant number of historical buildings have been built with a masonry approach in Turkey, and despite the large number of earthquakes they have experienced, most of them continue to serve but partial destructions may occur. In this respect, those masonry structures have become the focus of attention of researchers in terms of soil-structure interaction. The influence of earthquake characteristics on a masonry bridge in Gaziantep, Turkey was investigated through SSI considerations and a fixed base approach. The far-field earthquakes were observed to be as influential as near-fault earthquakes on the masonry structure in terms of spectral accelerations (Güllü and Karabekmez, 2017). Masonry minarets of mosques or towers with similar geometrical aspects are recognized to be one of the most vulnerable structures with respect to seismic events with their slenderness (Milani et al. 2012; Casolo et al. 2013). The seismic performance of minarets, which are tall and thin structures, is affected by nonlinear dynamic soil-structure interaction and earthquake motion (Bayraktar and Hökelekli, 2020). The effect of soil-foundation-structure interaction on the seismic demand of masonry structures was investigated through a set of non-linear dynamic analyses and the effect of soil deformability on the demand of historical towers (De Silva, 2020). The significance of the site amplification effect on masonry structures was emphasized in further studies (Brunelli et al., 2022;

Sextos et al., 2018; Stewart et al., 2016; Brando et al., 2016). In soft soil conditions, the variation of seismic waves with geological effects is one of the main concerns of soil-structure interaction analysis. The effect of soil-foundation resilience is important for soft soil profiles, which in most cases leads to increased brittleness, but gradually fades for stiffer soils (Petridis and Pitilakis, 2020). The relation between ground motion amplification due to geological conditions and structural damage indicates that the damage pattern in masonry structures is related to site effects (Brando et al., 2020).

This study is unique in that it deals with the seismic soil-structure interaction of a masonry building, as well as the soil-structure interaction studies carried out by considering the soil properties of structures built with prefabricated structural elements such as reinforced concrete or steel in the literature. It is a very rare situation in terms of practical applications that the structure discussed in this study is dismantled from the place where it was first built and reconstructed with the same building elements in another location, which adds originality to this study. In this respect, soil-structure interaction analysis of a relocated historical masonry Mosque is examined in this study. In the first place, a comprehensive literature review on relocation, interventions after relocation, and the construction process of Çelebiağa Mosque were performed.

Additionally, observational and technical site investigations were conducted to determine the structural and spatial features of the building. At the end of the site investigations, a simple survey of the building was prepared to determine its spatial and structural dimensions. The sub-foundation soil modeling was performed with the geological data derived from site investigations. Winkler elastic sub-foundation soil model was adopted in the numerical model. In the dynamic analysis, records of January 24, 2020, Sivrice earthquake, and the August 17, 1999, Kocaeli earthquake were used, which caused significant structural damages in their impact area. As a result of the simulations, the variation in the lateral displacement and accelerations were measured at different heights of the structure, and evaluations were made on the soil-structure interaction derived as a result of dynamic analysis.

2. Çelebiağa mosque

In order to protect historical and cultural values, with the cooperation of universities and public institutions, archaeological excavations, surveying and restoration work, and research for ethnography, folklore, and music were carried out in the settlements, which will be flooded after the construction of the Keban Dam, between the years of 1965 and 1975. During these studies, a castle, two mosques, three baths, a pavilion, a church, an inn, and a madrasah were ascertained in the Pertek settlement area (Danık, 2004). The Çelebiağa Mosque, which is the subject of the article, has also been let into the historical buildings, which need to be preserved, in the region. As a result of the detailed research carried out by the teams, it was decided to protect the Çelebiağa Mosque by relocating from its location to another one (Burat, 1973). That period's existing technical and physical conditions were evaluated, and it was decided to dismantle them one by one and transport the building elements, with the numbering method. Correspondingly, the surveying and determination works of the mosque were carried out between the years of 1968 and 1969 by the Restoration Department of the Middle East Technical University and the surveying groups of the General Directorate of Foundations (Tükel and Bakırer, 1970).

Çelebiağa Mosque was built on the foothills of Pertek Castle in 1570, with the imaret, madrasah, cemetery, and fountain adjacent to the building, where it is first located (Figure 1) (Danık, 2004). After the relocation decision of the mosque, it was reconstructed on a sloping land descending from north to south, at the exit of the Elazig highway of Pertek District. (Figure 2). Within the context of fieldwork, simple surveying drawings of the building were obtained by taking the necessary measurements to understand the geometry of the building (Figure 3). In the building, there is a square-planned big prayer hall (harim), which is entered by passing the three-section narthex with a short side of 3.80 m and a long side of 12.90 m, located on the northern axis. The outer part of the big prayer hall is 11.20 m x 11.20 m long, and the interior is 9.10 m x 9.10 m long. The big prayer hall is surrounded by masonry stone walls with a thickness of approximately 1.00 m, and a height of 5.50 m when measured indoors. The big prayer hall is covered by a dome with a diameter of 8.15 m and a height of 9.50 m from the ground when measured from the interior, which is supported by masonry stone walls and placed on an octagonal high pulley. In the big prayer hall, passes to the dome are provided with squinches. In the west of the big prayer hall, there is a rectangular planned second prayer hall covered with a barrel vault. On the west wall of the second prayer hall, there is a minaret at 24.75 m above the ground and a fountain adjacent to the minaret.

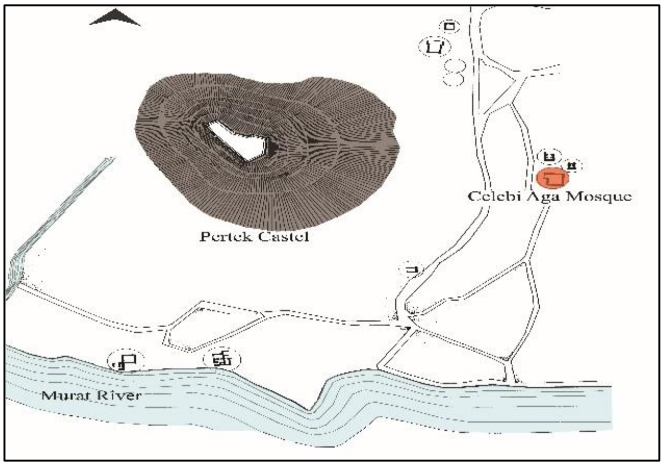

Figure 1. The original location of the mosque (Erder et al., 1967).

Figure 2. View of the Çelebiağa Mosque in the transferred location.

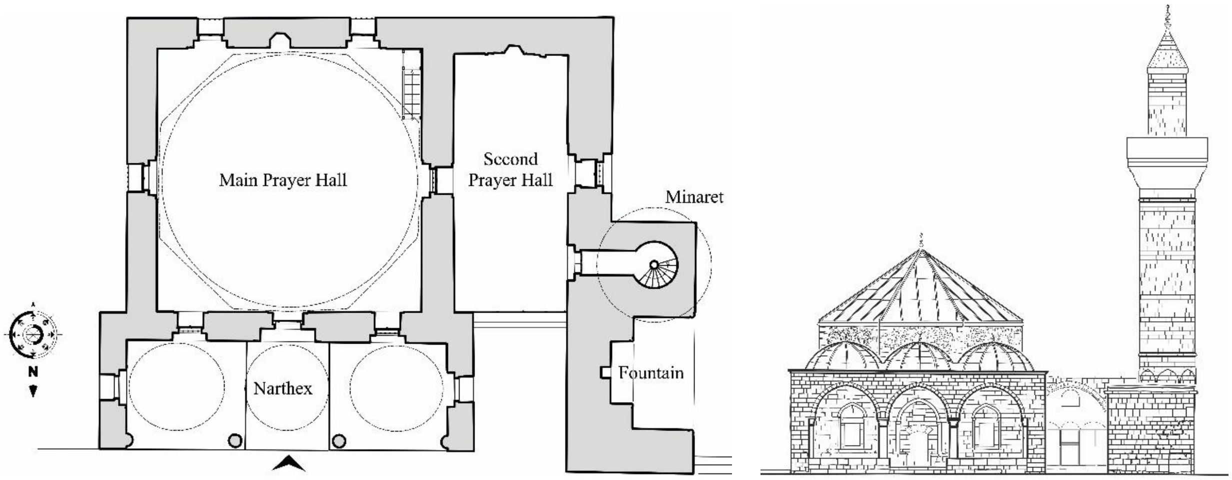

Figure 3. Drawings of plan and appearance, from simple surveying studies that are formed to understand the geometry of the building.

Various maintenance and repair works were carried out in different periods between the years of 1977 and 1988, to solve the structural damages in the Çelebiağa Mosque that emerge after the relocation process. Within the context of the study, the existence of some structural problems in present conditions was determined during the observational and technical visits to the area. In a significant part of the arch elements in the interior, deficiencies in the joint filling were determined (Figure 4). Humidity/insulation problems, which are thought to be caused by the roof covering, were confronted in the dome elements. Brittle fractures up to 2 cm in width were determined from place to place, especially in the junction areas of the windows in the dome (Figure 5). The stones used at the masonry walls in the interior were broken/spilled partly (Figure 6). Significant implementation defects were detected at the stone joints in the interior (Figure 7). On the stone elements in the exterior walls of the building, hollows, fractures, and spills were observed (Figure 8). Insulation/humidity problems and color changes were determined in the parts of the exterior walls of the building close to the ground (Figure 9).

Figure 4. Deficiencies in the joint filling of the arch elements in the interior.

Figure 5. Humidity/insulation problem of the windows in the dome.

Figure 6. A sample of broken/spilled stones in the interior wall.

Figure 7. One of implementation defects at the stone joints in the interior.

Figure 8. Some hollows, fractures, and spills or exterior walls.

Figure 9. A sample for Insulation/humidity problems of exterior walls.

3. Site description

Pertek is a district of Tunceli province, located in the upper Euphrates section of the eastern Anatolian ~~region~~, in the Murat mountainous region. It is surrounded by the natural valley, which is the extension of the eastern Taurus mountains in the northwest, the Murat River, which stretches from east to west in the south, and the Keban dam lake. The region is in the south of the Süpürgeç mountain, which is in the southern part of the Sakaltutan mountains. The district is located between the East Anatolian Fault Zone (EAFZ) and the North Anatolian Fault Zone (NAFZ). The EAFZ is a strike-slip fault zone located between Karlıova and İskenderun Bay in eastern Turkey. It extends in the northeast-southwest direction from Karlıova triple junction to Maraş, at the northern end of the dead sea fault zone.

The tectonic events that have been active in the region from the late Cretaceous to the present have played an important role in the geotectonic structure of Turkey. The region was under the influence of compression stress in the north-northeast direction during the Alpine Orogeny period (Tatar, 1987). A fault map showing lateral continuity in the topography was drawn around Pertek, and the findings showed that the Pertek fault is located in the compression zone between Erzincan, Karlıova, and Elazığ, which is bounded by the NAFZ in the north and the EAFZ in the east (Herece and Acar, 2016). The fault extends in the south-east and north-west directions, with a length of 40 km, the southeast extension of the fault is damped under the Keban Dam Lake, and the northwest extension is extended along the Kinzir stream in the northwest of Gökçe district (Figure 10). The seismic hazard map prepared by considering current earthquake source parameters, earthquake catalogs, and mathematical models is given in Figure 11. As is known, in this map, the maximum ground accelerations are shown instead of earthquake zones. The geological map of the investigation area is shown in Figure 12.

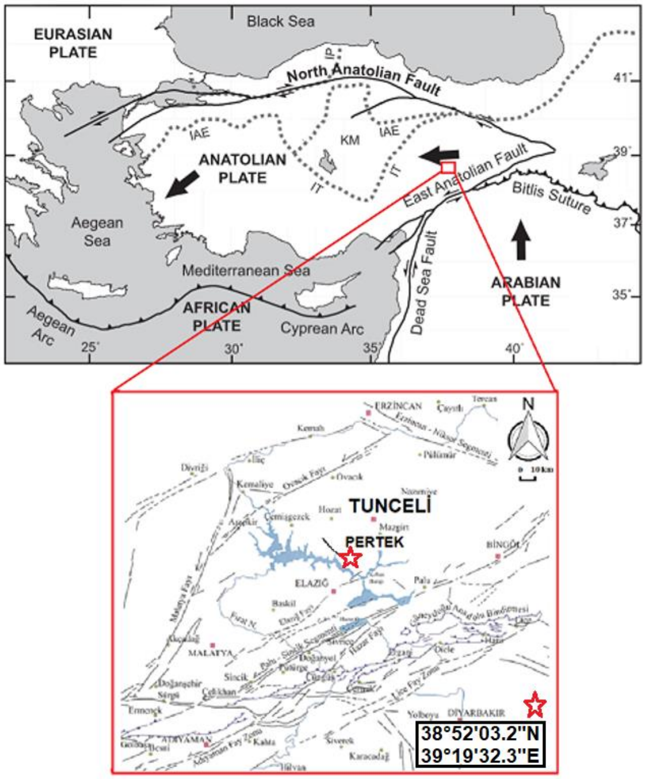

Figure 10. The simplified tectonic map of eastern Turkey showing major structures, neotectonic provinces and the location of the Çelebiağa Mosque (DSFZ – Dead Sea Fault Zone, EAFZ – East Anatolian Fault Zone, NAFZ – North Anatolian Fault Zone, NEAFZ – Northeast Anatolian Fault Zone) (Karasözen et al., 2014).

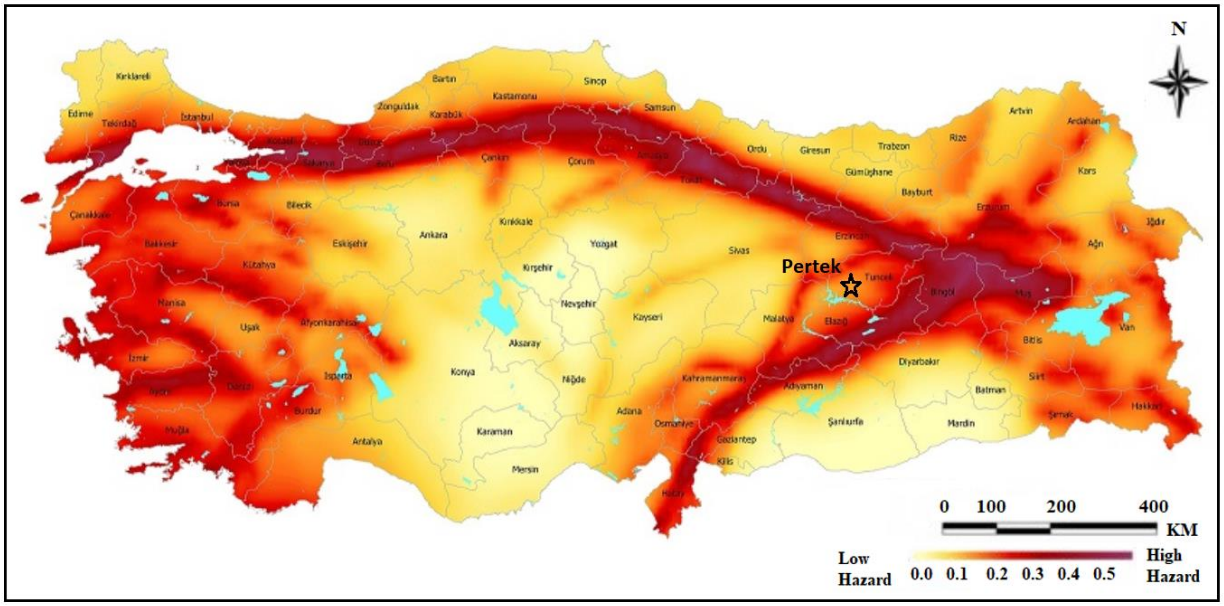

Figure 11. The seismic hazard map of Turkey (GDDA, 2019).

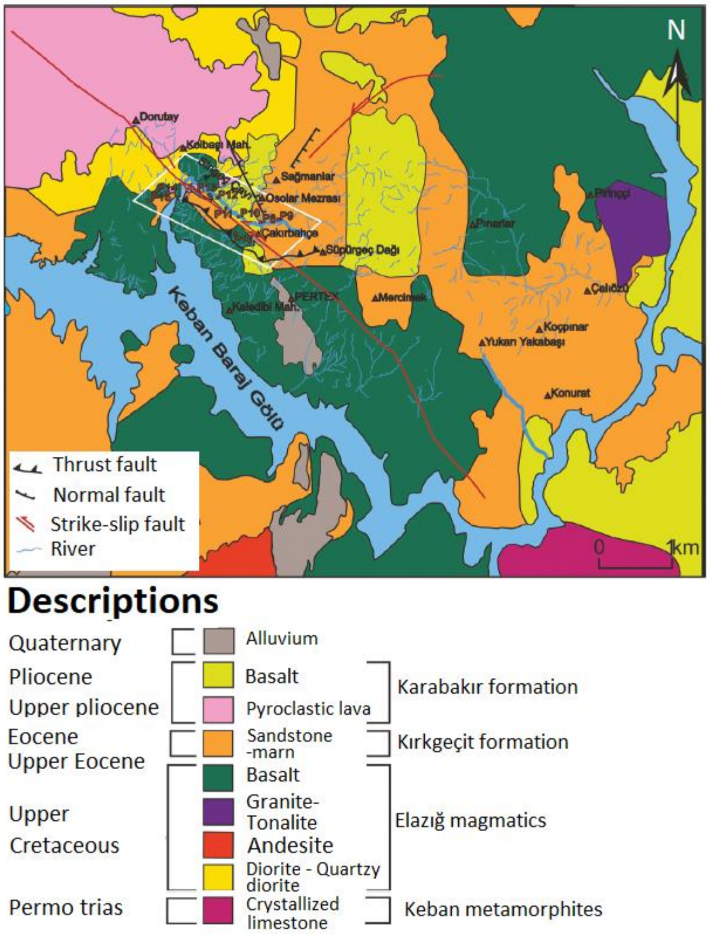

Figure 12. Local geology of the investigation area (modified from Balaban et al., 2020).

4. Numerical model and analysis

In this study, the effect of soil properties on the dynamic behavior of a mosque model under earthquake loads was investigated. For this purpose, the soil-structure model was created by the SAP2000 software program. The model of the Çelebiağa mosque which is still giving a public service as a religious structure was developed. The architectural features of the Çelebiağa mosque, which is a masonry structure, were mentioned in the previous section and the model was developed conforming to the original structure. Kufeki, which is a local name of a stone encountered in the region, was used in the construction of the building. The engineering properties of the stone were determined with laboratory tests in Elazig, Turkey. The material properties of the stone were summarized in Table 1.

The masonry structure consists of stones, and the upper cover of the dome which is defined as a shell element in numerical analysis. Also, the foundation and the underlying soil of the chimneys were developed by using solid finite-elements which is called as "Direct Method" for SSI in the technical literature (Güllü and Pala, 2014; Türkeli, 2020). In this method, all geometric and mechanical properties and nonlinear behavior in the ground and pavement can be considered. In order to express the infinity of the soil environment, artificial boundary conditions called "permeable boundaries - transmitting boundaries" are applied to the outer boundaries of this environment (Kausel, 1988, Mengi and Tanrıkulu, 1993). Thus, seismic waves that propagate outward in the soil environment by reflecting from the foundation and returning from the superstructure are prevented from returning to the ground environment by re-reflecting from the boundaries of the finite element model (Aydınoğlu, 2011).

Soil investigation studies were performed by a local soil survey company. The undisturbed soil specimens were taken and tested in the soil mechanics laboratory and design parameters were defined. The engineering evaluations on the investigation area prove a geological profile consisting of stratified soil layers and is quite difficult and complex to model the behavior of the soil layers resting on an elastic foundation with mathematical equations. Therefore, the elastic behavior of the foundation has been attempted to be defined with some idealizations. The soil environment in which the building was built was idealized using the Winkler foundation concept.

The Winkler model, which is based on the principle of representing the soil environment under the foundation with one-dimensional compressible elastic springs, accepts that there is an interaction between the pressure and the spring compression, which is described by the subgrade reaction coefficient. In this model, the soil, in a sense, shows linear deformations with the stresses transferred by the foundation on a series of springs independent of each other. The soil properties with parameters adopted in the numerical analysis were given in Table 2. The view of the numerical model with determined nodal points was represented in Figure 13. Two real earthquake records; the Kocaeli NS (1999) and the Sivrice NS (2020) were applied to the numerical model. The acceleration time history of the applied earthquakes with response and amplitude spectra was given in Figure 14. The PGAs of the north-south components of both the Kocaeli and Sivrice earthquakes were as 0.32g and 0.24g, respectively. Both earthquakes applied to the numerical model are NS components of the Kocaeli (1999) and Sivrice (2020) earthquakes. Considering the site plan of the mosque, the earthquake force was applied in the x direction (i.e. parallel to the long facade of the building) at the bottom level of the soil profile (i.e. -20 m).

Table 1. Average material properties of the stone.

Specimen	G_s (g/cm^3)	W_a (%)	n (%)	σ_c (MPa)	σ_t (MPa)	E (GPa)
Küfeki stone	2,68	2,93	0,11	94	11,45	30

Table 2. Summary of the soil profile.

Soil type	Layer depth (m)	Young's modulus (mPa)	Shear modulus (t/m^2)	SPT-N$_{60}$	Vs $_{30}$ (m/s)	Unit weight (kN/m^3)	Poisson' s ratio	Ks (kN/m^3)
Gravelly-clayey sand	0-3	10	6550	6-8	195	16	0,3	1000
	3-5	10	7800	8-11	220	16	0,3	1000
	5-12	15	9000	11-14	238	16,5	0,3	1470
	12-20	19	10050	14-19	270	17	0,3	1860

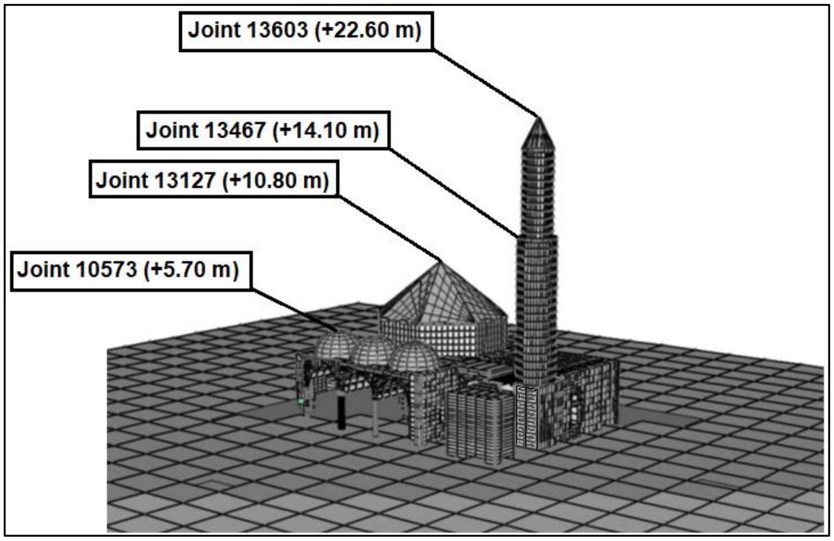

Figure 13. View of the numerical model.

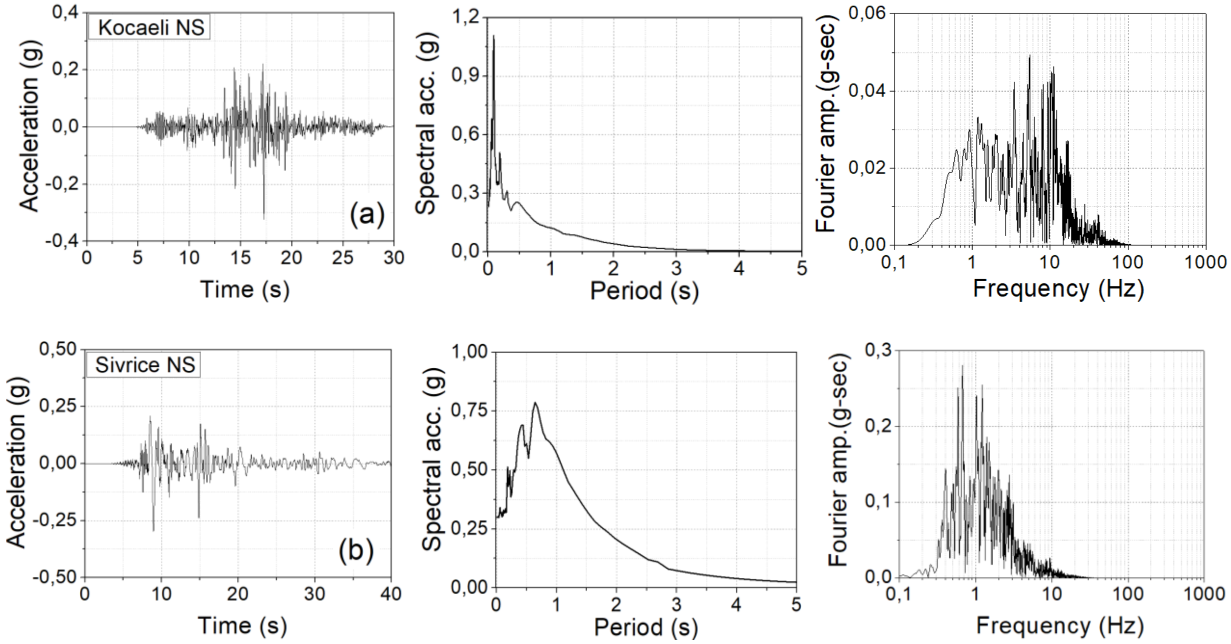

Figure 14. Acceleration time history, response and amplitude spectrum of input motions; (a) Kocaeli NS, (b) Sivrice NS earthquake.

5. Results and discussions

Four nodal points with different heights were determined for the evaluation of displacements and transmitted accelerations. Figure 15 shows the selected nodal points to evaluate the dynamic effect on the developed model. The PGA of the Kocaeli (1999) earthquake applied to the model is 0.32g. The transmitted acceleration at the flag level of the minaret was measured as 0.51g which corresponds to a 60% increase by input motion (Figure 15a). The acceleration at the balcony level is measured as 0.38g with a 19% increase in applied motion. The nodal points of the model at greater heights induced an amplification in transmitted accelerations. At upper and lower dome levels, the induced accelerations were measured as 0.23g and 0.02g, respectively. As can be seen, the influence of height on accelerations has emerged as amplification in transmitted accelerations. Consistent with the literature studies, minarets as integral parts of the structure are the most vulnerable to earthquake-induced damages (Yıldız et al., 2021). The main reason for this is that the tensile stresses are concentrated in the transition region of the minaret. In this region, the cross-sectional area is considerably reduced in the transition from a square to a circular section (Ural and Çelik, 2018). As a matter of fact, it has been stated in similar studies that the height of the building is a parameter that should be taken into account in soil-structure interaction analyses (Dok et al., 2015).

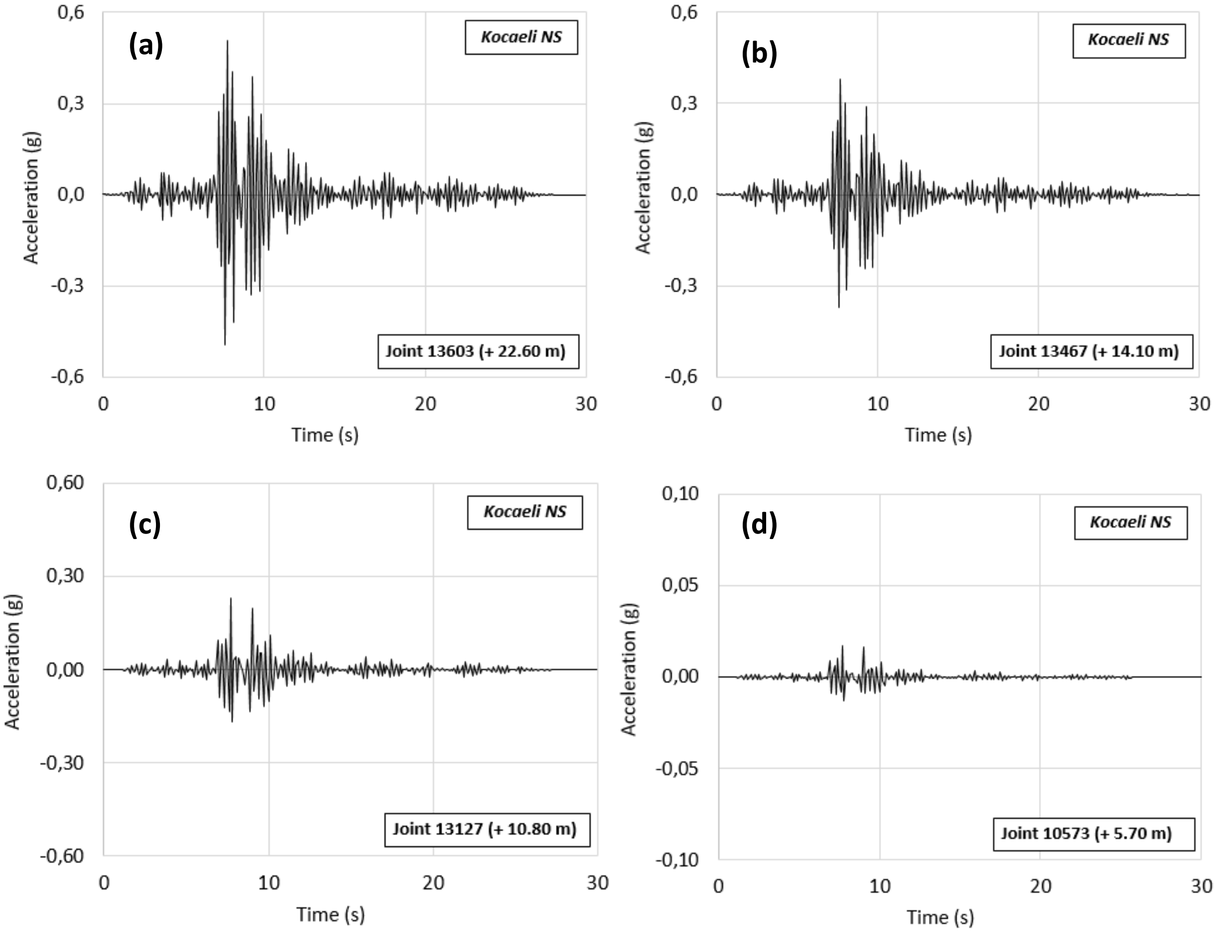

Figure 15. Acceleration time histories of the model subjected to Kocaeli NS earthquake

The response of the nodal points to the applied ground motion with varied damping ratios is given in the time domain in Figure 16. The ground motion response spectra given in the earthquake code for the Z3 soil class were compared with the response spectra obtained from the analyses. DD-2 earthquake ground motion characterizes infrequent earthquake ground motion in which the probability of exceeding the spectral magnitudes in 50 years is 10% and the corresponding recurrence period is 475 years. This earthquake ground motion is also called standard design motion. Under the determined ground motion level and geological conditions, the PGA at any part of the structure is expected not to exceed 0.90g. Especially at the nodal points determined on the minaret (i.e. Node 13603 and 13647), the design spectrum remained below the calculated spectral accelerations. However, it was observed that the response spectra obtained at higher periods of the minaret and the lower and upper domes are above the design spectrum. These results indicate high spectral amplification especially in periods longer than 1 second.

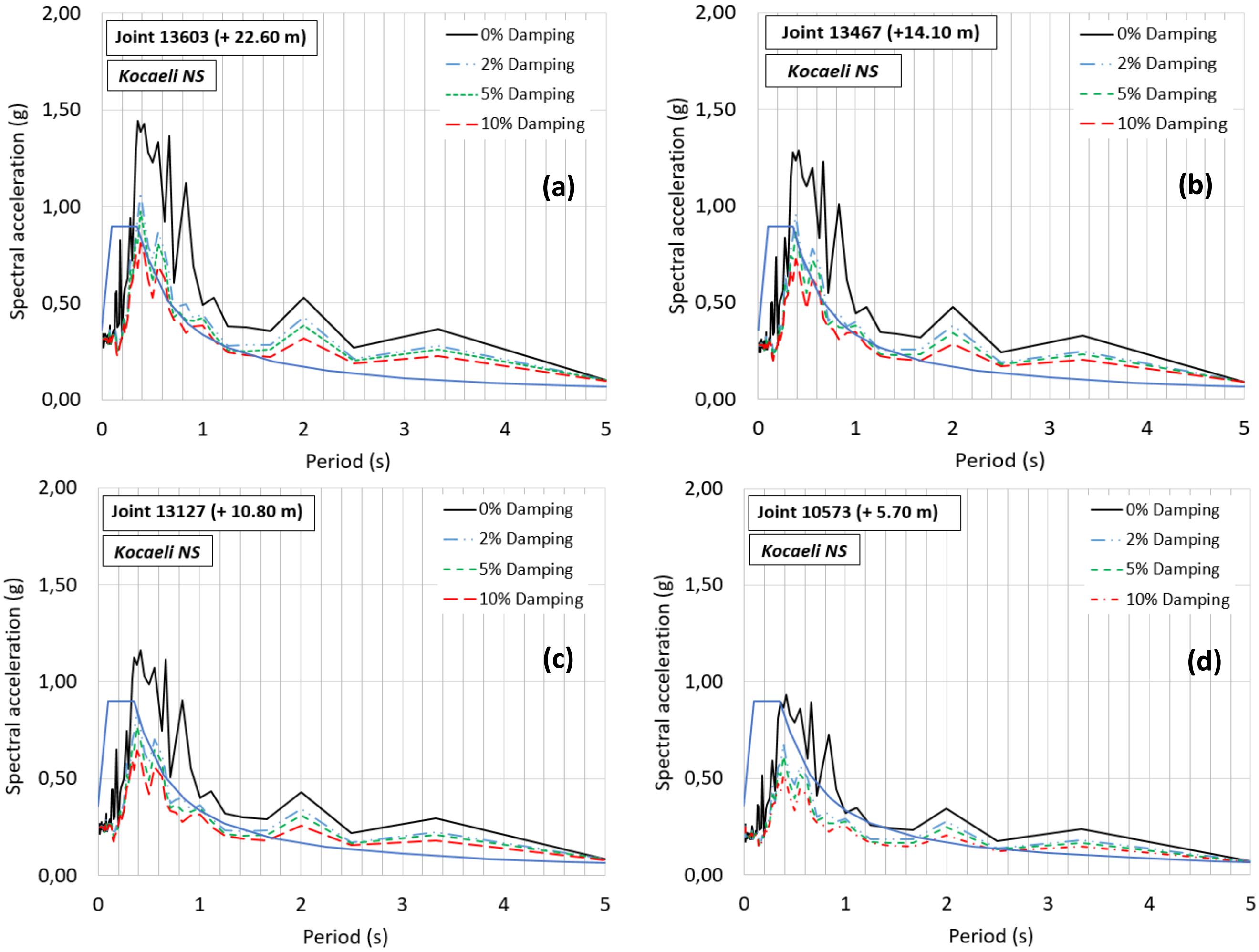

Figure 16. Response spectra of the model subjected to Kocaeli NS earthquake

Displacement time histories of the nodal points were represented in Figure 17. Especially the behavior of tower-type structures under dynamic loadings is important. Minarets are sensitive to lateral loads as they are long and thin structures. Due to the slenderness effect, significant damages occur in such structures under severe earthquakes (Kılıç et al., 2020). The maximum horizontal displacement at the flag level of the minaret having 22.60 m height from the sub-basement level was measured as 11 cm. The lateral displacement for nodal point 13467 with 14.10 m height from the basement level was measured as 8 cm. As expected in horizontal displacement measurements, the measured displacement decreases as the height of the measurement point decreases. For nodal points 13127 and 10573 having 10.8 m and 5.7 m height from the basement level, measured lateral displacements are at lower levels. The deficiencies and shear cracks in the structural elements can be attributed to the Sivrice earthquake, the epicenter of which is very close to the location of the mosque (i.e. 60 km). The foundations of high and slender structures, the stresses developed by the earthquake forces, and the structural loads, together with the insufficient foundation depth, can easily exceed the bearing capacity of the soil and the structures can be damaged. The amplitudes of the seismic waves under the applied earthquake in loose soils are quite large. The large amplitudes can cause large deformations in the building foundations and accordingly in the structure itself (Gündüz and Arman, 2005). However, it should be noted that these cracks are not at a level that will seriously affect the structural performance as of today.

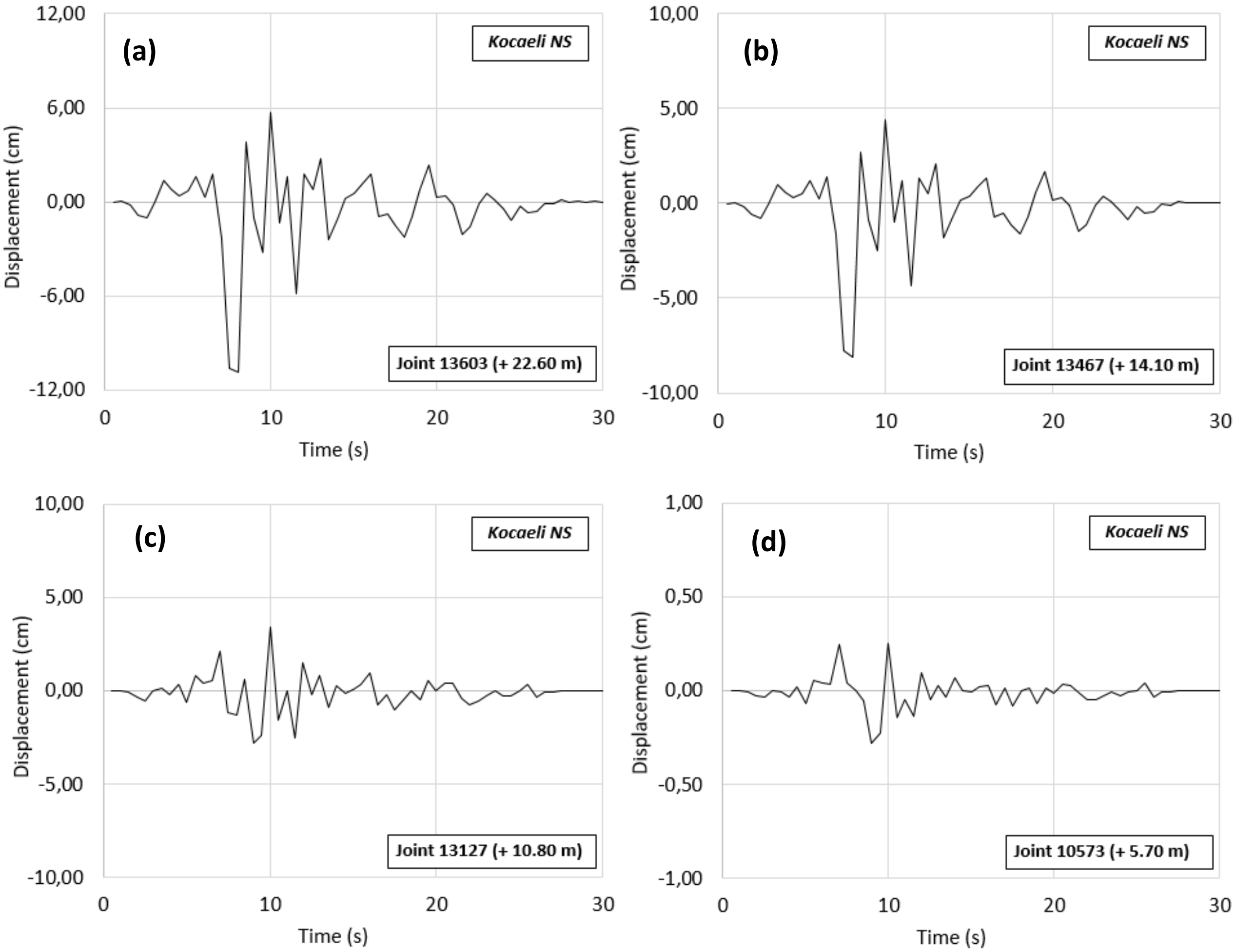

Figure 17. Displacement time histories of the model subjected to Kocaeli NS earthquake

After the January 24, 2020 Sivrice earthquake, it was observed that rural and masonry structures were quite high among the structural destructions in the region. These include masonry mosques with typical structural damages. Figure 18 shows the acceleration-time histories measured in the model under the Sivrice earthquake. The PGA of the NS component of the Sivrice earthquake is 0.24g. The transmitted acceleration was measured as 0.94g at the flag level of the minaret. As a result of the observational investigations, local shear cracks were found on the minaret of the mosque. This type of structural damage was encountered by the researchers during their studies in the study areas immediately after the earthquakes (Günaydin et al., 2021; Bayrak et al., 2021). At lower heights of the minaret, an attenuation in transmitted accelerations is observed. The transmitted acceleration at the balcony level represented by joint 13467 is measured as 0.7g while it is around 0.45g for the main dome. The accelerations measured at the lower dome are much lower than the input motion.

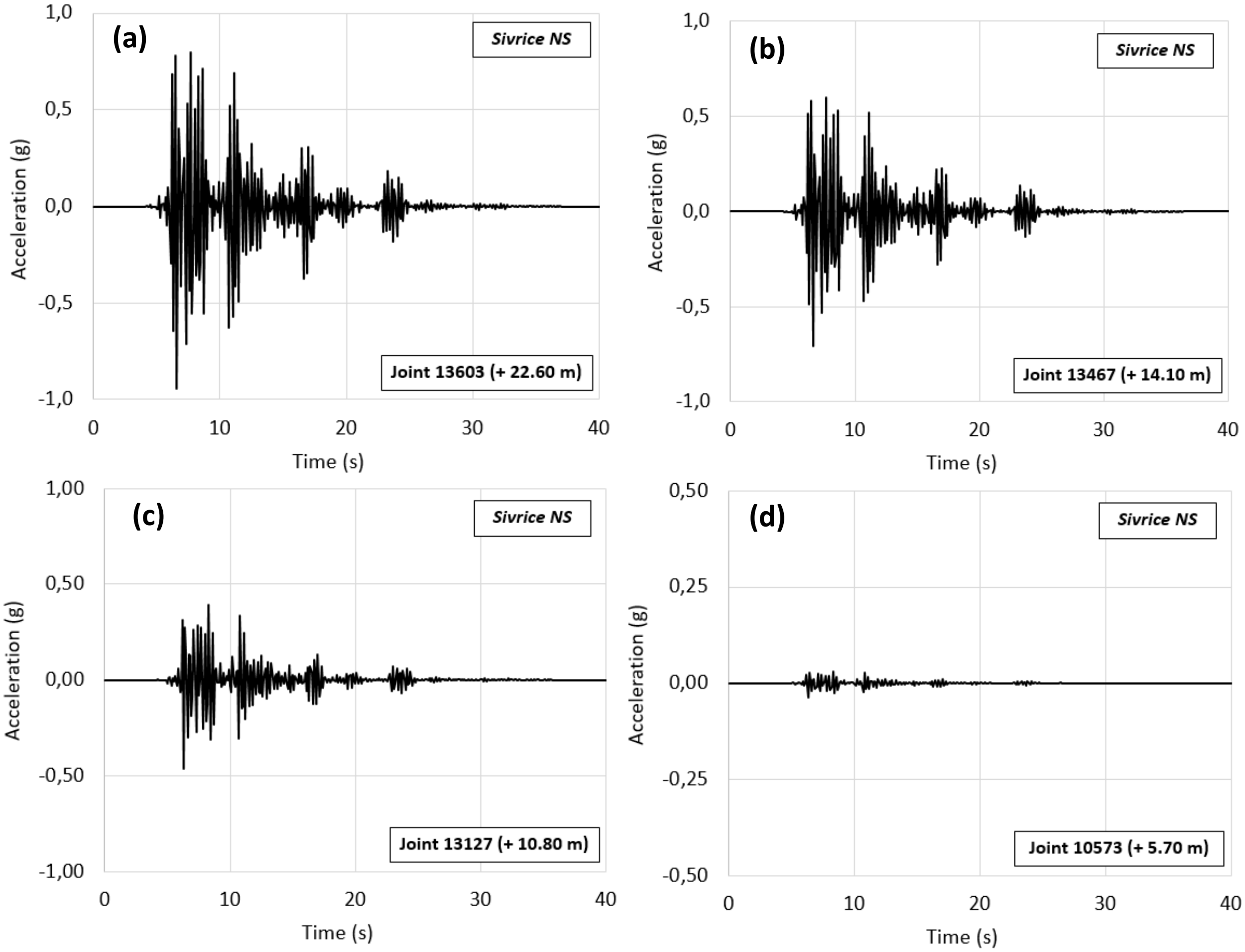

Figure 18. Acceleration time histories of the model subjected to Sivrice NS earthquake

The response spectrum of the nodal points for damping ratios of 0%, 2%, 5% and 10% are demonstrated in Figure 19. The earthquake design hazard level was determined for earthquake ground motion, with a 10% probability of exceedance within 50 years. As can be seen, damped records for none of the nodal points exceed the design response spectra which is defined as 0.90 g in maximum by DD-2 earthquake ground motion. The spectral ordinates at both minaret and dome levels also appear to be consistent with the design spectrum. As a result of the observational examinations carried out, it was observed that there was no significant structural damage in the mosque, which was modeled by taking into account the local soil conditions. In accordance with the results of the analysis, the recent Sivrice (2020) earthquake, which happened at a 60 km epicentral distance, did not cause any serious structural damage to the masonry mosque structure. Especially in Malatya and Elazig, the destruction of masonry structures after recent earthquakes were largely attributed to the low quality of workmanship and construction (Günaydin et al., 2021). Conversely, no significant structural deflection was observed in this structure.

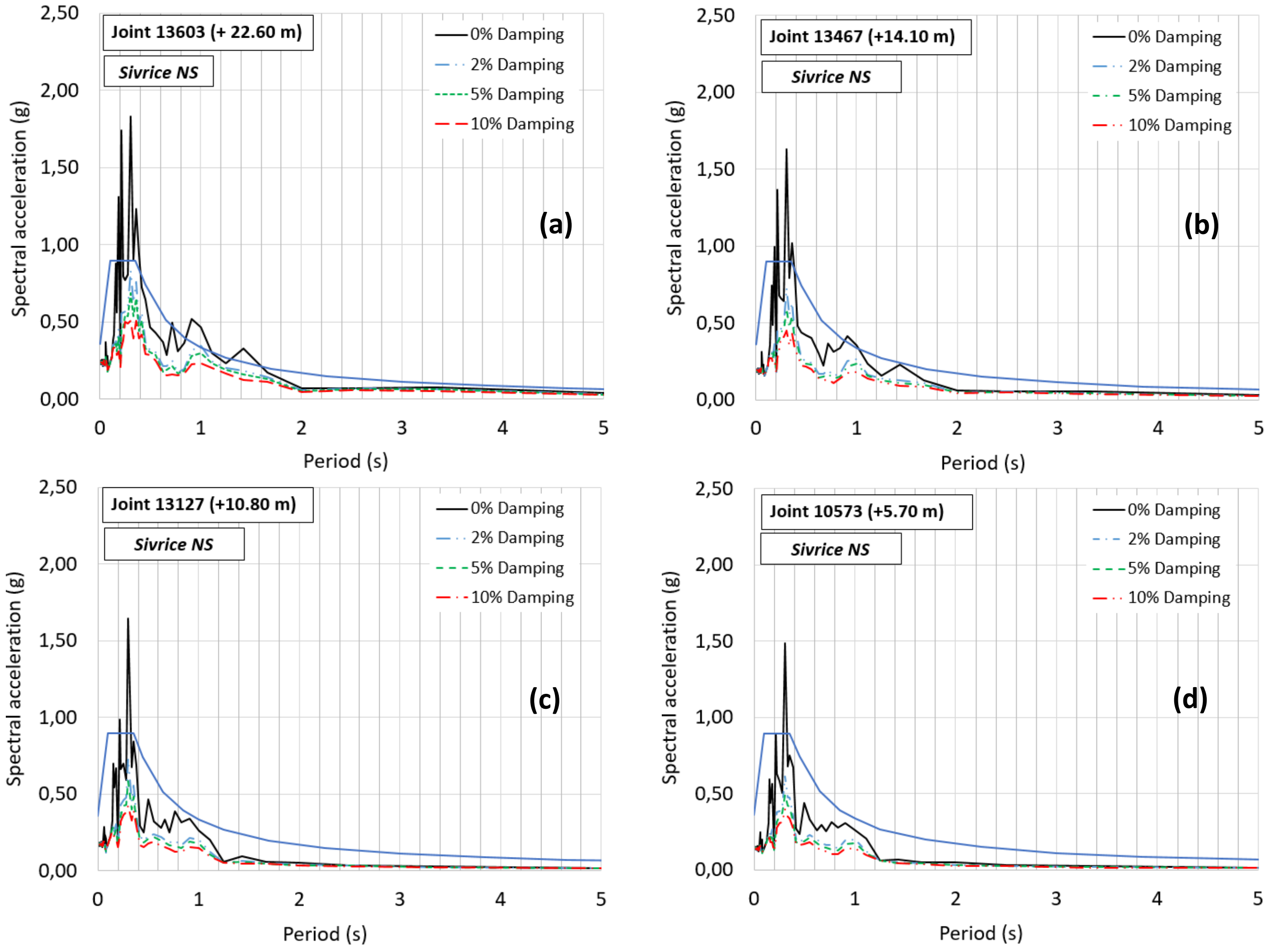

Figure 19. Response spectra of the model subjected to Sivrice NS earthquake.

The displacement time histories of the nodal points under Sivrice NS earthquake were demonstrated in Figure 20. The maximum lateral displacement was calculated as 11 cm for the flag level of the minaret. The lower level of the minaret and domes responded to the dynamic loadings with lower maximum displacements. The lateral displacement for the balcony level of the minaret was calculated as 8.5 cm and 8 and 6 cm for the upper and lower domes, respectively. The horizontal displacements obtained from this masonry mosque, which are significantly similar to the Sungurbey mosque examined in terms of both structural features and local ground conditions, are close to each other (Yıldız et al., 2021).

Lateral displacements measured in minarets are in proportion to their height. However, the proximity of the period of the minaret and the ground dominant period causes the horizontal displacements and acceleration values to be high. Also, in the regions where the minaret cross-section changes, the stiffness decreases, causing the compressive and tensile stresses formed in this region to take large values. Due to the fact that the Kufeki stone, which is used as a building element, is resistant to compression, but it is a non-reinforced structure, the resistance against tensile is largely covered by the mortar. As the height of the nodal points on the structure increases, the stresses decrease and the displacements increase. This causes horizontal displacements to occur more in high and vulnerable building elements to fail under earthquake forces such as minarets compared to other regions. It is deduced that the minimal cracks seen on the minaret structure along its height may have been caused by the earthquakes it had survived.

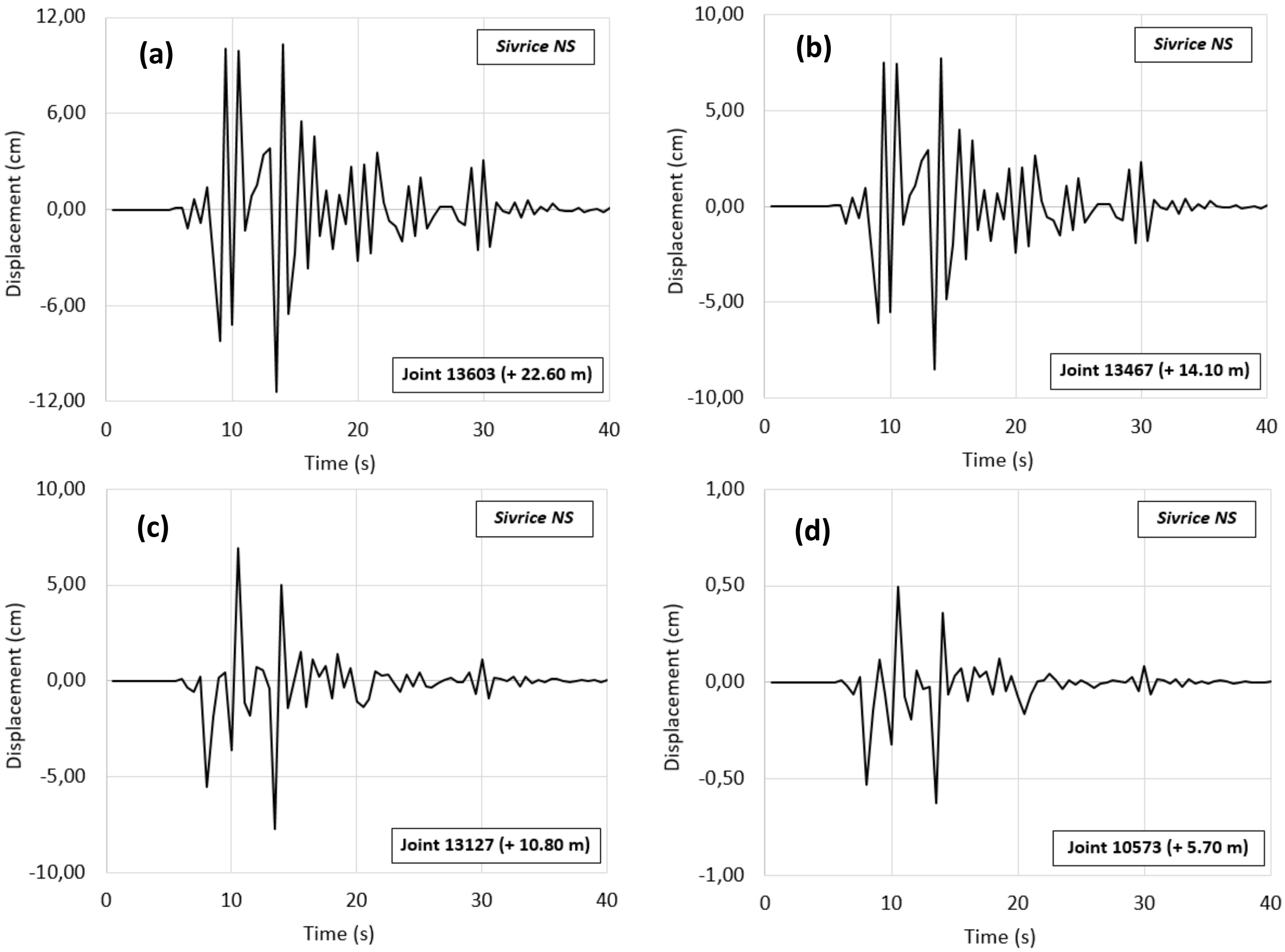

Figure 20. Displacement time histories of the model subjected to Sivrice NS earthquake

While the lateral loads of the main dome are transmitted to the ground via half and quarter domes, the minarets arising in connection with the mosque structure play an important role in the transfer of horizontal loads to the ground. Here, it is of great importance that the building is built especially close to the symmetrical plan understanding. Due to its weight, the earthquake forces acting on the structure are quite large, and the tensile stresses that occur are increasing. The very low tensile strength and ductility of the elements as a building material allow the formation of tensile cracks in carrier elements exposed to earthquake effects. Observational findings show that cracks of varying degrees occur in masonry walls, close to door and window openings (Figures 4 to 9). Especially in the region where the minaret changes cross-section, the importance of stone and mortar material used as a building element has come to the fore.

The compressive strength of the stone used in the building was obtained as 94 MPa (Table 1). Although it is very difficult to determine experimentally, it is known that the strength of the 2-3 mm thick mortar, existing between the stones, has a binding feature against pressure which is much lower than the strength of the stone. It is accepted that this situation has an effect on the joint openings observed between the stones forming the structure. For this reason, it is known that additional constructive measures may be taken to ensure interlocking when necessary, especially in the construction of the minaret-type structures (i.e. steel connection elements).

Masonry structures are usually not highly resistant to tensile stresses and these stresses control the behavior of the structure under earthquake forces. Because the materials such as stone, brick, adobe mortar, and concrete that make up the masonry structure have high compressive strength but low tensile strength. Since these structural elements and binding materials are brittle, they undergo little deformation when subjected to pressure and tension. Therefore, the horizontal forces caused by the earthquakes generate a shear force on masonry walls. Herein, the masonry mosque structure is heavy and rigid. In cases where it is exposed to an earthquake, it generates a large earthquake force due to its heavy mass. The non-ductile behavior of masonry structures under tension and compression causes the structure to collapse abruptly without any significant plastic deformation (Celep and Kumbasar, 2004). It is natural for tensile and shear cracks to occur in carrier elements that cannot meet the tensile stresses arising from earthquake forces or changes in the ground. However, no cracks that would affect the structural performance were observed in the Çelebiağa mosque. Potentially, the directions or shapes of these cracks may vary depending on the workmanship of the structure, the materials used, and the gaps in the walls, together with the earthquake. These cracks can often occur in sections around window and door openings (Varol, 2016).

Although these damage types are described separately from the geological effects, the earthquake forces transmitted to the structure depending on the local soil conditions either amplify these damages or keep them at a certain level. In stratified soil environments as in this study, the density, stiffness, thickness, shear wave velocity, damping rate, and other physical and kinematic properties of successive soil layers relative to each other. Accordingly, the intensity of propagating seismic waves affects the level of soil amplification.

It is commonly known that the amplitudes and dominant vibration periods of earthquake waves increase in stratified soils and cause significant structural damage at long distances by creating a semi-resonance event (Kaptan and Tezcan, 2012). In order to perform seismic amplification analysis of soil layers, the physical and mechanical properties of each layer should be determined precisely by both field and laboratory experiments. Therefore, soil properties are accepted as one of the most important factors that determine the structural behavior under earthquake loads. The aforementioned types of earthquake damages, which are expressed in masonry structures, are categorized as out-of-plane behavior, in-plane behavior and situations where these two behaviors are observed together.

Conclusion

In this study, the seismic-soil-structure interaction of the historical Çelebiağa Mosque located in Pertek district of Tunceli, which was first built in 1577 but later dismantled and rebuilt using the same materials, was examined. Soil profile information in the study area was determined as a result of site investigations and laboratory tests made by a local soil company. The architectural project for the superstructure model was examined, and the soil profile was modeled using the soil characteristics of the region. SAP2000 finite element analysis program was used in the analysis. Sivrice (2000) and Kocaeli (1999) earthquake records, which happened in the region recently, were used in the dynamic analysis. The results obtained from the analyzes are given in terms of the response spectrum, transmitted acceleration, and lateral displacement. The results obtained are as follows;

1. As a result of the numerical analysis, it has been revealed that local soil conditions significantly affect the response of the structure. Dynamic analyzes performed without considering local soil effects may not reflect the real situation with sufficient accuracy.

2. Considering the effect of underlying soil conditions, amplifications with different levels were observed under the Kocaeli and Sivrice earthquakes. This is attributed to the fact that both earthquakes have different characteristics and frequency content.

3. The peak ground acceleration was obtained as 0.51g at the flag level of the minaret under the Kocaeli earthquake and 0.94g under the Sivrice earthquake. Again, the maximum horizontal displacements of the minaret at the flag level were obtained as 11 cm and 8.5 cm under the Kocaeli and the Sivrice earthquakes. An increase of up to 60% was observed in the minaret's flag level at transmitted accelerations. At lower height joints, both the amplitude of accelerations and horizontal displacements get lower.

4. Although no structural damage was observed as a result of the Sivrice (2020) earthquake, the high fragility of long and thin structures is likely to pose a problem in the case of similar and larger earthquakes.

5. The maximum lateral displacement under the applied earthquake records was measured at the minaret flag level. This lateral displacement is in line with the Sungurbey mosque, which has similar ground and structural features.

This study was carried out to examine the dynamic soil-structure interaction of a historical masonry structure. Sungurbey Mosque, which has local soil characteristics, is reliable in terms of obtaining results close to the soil-structure integration analysis, but using different software tools. However, it is important to perform the dynamic soil-structure interaction studies, especially for masonry structures. The method used within the scope of the study will help to detect the damages that will occur in earthquake situations due to local geological conditions in historical buildings to be relocated. This approach will contribute to the preservation of the historical and cultural characteristics of the structures and their transfer to future generations in a sustainable way.

Author contributions: Conceptualization: Ö. Yıldız and E. Doğan; Methodology, Ö. Yıldız; Numerical Analysis: Ö. Yıldız; Interpretations of results: Ö. Yıldız; Investigation: Ö. Yıldız and E. Doğan; Writing -original draft: Ö. Yıldız and E. Doğan; Writing -review & editing: Ö. Yıldız

Funding: Not applicable.

Conflicts of interest: No conflicts of interest are disclosed by the authors.

References

Aydemir, M.E. (2010). Zemin Yapı Etkileşiminin Yapısal Davranış Parametreleri Üzerine Etkisi. M.Sc Thesis, Yıldız Teknik Üniversitesi, Türkiye. (In Turkish)

Aydınoğlu, M. N. (2011). Zayıf zeminlerde yapılan binalarda dinamik yapı-kazık-zemin etkileşimi için uygulamaya yönelik bir hesap yöntemi. Kandilli Rasathanesi ve Deprem Araştırma Enstitüsü, Deprem Mühendisliği Bölümü, Rapor, (2011/1). (In Turkish)

Balaban, T. Ö., Okan, Ö. Ö., Sancar, T., & Önal, A. Ö. (2020). Pertek (Tunceli) Jeotermal Alanının Antropojenik Kirliliğinin Değerlendirmesi. *Türkiye Jeoloji Bülteni*, *63*(1), 83-96. (In Turkish)

Bayrak, O.F., Bikçe, M. & Erdem, M.M. (2021). Failures of structures during the January 24, 2020, Sivrice (Elazığ) Earthquake in Turkey. Nat Hazards 108:1943–1969. https://doi.org/10.1007/s11069-021-04764-z.

Bayraktar, A., & Hökelekli, E. (2020). Influences of earthquake input models on nonlinear seismic performances of minaret-foundation-soil interaction systems. *Soil Dynamics and Earthquake Engineering*, *139*, 106368.

Borja RI, Chao HY, Montans FJ & Lin CH. 1998. Nonlinear SSI Analysis. Preproceedings UJNR Workshopon Soil Structure Interaction, California.

Brando, G., Pagliaroli, A., Cocco, G., & Di Buccio, F. (2020). Site effects and damage scenarios: The case study of two historic centers following the 2016 Central Italy earthquake. *Engineering geology*, *272*, 105647.

Brunelli, A., De Silva, F., Piro, A., Parisi, F., Sica, S., Silvestri, F., & Cattari, S. (2021). Numerical simulation of the seismic response and soil–structure interaction for a monitored masonry school building damaged by the 2016 Central Italy earthquake. *Bulletin of Earthquake Engineering*, *19*(2), 1181-1211.

Burat, O. (1973). Pertek Baysungur Camii'nin Taşınması. Vakıflar Dergisi 10: 290-298.

Casolo, S., Milani, G., Uva, G., & Alessandri, C. (2013). Comparative seismic vulnerability analysis on ten masonry towers in the coastal Po Valley in Italy. *Engineering Structures*, *49*, 465-490.

Celep, Z., & Kumbasar, N. (2004). Deprem muhendisligine giris ve depreme dayanikli yapi tasarimi. Beta Dagitim, Istanbul. (In Turkish)

Danık, E. (2004) Pertek Baysungur ve Ali Çelebi Camii. Vakıflar Dergisi 28: 185-210. (In Turkish)

De Silva, F. (2020). Influence of soil-structure interaction on the site-specific seismic demand to masonry towers. *Soil Dynamics and Earthquake Engineering*, *131*, 106023.

Dok, G., Aktaş, M. & Kırtel, O. (2015). Effect of Number of Story and Soıl Class in Nonlınear Pushover Analysıs of Two Dımensıonal Rc Frames Consıderıng Soıl Structure Interactıon. In: Eighth National Conference on Earthquake Engineering, Istanbul, Turkey, 11May-14 May 2015.

Erder, C., Stoop, P., Pratt, P.P., Bakırer, Ö., Tükel, A., Tayga, N., Rhodes, L., Mad, E., Özdural, A. & Üstünkök, O. (1967). Doomed by the Dam. Ankara: Türk Tarih Kurumu Basımevi, pp.6.

Fleming, J.F., Screwvala, F.N. & Kondner, R.L. (1965). Foundation Superstructure Interaction Under Earthquake Motion. In: Third World Conference on Earthquake Engineering, New Zealand, 22 January-1 Fabruary 1965, Vol.1 pp.122-130.

GDDA, General Directorate of Disaster Afairs (2019). Seismic Hazard Map of Turkey. Ministry of Public Works and Settlement of Turkey, Ankara (In Turkish

Güllü, H. & Pala, M. (2014). On the resonance effect by dynamic soil–structure interaction: a revelation study. Natural Hazards 72(2): 827-847.

Günaydin, M., Atmaca, B., Demir S, et al. (2021). Seismic damage assessment of masonry buildings in Elazığ and Malatya following the 2020 Elazığ-Sivrice earthquake. Bulletin of Earthquake Engineering 19(6): 2421-2456.

Gündüz, Z. & Arman, H. (2005). Zemin Davranışına Uygun Yapı Tasarımı İlkeleri ve Uygulanabilirliği. In: Kocaeli 2005 Deprem Sempozyumu, İzmit, Türkiye, 23-25 March 2005, pp. 1237-1243. Kocaeli Üniversitesi. (In Turkish)

Herece, E.İ. & Acar, Ş. (2016). Pertek (Tunceli) dolayının Üst Kretase Tersiyer Jeolojisi/ Stratigrafisi. MTA Dergisi 153: 1-43. (In Turkish)

Kaptan, K. & Tezcan, S. (2012). Deprem Dalgalarinin Zemin Büyütmesi Üzerine Örnekler. TÜBAV Bilim Dergisi, 5(4), 17-32. (In Turkish)

Karasözen, E., Özacar, A. A., Biryol, C. B., & Beck, S. L. (2014). Seismicity, focal mechanisms and active stress field around the central segment of the North Anatolian Fault in Turkey. Geophysical Journal International, 196(1), 405-421.

Kılıç, İ., Bozdoğan K..B, Aydın, S., Gök, S.G. & Gündoğan, S. (2020). Kule tipi yapıların dinamik davranışının belirlenmesi: Kırklareli Hızırbey Camii minaresi örneği. Politeknik Dergisi 23(1): 19-26. (In Turkish)

Lysmer, J. & Kuhlemeyer, R.L. (1969). Finite Dynamic Model for Infinite Media. Journal of the Engineering Mechanics Division, ASCE. 95(4): 859-877.

Milani, G., Casolo, S., Naliato, A., & Tralli, A. (2012). Seismic assessment of a medieval masonry tower in Northern Italy by limit, nonlinear static, and full dynamic analyses. *International Journal of Architectural Heritage*, *6*(5), 489-524.

Petridis, C., & Pitilakis, D. (2020). Fragility curve modifiers for reinforced concrete dual buildings, including nonlinear site effects and soil–structure interaction. *Earthquake Spectra*, *36*(4), 1930-1951.

Sextos, A., De Risi, R., Pagliaroli, A., Foti, S., Passeri, F., Ausilio, E., ... & Zimmaro, P. (2018). Local site effects and incremental damage of buildings during the 2016 Central Italy earthquake sequence. *Earthquake Spectra*, *34*(4), 1639-1669.

Sorrentino, L., Cattari, S., Da Porto, F., Magenes, G., & Penna, A. (2019). Seismic behaviour of ordinary masonry buildings during the 2016 central Italy earthquakes. *Bulletin of Earthquake Engineering*, *17*(10), 5583-5607.

Stewart, J. P., Zimmaro, P., Lanzo, G., Mazzoni, S., Ausilio, E., Aversa, S., ... & Tropeano, G. (2018). Reconnaissance of 2016 Central Italy earthquake sequence. *Earthquake Spectra*, *34*(4), 1547-1555.

Tatar, Y. (1987). Elazığ bölgesinin tektonik yapıları ve Landsat fotğrafları üzerinde yapılan bazı gözlemler. H.Ü. Yerbilimleri Dergisi 14: 295-308.

Tükel, A & Bakırer, Ö. (1970). 1968 Yılı Keban Projesi Restorasyon Çalışmaları Ön Raporu, Report for 1968 Yaz Çalışmaları. Report no. 1, Ankara, Türkiye.

Türkeli, E. (2020). Payanda ve FRP ile Güçlendirilmiş Betonarme Minarelerin Karşılaştırmalı Sismik Analizi. Doğal Afetler ve Çevre Dergsi 6:1–18. https://doi.org/10.21324/dacd.573368 (In Turkish)

Ural, A. & Celik, T. (2018). Dynamic Analyses and Seismic Behavior of Masonry Minarets with single Balcony. Aksaray University Journal of Science and Engineering 2(1): 13-27.

Varol, K. O. Ç. (2016). Depreme maruz kalmış yığma ve kırsal yapı davranışlarının incelenerek yığma yapı yapımında dikkat edilmesi gereken kuralların derlenmesi. Çanakkale onsekiz mart üniversitesi fen bilimleri enstitüsü dergisi, 2(1), 36-57. (In Turkish)

Waas, G. (1972). Analysis Method for Footing Vibrations Thorough Layered Media. Report for Earth Vibration Effects and Abatement for Military Facilities. Report 3, 01 September 1972. US Army Engineer Waterways Experiment Station, Missisipi.

Wilson, E.L. (1969). A Method of Analysis for the Evaluation of FoundationStructure Interaction. Proceedings of the Fourth World Conference on Earthquake Engineering, pp. 87-89. Santiago-Chile.

Yıldız, Ö., Doğan, E. & Yamak, F.B. (2021). Seismic soil-structure ınteraction of a masonry structure: Sungurbey Mosque. International Journal of Innovative Engineering Application 5(2): 273-249. https://doi.org/10.46460/ijiea.1004627.

Kausel, E. (1988) "Local transmitting boundaries", J. Eng. Mech. Div. ASCE, Vol 114, pp.1011-1027.

Mengi, Y. And Tanrıkulu, A.K. (1993) "Absorbing boundary conditions in soil-structure analyses" in Dynamic Soil-Structure Interaction, ed. P Gülkan & R.W. Clough. ATO Advanced Study Institute, Kemer-Antalya, Turkey, July 8-16 1992, Kluwer Academic, Dordrecht, 1993, pp.111-146.