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The Effects of Earthquake Reality on Historical Minarets, Evaluations Specific to the February 06, 2023 Kahramanmaraş Earthquake

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Abstract

When the masonry structures in the region were examined because of the February 6 Kahramanmaraş earthquake in Turkey, it was observed that mosque minarets were mostly damaged by overturning. Minarets, which are important for Islamic architecture, are susceptible to collapse under earthquakes due to their thin forms and high fragility rates. The behavior of structures against earthquakes is determined using various parameters. These parameters include material properties, location conditions, structural properties and existing damage. In this study, the translation ratios of the minaret of the Great Mosque of Kahramanmaraş, which is determined according to the typological characteristics in the earthquake zone with seismic risk, were calculated according to the probability of exceeding the performance limit values under the earthquake acceleration at the epicenter of Pazarcık-Kahramanmaraş and DD2 level, which occurred on 06.02.2023. The seismic behavior results of the models obtained according to the location of the minaret with the mosque (rising within the structure, adjacent to the structure and built separately from the structure) and soil class ZA, ZD were compared. The earthquake behavior of the minaret was analyzed by finite element analysis in SAP 2000 software. As a result of the study, it was determined that the displacement, maximum shear force and base shear force values obtained in the Pazarcık-Kahramanmaraş earthquake had larger values compared to the DD2 level earthquake level. The largest displacement occurred in the Pazarcık-Kahramanmaraş earthquake in Model 1 in the ZD soil class when the minaret was located separately from the structure. When the displacement values of the minaret are analyzed, it reached the highest level at the bracelet level.

1. Introduction

Historical buildings are the elements that constitute cultural heritage. Anatolia, home to many civilizations, has structures built with different techniques and materials. Minarets, which have an important meaning in terms of Islamic belief, are tall, delicate structures built in the form of towers (Işık, et al., 2022). Stone, brick, wood and mortar were used together in historical minarets. Minarets are cantilevers extending to the ground as a static feature. They have low flexibility under horizontal loads and exhibit brittle behavior. It is easy to crumble under deformations. These types of structures break suddenly without undergoing plastic deformation with loads slightly above the safety limits. They can immediately become unstable from their steady state equilibrium (Erdoğan, et al., 2010). Most of the historical buildings are located in earthquake zones and are frequently exposed to moderate and severe earthquakes. Therefore, it is important to protect historic masonry structures and evaluate their structural safety.

Many researchers have experimentally and analytically investigated masonry minarets in terms of seismic load. Nohutçu, 2019 investigated the seismic effect on a historic masonry minaret under different ground motions. Mortezaei, et al., 2012; performed structural analysis to evaluate the structural behavior and the effect of seismic loads on a masonry minaret under applied static and dynamic loads using the finite element method. Doğangün, et al., 2006; evaluated the performance of masonry minarets in Turkey against winds and earthquakes. Livaoğlu, et al., 2006; investigated the effect of geometric properties on the dynamic behavior of historic masonry minarets. Hökelekli and Al-Helwani, 2019; studied the effect of soil properties on seismic damage assessment of historic masonry minarets and soil interaction systems. El-Attar, et al., 2005; investigated the seismic vulnerability of a representative Mamluk-style minaret. The study evaluated seismic protection techniques, presented a realistic three-dimensional study, conducted ambient vibration tests and obtained a finite element model of the minaret. Korumaz, et al., 2017; performed a deflection analysis with a finite element model based on terrestrial laser scanning (TLS) to identify the structural health of a historic minaret.

Established in the northeast of the Mediterranean region, Kahramanmaraş is a city that has been relocated several times due to the earthquake zone of the region (Eker, 2013). Maraş, which has been home to many different civilizations until today, is extremely important because it is located on the trade routes connecting Mesopotamia, Syria and Central Anatolia. The minarets of the central Kahramanmaras belonging to the Ottoman Period are important architectural elements showing the effects of the Principalities Period and Dulkadiroğulları Principality (Sönmeztürk, 2022).

On 06.02.2023 at 04:17, an earthquake with a magnitude of Mw7.7 and a focal depth of approximately 8.6 km occurred in the Eastern Anatolia region. The epicenter of the earthquake was Pazarcık-Kahramanmaraş (AFAD, 2023). Investigations revealed that at least three different segments with a minimum length of 300-350 km ruptured together (USGS NEIC, 2023; Garini ve Gazetas Report, 2023). The earthquake that occurred on the Eastern Anatolia Fault Zone caused loss of life and property in 11 provinces. As a result of the field surveys carried out in the center of Kahramanmaraş, intense structural damages were observed. The settlement area of old Kahramanmaras was built on soft and alluvial young ground, the bedrock was deep and the high acceleration values seen in a wide period scale because of the acceleration released during the earthquake caused destruction due to the resonance effect in the ground conditions. While no damage was observed in the structures located at higher altitudes on more solid and older rocks, less destruction and heavily damaged structures were observed in the transition section between the two areas (GTÜ/MARTEST, 2023).

When determining the seismic behavior of structures, seismicity parameters and the location of construction should be considered. The interaction between the structure and the ground plays an important role in determining seismic behavior correctly. The architectural and material properties of the 19 minarets in the center of Kahramanmaraş examined in this study differed. Ten of the minarets were built adjacent to the building, the minarets of eleven mosques have a cylindrical body form, the bodies and square pedestals are built of cut stone material. Ten of them have polygonal (nine of them are dodecagonal, one of them is octagonal) bodies. Four of them have pulpit sections, eighteen minarets were built with single balconies, while Divanlı Mosque Minaret was built with double balconies. Eighteen of them have an upper part of the minaret section made of cut stone, only the upper part of the minaret section of the Duraklı Mosque minaret is made of brick. The upper part section has a thick and short cylindrical form but has a thinner structure than the bodies of the minarets. All the cones end in a conical cone shape. The cones were built with cut stone, concrete, wood and lead-coated materials. The luminaries are not original but were added later. Wooden materials were used for the balustrades and the cone section covering the upper part of the closed balconies built in the pavilion type.

06.02.2023 As a result of the Mw 7.7 earthquake centered in Pazarcık district of Kahramanmaraş province, most of the central minarets were damaged. Damaged minarets are given in Table 1.

Table 1. Characteristics of minarets severely damaged in the Kahramanmaraş earthquake

Name	Image	History	Location	Height
Kahramanmaraş Ulu Mosque Minaret		1442-1454	Built Separate from Structure	22,10 m.
Hatuniye Mosque Minaret		1509-1510	Built Separate from Structure	21,30 m.
Saraçhane Mosque Minaret		1618	Built Adjacent to Structure	17 m.
Şekerli Mosque Minaret		1695-1696	Within the Structure has risen	14 m.
Acemli Mosque Minaret		1912-1914	Built Adjacent to Structure	30 m.
Şıh Mosque Minaret		XVII	Within the Structure has risen	21,67 m.
Bogazkesen Mosque Minaret		XVII	Built Adjacent to Structure	21,60 m.
Bektutiye Mosque Minaret		1891	Built Adjacent to Structure	18,78 m.

The earthquake data records of Pazarcık-Kahramanmaraş and DD2 level earthquake that occurred on 06.02.2023 were used as earthquake acceleration. The aim is to determine the seismic behavior and performance of the minaret in relation to the structure and to reveal the effects of different earthquake grounds. Three-dimensional finite element models of the minaret were created, structural analyses were performed and the numerical dynamic properties were determined numerically.

As a result of 19 minarets investigated in the center of Kahramanmaras, the analysis study was carried out on the minaret of Ulu Mosque to compare different formal and soil properties through a single model. The effect of the minaret's bearing conditions with the mosque and the soil class against the earthquake were analyzed. The structure suffered severe damage because of the earthquake centered in Kahramanmaraş on 06.02.2023 (Figure 1).

(a) (b)

Figure 1. (a) Ulu Mosque and Minaret (Gönültaş, 2018), (b) The Ulu Mosque and its minaret, which were destroyed as a result of the 06.02.2023 Kahramanmaraş-centered earthquake (Yurtbakan, 2023)

The rectangular-plan mosque, which extends in the east-west direction, consists of a forecourt (last congregation area), a prayer hall and a minaret. It opens to the courtyard through a monumental portal on the west. Access to the prayer hall is provided through two rectangular doors located at the southwest and northeast corners (Figure 2). The north and east sides of the mosque are surrounded by a later-added courtyard with domed porticoes, next to which non-original toilet and ablution facilities have been placed. A forecourt covered with a wooden roof has been added to the north of the prayer hall. On the western side, there is also a women's gallery extending in the north-south direction (Gönültaş, 2018).

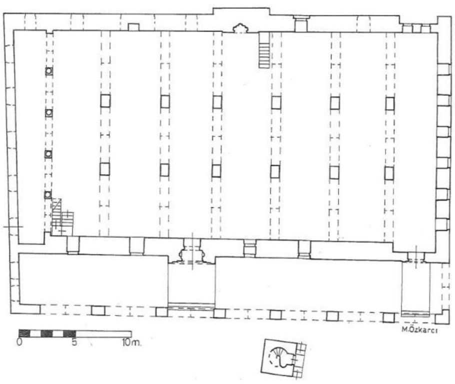
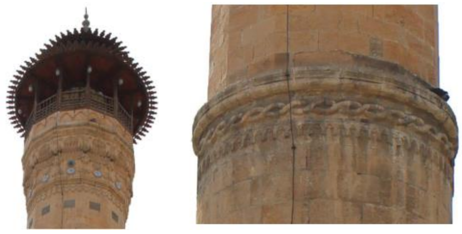


Figure 2. Ulu Mosque and Minaret ground floor plan (Gönültaş, 2018)

When examined in terms of construction material, rubble and rough-hewn stone body walls, cut stone and marble in two colors were used in the crown door, yellowish stone in the minaret, and wooden material in the cover system of the mosque (Sönmeztürk, 2022).

The minaret, built separately from the mosque, is made of cut stone material and its height is 22.10 meters. The rostrum is reached by seventy-six stone steps. The height of the square-shaped pedestal is 4.00 meters, built of cut stone material. The octagonal shaped shoe section was formed by beveling the corners after the base. The body is composed of two sections, dodecagonal and cylindrical. The minaret has a single balcony and the balustrades are made of stone and wood. The upper part section is short and blunt, and the wooden roof and wooden poles are covered with wide eaves. The minaret ends with a conical cone. The tip ornament is not in its original state but was added later (Figure 3).



(a) (b)

Figure 3. (a) Ulu Mosque Minaret, (b) bracelet detail

2. Method

The structural behavior of masonry minarets is obtained through computational resources. The Finite Element Method (FEM) enables the evaluation of the load capacity of masonry structures and the analysis of their mechanical behavior by considering their non-linear behavior (Adam, M. A., et al., 2020). The dynamic behavior of masonry towers depends on the intensity of the ground shaking, the frequency content of the earthquake wave and the soil type (Soyluk and İlerisoy, 2013).

Considering that the stone and mortar used in the minaret of the Ulu Mosque behave like a homogeneous material, their mechanical properties were evaluated with reference to the studies assumed in the literature. The properties of the stone material given in the current studies are given in Table 2.

Table 2. Material properties of stone material in the current literature

Source	E (Mpa)	υ	g (kg/m3)
Doğangün, et al., 2008	3000	0.2	2500
Çakır, et al., 2011	8500	0.2	2300
Sepetçi, 2012	450	0.2	2400
Şeker, et al., 2014	10180	0.17	2358
Erdoğan, et al., 2014	7360	0.2	2500
Günal, et al., 2018	10000	0.2	1800
Nohutçu, 2019	12240	-	2200
Yurdakul, et al., 2021	16649	0.12	1820

The thickness of the minaret was modeled as 30 cm for the central stone, 45 cm for the outer wall, 20 cm for the stair flooring and 55 cm for the bracelet section. The diameter of the core in the center carrying the staircase modeled as a frame was determined as 60 cm and the dimensions of the wooden column were determined as 30 x 50 cm. The material properties of the stone and wood used in the study are given in Table 3 and Table 4.

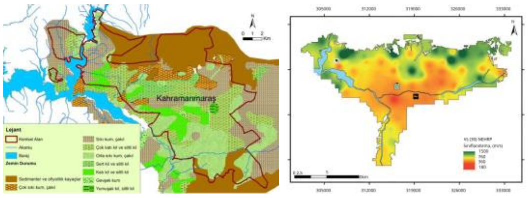
Table 3. Material properties of stone and wood used in the study

Material Properties	Stone	Wood
Unit Volume Weight (kN/m3)	24,51	9,80
Modulus of Elasticity (MPa)	1.0000	588,5
Poisson Ratio	0.17	0.20
Shear Modulus (G)	4273923	245209,16

Table 4. Material properties of the stone core and wooden column used in the study

Material Properties	Stone Core	Wooden Column
Cross-section (axial) area (m^2)	0,2827	0,15
Moment of inertia about 3 axis ($kN{\cdot}m^2$)	6,362E-03	3,125E-03
Moment of inertia about 2 axis ($kN{\cdot}m^2$)	6,362E-03	1,125E-03
Shear area in 2 direction (m^2)	0,2545	0,125
Shear area in 3 direction (m^2)	0,2545	0,125
Torsional constant (m^4)	0,0127	2,817E-03

Kahramanmaraş and its immediate surroundings are morpho tectonically on the collision zone of the Anatolian Plate and the Arabian Plate. Kahramanmaraş is under the influence of the Eastern Anatolian Fault and Dead Sea Fault formed in the Miocene. As a result of the relationship between soil properties and earthquake intensity, morphological and geologic properties of the building as well as its structural properties are important in the damage that will occur in the building during an earthquake (Sandal and Karademir, 2013) Figure 4. shows the soil properties in Kahramanmaraş and the shear wave velocity map for the city center. As a result of the maps, it is observed that the ground conditions are very variable on a city basis. Vs (30) (average shear wave velocity for the upper 30 m in soils) distributions show that there are various soils ranging from soft soils to rocky soils. It is determined that the characteristics of the structure and different ground conditions affect the damage distribution (GTÜ/MARTEST, 2023).



(a) (b)

Figure 4. (a) Ground Condition of Kahramanmaraş and Its Surroundings (b) Shear wave velocity map of Kahramanmaraş city center (Sandal and Karademir, 2013, Naji, et al, 2020)

For a comparative evaluation, the evaluation was made according to the local soil class ZA and ZD classes in the Turkish Building Earthquake Code (TBDY) -2018 obtained as a result of the field investigation. Soil class properties are shown in Table 5 and Table 6.

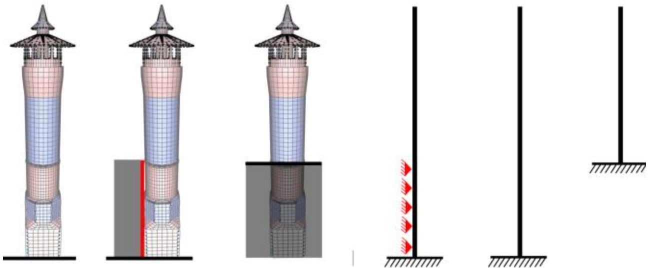
Table 5. ZA and ZD Soil Classes (TBDY-2018)

Local Ground Grade	Soil Type	Average in the top 30 meters		
		(Vs)30 [m/s]	(N60)30 [coup /30 cm]	(cu)30 [kPa]
ZA	Solid, hard rocks	> 1500	-	-
ZD	Moderate to dense layers of sand, gravel or very solid clay	180 – 360	15 – 50	70 – 250

Table 6. ZA and ZD Soil Class Properties (AFAD, 2023)

Values	ZA Ground Class	ZD Ground Class
SS (Short period map spectral acceleration coefficient)	1.163	
S1 (map spectral acceleration coefficient for 1.0 second period)	0.310	
PGA (Maximum ground acceleration [g])	0.489	
PGV (Maximum ground speed [cm/sn])	31.388	
FS (Local Ground Effect Coefficient for Short Period Region)	0.800	1.035
F1 (Local Ground Effect Coefficient for 1.0 second period)	0.800	1.990
SDS (Short period design spectral acceleration coefficient)	0.930	1.203
SD1 (design spectral acceleration coefficient for 1.0 second period)	0.248	0.617

Three-dimensional (3D) solid model of Kahramanmaraş Ulu Mosque minaret was prepared in SAP2000 Finite Elements program. The structure consists of a total of 5490 meshed areas. The building is modeled as built-in in model 1. Considering adjacent to the mosque in Model 2, a fixed support is assigned along the wall up to the body, and a built-in support is defined where the interaction with the ground will take place. In Model 3, on the other hand, the shoe part was ignored, and it was analyzed by taking a built-in support from the body part, which is thought to work with the mosque and rises within the mosque (Figure 5.). The weight of the structure is 2414 kN in Model 1 and Model 2; In Model 3, it is 1485 kN.



(a) (b)

Figure 5. (a) Model 1 (discrete), Model 2 (adjacent) and Model 3 (within) finite element support conditions (b) mathematical model.

Full contact of points is very important for load transfer in three-dimensional models in structures with different geometric cross-sections (Usta, 2021). The details and geometric dimensions of the minaret used in the modeling were obtained from the relevant literature studies. Since the stairs affect the dynamic behavior of the minarets (Usta, 2021), the stairs inside the minaret are included in the model. Since the displacement of the eaves on the cantilevered balcony in the modeled minaret is higher than the top of the building and it affects the modal movement of the building, it has been ignored in the analysis to get more accurate results. The values determined in the analysis study of the building according to TBDY- 2018 are given in Table 7.

Table 7. Analysis parameters according to (TBDY- 2018)

Earthquake Design Class (DTS)	1
Building Height Class (BYS)	5
Building Use Class (BKS)	2
Building Importance Factor (I)	1.2
Carrier System Behavior Coefficient (R)	2.5
Coefficient of Excess Strength (D)	1.5

3. Findings

In the spectrum analysis study carried out for the minaret, the DD2 earthquake level, which is the earthquake ground motion level that has a 10% probability of exceeding in 50 years as an earthquake level, was obtained from the AFAD website and the 6 February 2023 Pazarcık- Kahramanmaraş earthquake acceleration records Kahramanmaraş earthquake data were obtained from the seismic recording station AFAD-TADAS 4615. A total of three acceleration components, two horizontal and one vertical, were used in the analyses. The design spectra for the ZA and ZD ground classes are given in Figure 6. and Figure 7.

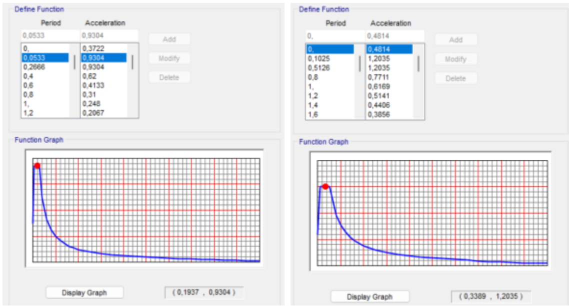
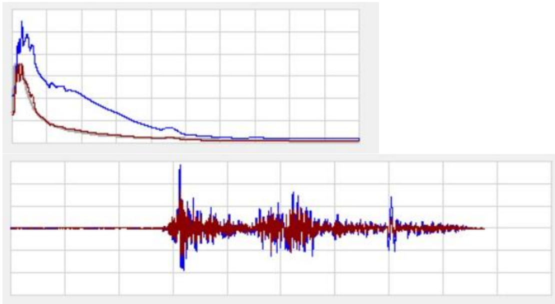
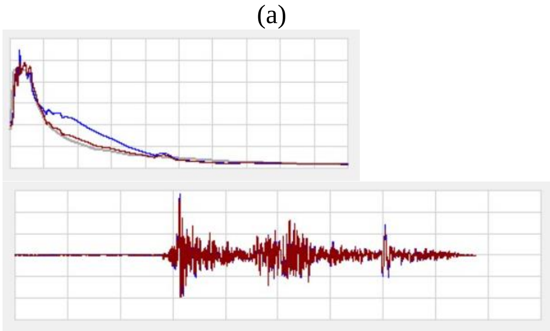


Figure 6. DD2 level Earthquake Level (a) ZA ground class and (b) ZD ground class according to the design spectra, time-acceleration graph



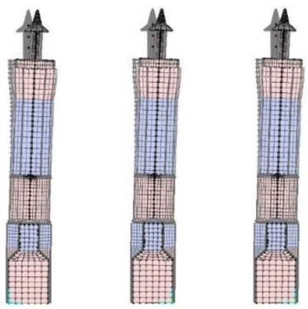
(a)



(b)

Figure 7. Pazarcık-Kahramanmaraş Earthquake (a) ZA soil class, (b) ZD soil class according to design spectrums, time-acceleration graph

The minarets, which are modeled as rising within the structure, adjacent to the building and built separately from the building, have been examined in terms of mode shapes and displacements. For the static analysis, the self-weight of the structure and other dead loads were considered. The first three mode shapes of the minaret are given in Figure 8. In Model 2 and Model 3, the translation directions are the same for modes 1-2 and 3.



(a) (b) (c)

Figure 8. The minaret (a) translation in the x direction (b) translation in the y direction (c) torsional modal movements around the axis.

Modal analysis is a type of analysis performed to obtain the dynamic characteristics of engineering structures called period, frequency and mode shape. This type of analysis is especially necessary for the evaluation of the correct design in newly designed structures. Parameters that affect the modal analysis results are the mass and rigidity of the structure.

Modal analysis is very important in terms of creating initial data for many structural analyses performed during the analysis of engineering structures. All structures are in a certain vibrational state in their current state. Since these vibrations are at a very low level, they cannot be clearly felt by people and cannot be perceived by the eye, they can only be measured with the help of a sensitive accelerometer. The parameters used to define a vibrating structure are mainly; period, frequency and mode shape and these parameters are called dynamic characteristics (Altunışık, et al., 2018). The modal frequency results of the minaret are given in Table 8 for each model and soil class.

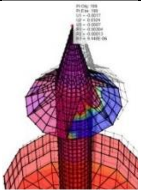
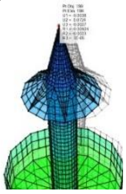
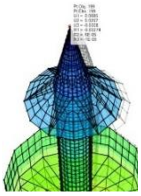
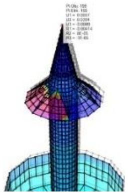
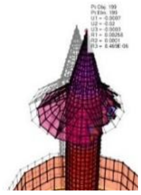
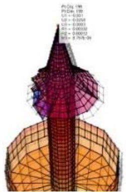
Table 8. Modal frequency values.

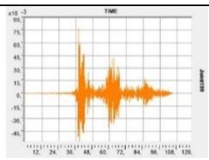
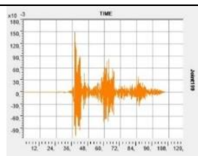
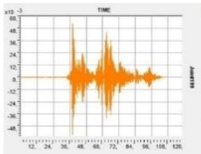
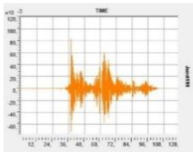
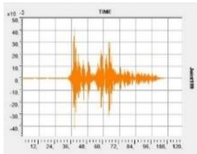
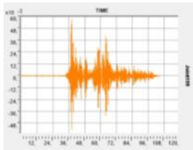
Model No	Mode-1 Frequency (Hz)	Mode-2 Frequency (Hz)	Mode-1 Frequency (Hz)
Mode-1 (Split)	2.06	2.08	8.86
Mode-2 (Adjacent)	2.85	2.95	9.96
Mode-3 (Included)	3.72	3.76	10.39

Model 3 has the highest Mod frequency values because its mass is lower than other models, its rigidity is higher, and Model 2 has higher Mod values than Model 1 because its stiffness is higher due to the increase in the number of supports. The reason why the Mode 1 and Mode 2 frequency values for each model are close to each other is that the structure is symmetrical in the x and y directions in the plan plane.

The methods performed depending on the displacement values are the structural performance evaluation method, which is based on non-linear analyzes used to determine the behavior of structures against earthquakes (Korkmaz and Kayhan, 2007). In masonry structures, displacements in the plane direction of the wall do not adversely affect the stability of the structure. Friction in the plane of the wall limits crack formation. In the process when the earthquake load affects in this direction, the cracks grow. As the focal depth increases, the destructiveness and damage values of the earthquake decrease and spread to wider ranges (Çarhoğlu and Korkmaz, 2013). The displacement results of the models according to the soil classes under the DD2 Earthquake Level and Pazarcık-Kahramanmaraş Earthquake acceleration records are given in Table 9.

Table 9. Maximum displacement results of models according to ZA and ZD Ground Class

Maximum Displacement (mm)	DD2 Earthquake Level	
	ZA Ground Class	ZD Ground Class
Mode-1 (Split)	 32 mm	 72 mm
Mode-2 (Adjacent)	 25 mm	 39 mm
Mode-3 (Included)	 20 mm	 25 mm

Maximum Displacement (mm)	Time History Pazarcik-Kahramanmaras Earthquake	
	ZA Ground Class	ZD Ground Class
Mode-1 (Split)	 77 mm	 149 mm
Mode-2 (Adjacent)	 56 mm	 83 mm
Mode-3 (Included)	 41 mm	 57 mm

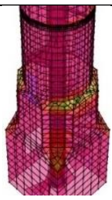
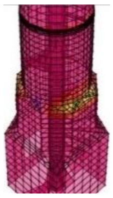
At the DD2 earthquake level, it was observed that the displacement increased by 125% when the soil strength (transition from ZA soil class to ZD soil class) decreased in Model 1. This decreases to 56% in Model 2 and 25% in Model 3. The order of displacement among the models in the ZA soil class is as follows, from Model 1 to Model 2 it decreases by 21%, from Model 2 to Model 3 by 20%, from Model 1 to Model 3 by 37.5%. In the ZD soil class, the displacement order between the models is as follows, from Model 1 to Model 2 it decreases by 45%, from Model 2 to Model 3 by 35.9%, from Model 1 to Model 3 by 65%.

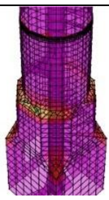
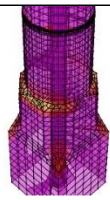
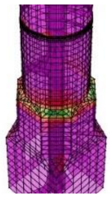
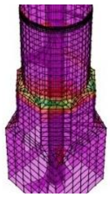
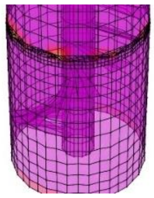
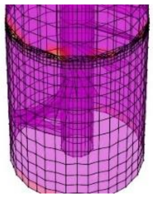
At the Pazarcık-Kahramanmaras earthquake level, it was observed that the displacement increased by 93% when the soil strength (transition from ZA soil class to ZD soil class) decreased in Model 1. This decreases to 48% in Model 2 and 39% in Model 3. The order of displacement among the models in the ZA soil class is as follows, from Model 1 to Model 2 it decreases by 27%, from Model 2 to Model 3 by 26%, from Model 1 to Model 3 by 46%. In the ZD soil class, the displacement order between the models is as follows, from Model 1 to Model 2 it decreases by 44%, from Model 2 to Model 3 by 31%, from Model 1 to Model 3 by 61%.

Considering the results, the displacement of the ZD soil class is greater due to the higher acceleration values than the ZA soil class. The decrease in the height of the building in Model 3 minimizes the ground-building interaction. If the minaret is adjacent to the building, the effect of the ZD soil class is reduced because the buckling length is shortened more.

Within the scope of the study, the maximum shear force values in the minaret were obtained (Table 10.). The reason why the maximum tension force in Model 3 occurs at a different point from Model 1 and Model 2 is that the minaret is located within the mosque and its support point changes.

Table 10. Maximum shear force values according to ZA and ZD Soil Classes

Shear Force Values (kN/m)	DD2 Earthquake Level	
	ZA Ground Class	ZD Ground Class
Mode-1 (Split)	 785,55 kN/m	 1607,97 kN/m
Mode-2 (Adjacent)	 1162,05 kN/m	 1716,44 kN/m
Mode-3 (Included)	 987,47 kN/m	 1245,4 kN/m

Shear Force Values (kN/m)	Pazarcik-Kahramanmaras Earthquake	
	ZA Ground Class	ZD Ground Class
Mode-1 (Split)	 1540,15 kN/m	 3086,25 kN/m
Mode-2 (Adjacent)	 1542,38 kN/m	 2242,83 kN/m
Mode-3 (Included)	 1681,76 kN/m	 2243,58 kN/m

When the shear force values were examined, it was observed that the highest value increased to 1716.44 kN/m and the cutting force was concentrated in the bracelet, which is the joining element in the transition from the cylindrical body form to the dodecagon body form. The minaret was damaged in the earthquake that took place on 06.02.2023 and collapsed.

Table 11. shows the values of the base shear forces obtained from the DD2 earthquake motion spectrum of the base shear forces determined according to the minaret structure position relationship for different local soil classes.

Table 11. Effect of ZA and ZD Soil Classes on base shear force

Basic Reactions (kN)	ZA Ground Class		
	FX (G+Ex)	FX (Pazarcik-Kahramanmaras)	FZ (1.4G)
Mode-1	645,051	1396,4	2817,214
Mode-2	658,587	1475,831	2817,214
Mode-3	678,672	1298,854	1723,482

Basic Reactions (kN)	ZD Ground Class		
	FX (G+Ex)	FX (Pazarcik-Kahramanmaras)	FZ (1.4G)
Mode-1	1313,409	2754,632	2817,214
Mode-2	1026,322	2576,891	2817,214
Mode-3	862,843	1976,34	1723,482

The reason why the basic response in Model 3 is higher than Model 1 and Model 2 is because the building works directly within the body of the mosque without a pedestal. The base shear forces obtained according to the

ZD floor class give more effect as the height of the building increases.

4. Discussion

In the study, finite element analyses conducted in SAP2000 environment revealed the decisive role of both local ground effect and structural system configuration on the dynamic behavior of the minaret. In the weak ground class ZD, significant increases were observed in displacement values as well as base and shear forces. Especially in Model 1 (separate structure), displacement increased by 125% compared to DD2 earthquake level, while this rate remained at 25% in Model 3. These results are consistent with studies showing that soil-structure interaction conditions extend the periods of structures in non-rigid grounds and the system becomes more sensitive to resonance.

Modeling results revealed that when the minaret is independent of the mosque structure (Model 1), both displacement and stress values are significantly higher compared to other models. This situation is parallel to the literature emphasizing that the boundary conditions and rigidity level of the structural system greatly affect seismic demands. In fact, a more balanced performance was observed in systems exhibiting integrated behavior between structural elements thanks to moment transfer and load sharing.

The distribution of shear forces shows that it reaches maximum values in the collar section, which is the geometric transition region. This stress, which reaches 3000 kN/m, especially in the Model 1 - ZD combination, indicates that the damage to the minaret will be concentrated in this region to a large extent. This observation is also supported by numerical and experimental studies showing that geometric discontinuities (diameter transitions, balcony beginnings) cause stress accumulation under seismic loads.

In the modal analysis, the first natural frequency of Model 3, which is integrated with the structure, was measured as 3.72 Hz, which was higher than the other models. This situation shows that the increased stiffness level increases the natural frequency and reduces seismic demands. Similarly, it has been shown in the literature that both frequency and shape modes become more stable in integrated systems. In line with these findings, it is suggested that in ensuring the earthquake safety of historical minarets, not only the geometric and material properties but also the local soil conditions and the integrity of the load-bearing system should be evaluated in a holistic manner.

5. Conclusion

In this study, the seismic behavior of the historical Ulu Mosque minaret was thoroughly analyzed using the finite element method, considering the effects of the February 6, 2023 Pazarcık-Kahramanmaraş earthquake. The analysis was conducted across different soil classes and various mosque-minaret configuration types. The results indicated that as ground acceleration increased, displacements also increased, and as soil strength decreased, displacements became more pronounced. In Model 1, the maximum base shear force in the FX direction under soil class ZD was recorded as 2754.632 kN, representing a 109% increase compared to the DD2 level earthquake scenario of the Pazarcık-Kahramanmaraş event. Examination of shear force distributions revealed that the highest displacement occurred under the ZD soil class during the same earthquake scenario in Model 1.

The findings clearly demonstrated the significant impact of soil class (ZA–ZD) and the minaret's spatial relationship with the mosque (separate, adjacent, or integrated) on seismic performance. Especially under weak soil conditions classified as ZD, substantial increases in displacement and shear forces were observed due to the combined effects of the structural system geometry and the interaction configuration with the mosque. This provides a practical basis for identifying critical damage zones in minarets and enables risk-based prioritization in conservation and strengthening projects.

The dynamic parameters obtained through the implemented three-dimensional finite element models offer a valuable contribution to the limited database in the literature concerning the behavior of historical minarets on weak soils. The concentration of shear forces particularly in the bracelet region reveals the amplifying effect of geometric transitions along the minaret shaft on seismic damage, which is a crucial outcome for identifying structural vulnerabilities.

This study, which extensively evaluates parameters such as soil class and mosque-minaret connection configurations in terms of their dynamic impact, provides comparative data to existing studies through its modeling strategies and material parameters used in structural analysis. Furthermore, the results of the modal analyses and base shear forces generated under seismic excitation constitute a scientific foundation for future restoration and retrofitting interventions.

The results obtained reveal that the structure-soil interaction, geometric configurations and material properties should be evaluated together for historical minarets located in regions with high earthquake risk. Although there are similar approaches in the literature, the fact that this study was conducted on both an original earthquake record and a specific historical structure shows that the findings offer site-specific, locally valid and applicable solution suggestions.

Author contributions

Türkan Büşra Başar: Conceptualization, Methodology, Discussions, Writing-Reviewing and Editing **Zeynep Yeşim İlerisoy:** Conceptualization, Methodology, Discussions, Writing-Reviewing and Editing **Mustafa Başar:** Data curation, Software, Validation.

Conflicts of interest

The authors declare no conflicts of interest.

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