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Structural evaluation for the preservation of an ancient Egyptian Obelisk in Istanbul, Turkey

Istanbul'da eski bir Mısır dikilitaşının koruma amaçlı yapısal değerlendirilmesi

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ABSTRACT

The "Obelisk of Theodosius" is one of the most important monuments located in the former Hippodrome in Istanbul, Turkey. The Obelisk with its sculpted base is 24.77 meters in height today, but historical recordings indicate that it was evidently higher originally. Additionally, the recordings show that some of the parts were left behind in Egypt due to transportation. The Obelisk has been exposed to many natural devastating events, particularly strong earthquakes. The monument is in a seismically very active region, Istanbul, located near one of the most devastating active faults of Turkey, the North Anatolian Fault. For the preservation of this obelisk, it is important to evaluate its seismic performance. For this purpose, in this study, the structural dynamic characteristics and the response of the obelisk were investigated. To achieve this aim, a numerical model was created using a finite element approach. In addition to this, real ground motion data were analyzed in this study. The most important finding of the study is that although the obelisk had experienced devastating earthquakes for a long time, revealed deformation is not noticeable. Its strength against earthquakes is most likely related to its constructed materials.

Keywords: Obelisk of Theodosius, numerical analysis, dynamic analysis, earthquake behavior.

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ÖZ

Theodosius Dikilitaşı İstanbul'daki eski Hipodrom'da bulunan en önemli anıtlardan biridir. Dikilitaş, heykel tabanıyla bugün 24.77 metre yüksekliğindedir, ancak tarihi kayıtlar orijinal yapının belirgin şekilde daha yüksek olduğunu göstermektedir. Ayrıca, kayıtlar bazı parçaların nakliye nedeniyle Mısır'da geride kaldığını göstermektedir. Dikilitaş, özellikle depremler olmak üzere birçok doğal yıkıcı olaya maruz kalmıştır. Bilindiği gibi, Dikilitaş'ın bulunduğu bölge sismik olarak çok aktiftir çünkü Türkiye'de potansiyel olarak en yıkıcı fay sistemine sahip olan Kuzey Anadolu Fayı ve onun segmentleri bu bölgede gelişmiştir. Dikilitaş'ın korunması için sismik performansını değerlendirmek önemlidir. Bu amaçla, bu çalışmada, yapısal dinamik özellikler ve Dikilitaş'ın tepkisi incelenmiştir. Bu amaca ulaşmak için sonlu elemanlar yaklaşımı kullanılarak sayısal bir model oluşturulmuştur. Buna ek olarak, bu çalışmada gerçek yer hareketi verileri analiz edilmiştir. Çalışmanın en önemli bulgusu, Dikilitaş'ın uzun süre yıkıcı depremler yaşamasına rağmen, ortaya çıkan deformasyonun belirgin olmadığıdır. Depremlere karşı dayanıklılığı büyük olasılıkla inşa malzemeleriyle ilgilidir.

***Anahtar kelimeler**: Theodosius Dikilitaşı, sayısal analiz, dinamik analiz, deprem davranışı.*

INTRODUCTION

There are a number of ancient monuments, which were founded during the ancient Egyptian period. Obelisks are one of the significant historical monuments with a high, four-sided shape that tapers into a pyramid at the top. Due to different reasons, they were moved to be located at around various parts of the world. The raw construction materials during the ancient Egypt period mainly comprised of building stones and clay-rich Nile mud (Klemm and Klemm, 2001). A geologic study carried out on the building stones of ancient Egypt well proved that a systematic quarrying organization was constructed to transport logistics over extreme distances and a high standard of stone masonry for the immense quantities of the different stone materials (Klemm and Klemm, 2001). Presently, one of these Obelisks, also known as the Obelisk of Theodosius, remains standing in the Hippodrome of Istanbul (Figure 1). In the years between 1479 and 1425 BCE, the Obelisk of Thutmose III originally stood at the temple of Karnak, Egypt. Then, this Obelisk was brought from Egypt by Roman emperor Theodosius I in the 4th century CE. The Obelisk was placed at the Hippodrome during more than half of 2 millennia. A part of the Obelisk was missing (Klemm and Klemm, 2001; Klemm and Klemm, 2008). Before the lower part was damaged from transportation or re-erection, it was approximately 34.9 m tall by now 19.5 m. The Obelisk remains standing on four bronze cubes rest on a marble pedestal.

Throughout history, many devastating earthquakes occurred in the city of Istanbul because of an active tectonic regime controlling the region. The long-term seismic activity of the Marmara region is exhibited in Fig. 1. As seen in Fig. 1, from 1500 to the present, many devastating earthquakes greater than 7 occurred in this region (e.g. Ambraseys and Jackson, 2000). Before this period, several earthquakes also should have occurred in this region. Such seismic events caused noticeable damages to the new and historical structures in Istanbul.

Many studies were performed to investigate the seismic behavior of historical structures to reveal that they are significantly vulnerable to earthquakes (Cakti et al., 2015; Cakti et al., 2016; Saygili, 2019). For the preservation of this obelisk, the structural dynamic characteristics and the seismic response are investigated. A numerical model was created using a finite element approach and nonlinear dynamic analyses are performed under real ground motions.

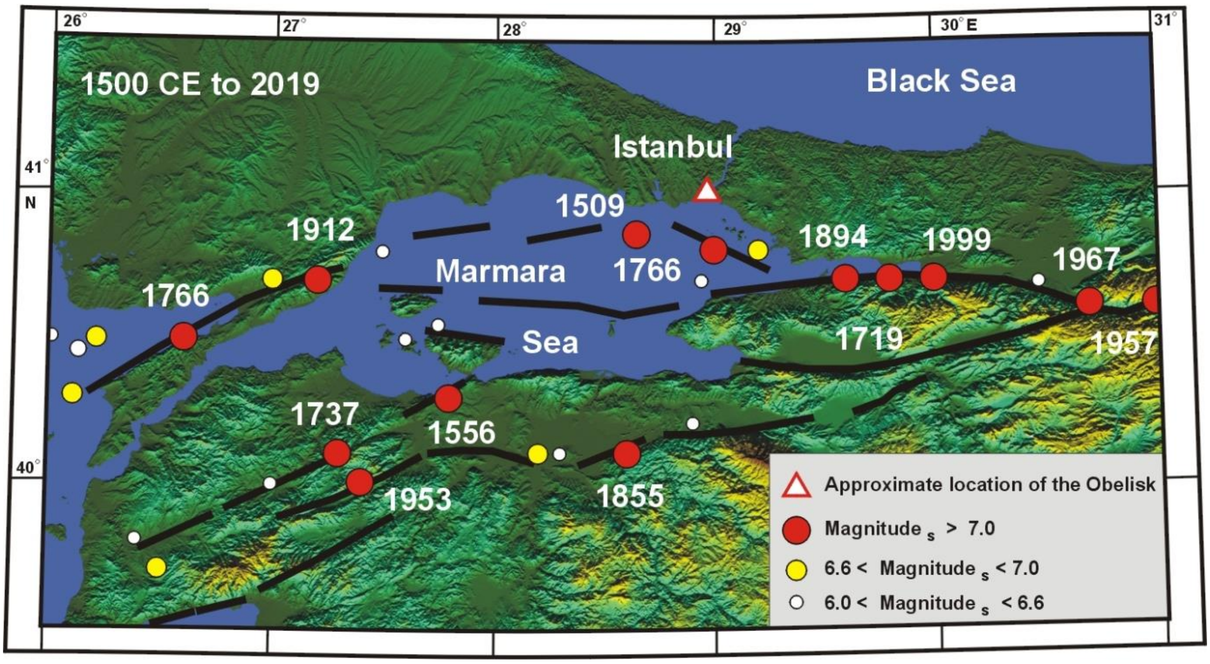

Figure 1. Map showing the major earthquakes occurred near Istanbul city, since 1500 CE, along the western part of the North Anatolian Fault Zone with fault segments represented by black lines (modified from Ambraseys and Jackson, 2000). Numbers correspond to occurrence years of the earthquakes with magnitudes measured or estimated to be greater than 7.0.

Şekil 1. 1500 yılından beri Istanbul şehri yakınlarında kırıkları siyah çizgilerle gösterilen Kuzey Anadolu Fay Zonu boyunca meydana gelen büyük depremler (Ambraseys ve Jackson, 2000'den değiştirilerek alınmıştır). Sayılar büyüklüğü 7.0 dan büyük olduğu ölçülen veya tahmin edilen depremlerin oluş yıllarına karşılık gelmektedir.

Numerical Model

An investigation on the Obelisk of Theodosius with the aid of an electronic distance-measuring instrument of a total station was performed (Saygili, 2019). Information on the geometrical properties and structural details of the Obelisk were acquired from (Saygili, 2019). The existing height of the Obelisk is 19.46 m including the pyramidal part at the top. The taper part is 2.67 m and the dimensions of the pyramidal base are 1.67 m and 1.64 m. The Obelisk stands on four bronze cubes. The total height of the Obelisk including the marble pedestal and stone masonry is approximately 24.77 m (Saygili, 2019). A numerical model of the Obelisk was created using SAP2000 (SAP2000) which is a general finite element software. Eight-node elements that have six quadrilateral faces with a joint at each corner were used to model the 3-D structure. The main reason for using solid elements is to distribute the stiffness and mass accurately along the whole structure. The base of the obelisk was considered as completely constrained. Another issue was the material properties. The Obelisk is a red Aswan granite, resting on four bronze cubes and marble. In the literature, there are a number of studies considering the mechanical properties of obelisks all around the world (Vasconcelos, 2005; Sadan et al., 2007; Arslan, 2016; Darwish and Rashwan, 2018). The material properties of the Obelisk were determined using information inferred from studies given above. The elasticity modulus was assumed as 3.92 GPa for the Obelisk, 70 GPa for the marble and 90 GPa for the bronze cubes.

Model Analysis

In order to determine the dynamic characteristics of the Obelisk of Theodosius, the numerical model was statistically analyzed under self-weight. The obtained results provide a realistic assessment of seismic response of existing structures under ground shaking. The first six mode shapes are shown in Fig. 2. The mode shapes and corresponding natural frequencies, modal participation factors of the Obelisk obtained from analytical modal analysis are listed in Table 1. As expected the largest modal participation factor of 57% is in translation in the y direction and 0% in the other directions.

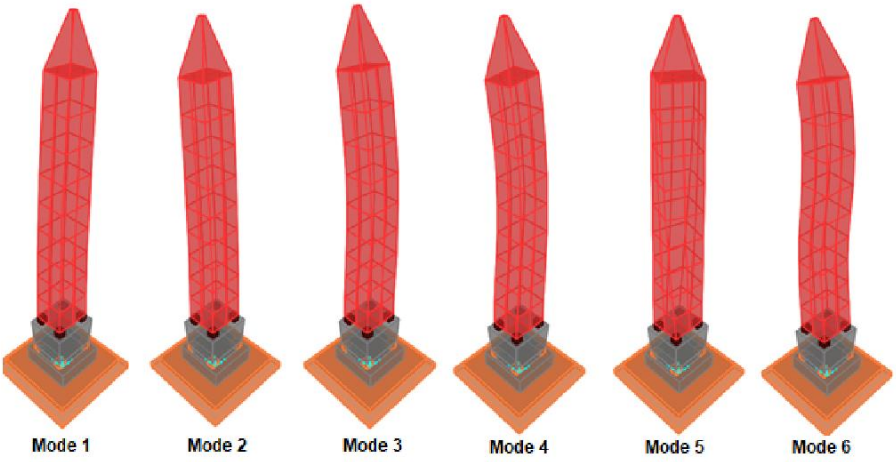

Figure 2. The first six mode shapes.

Şekil 2. İlk altı mod şekli.

Table 1. The mode shapes, corresponding natural frequencies, and modal participation factors.

Çizelge 1. Mod şekilleri ve bunlara karşılık gelen doğal frekansları ve modal katılım faktörlerini şekillendirir.

Mode No	Period (sec)	Frequency (cyc/sec)	Translation in X direction	Translation in Y direction	Translation in Z direction
Mode 1	1.129	0.886	0%	57%	0%
Mode 2	0.996	1.004	57%	0%	0%
Mode 3	0.23	4.348	0%	22%	0%
Mode 4	0.206	4.847	22%	0%	0%
Mode 5	0.172	5.823	0%	0%	0%
Mode 6	0.094	10.582	0%	9%	0%
Mode 7	0.093	10.73	0%	0%	80%
Mode 8	0.086	11.589	9%	0%	0%
Mode 9	0.071	14.126	0%	0%	0%
Mode 10	0.055	18.214	0%	5%	0%

The first fundamental frequency, 0.886 Hz is not the same with the one acquired from the opposite direction, which is 1.004 Hz. This means that the layout of the Obelisk is geometrically unsymmetrical. It was observed that in the x direction modal participation factor for the first mode is 57% and 0% in the opposite direction. From the modal analysis, the acquired modes above the fourth mode have the same values of the model participation factors in the x and y direction. As seen in Table 1, the natural frequencies are gradually decreasing with the increase in participation ratios. Furthermore, for the fifth and ninth modes modal participation factors are zero in x, y and z direction. However, the largest modal participation factor, 80% at the seventh mode took place in the z direction. The fundamental natural frequency of the Obelisk is 0.888 Hz, which is consistent with the range of the dominant frequencies of earthquakes (Tedesco et al., 1999; Darwish and Rashwan, 2018). This suggests that under a seismic event greater than Mb 7 expected in the Marmara Region, the Obelisk would be experiencing critical damage due to resonance.

Time History Analysis

The magnitude of an earthquake can influence ground shaking in many ways. Large earthquakes generally produce ground motions with large amplitudes and long durations. Additionally, such earthquakes can produce strong shaking over much larger areas than smaller earthquakes. The amplitude of ground motion decreases with increasing distance from the focus of an earthquake. The frequency content of the shaking varies with distance. Therefore, the frequency of ground motion is a significant factor in determining the intensity of damage to structures and which structures are affected. Therefore, as selecting events for this study, the distance between events and the obelisk and magnitudes of earthquakes were considered. The 1999 Marmara Earthquake (Mw= 7.5) and the 2000 Hendek-Akyazi Earthquake (Mw=5.8) occurred in the Marmara region were selected for this study. To investigate the variation of seismic behavior of the structure in the time domain, the numerical model was subjected to ground motion records of the sea of the 1999 Marmara Earthquake (Mw=7.5) and the 2000 Hendek-Akyazi Earthquake (Mw=5.8) in two principal directions. As is known, the magnitude of an earthquake, the depth, the type of faulting, etc. are significant parameters in determining the amount of ground shaking that might be produced at a particular place. Ground motions were selected from the Center of Engineering Strong Motion Data. Both earthquakes were recorded by seismic stations operated by Bogazici University, Kandilli Observatory and Earthquake Research Institute (KOERI), Regional Earthquake-Tsunami Monitoring Center (RETMC). In this study, two seismic stations acceleration records were selected. They are shown in Fig 3 and Fig 4, respectively. The sea of the Marmara ground motion was obtained from the station ARC and the seismic excitation of Akyazi was acquired from the station BTS. For the time history analysis, the Newmark direct integration approach that yields the constant average acceleration method was used. The methodology is based on the integration of structural properties and behaviors at a series of time steps that are small relative to loading duration. Also, the technique is based on performing an integration at every time step of the recording (SAP200). The response of the Obelisk in terms of lateral displacements was evaluated. In X and Y directions, displacement time histories of the top of the Obelisk under the Marmara Earthquake, 1999 (Mw=7.5) and Hendek-Akyazi Earthquake, 2000 (Mw=5.8) are given in Figs. 5 and 6, respectively. As shown in Figs. 5 and 6, the maximum horizontal displacement at the top of the Obelisk is 1.66 mm under the Marmara Earthquake, 1999 (Mw=5.0). In addition to that, the maximum horizontal displacement at the top of the Obelisk reached 0.58 mm under the Hendek-Akyazi

Earthquake, 2000 (Mw=5.8). Under the 1999 Marmara Earthquake, (Mw=7.5), the Obelisk experienced higher top displacement with respect to the ground motion with a magnitude of (Mw=5.8). It is most likely related to the distance between the Obelisk and the source.

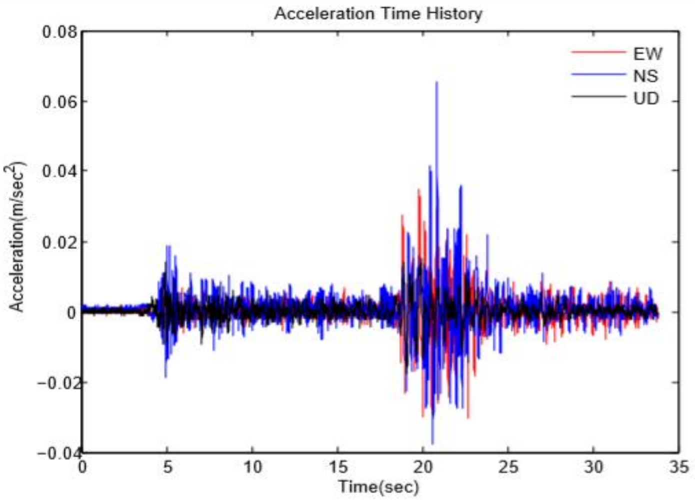

Figure 3. The Sea of Marmara ground motion acceleration obtained from the seismic records of the station ARC.

Şekil 3. ARC istasyonunun sismik kayıtlarından elde edilen Marmara Denizinin ivme hareketi.

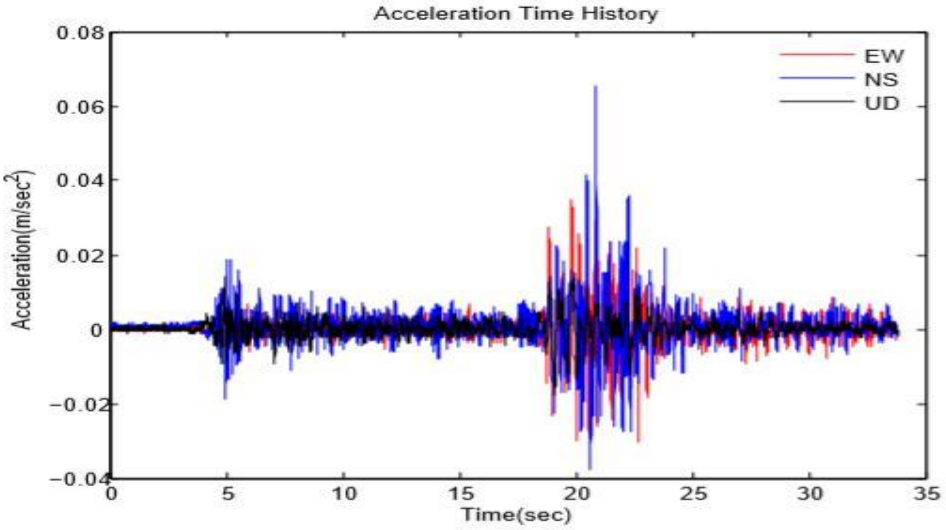

Figure 4 The Sea of Marmara ground motion acceleration obtained from the seismic records of the station BTS.

Şekil 4. BTS istasyonunun sismik kayıtlarından elde edilen Marmara Denizinin ivme hareketi.

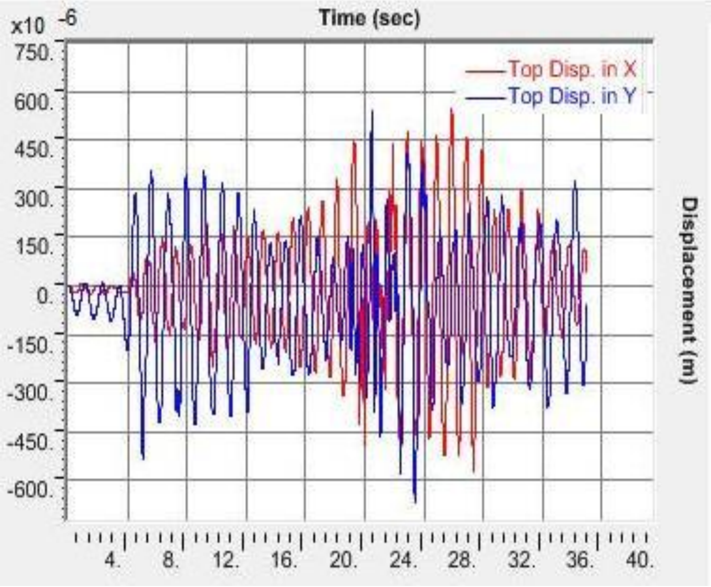

Figure 5. Displacement time histories of the top of the Obelisk under Hendek-Akyazi, Turkey Earthquake.

Şekil 5. Türkiye, Hendek-Akyazı depremi altında Dikilitaş'ın tepesinin yer değiştirme zaman kayıtı.

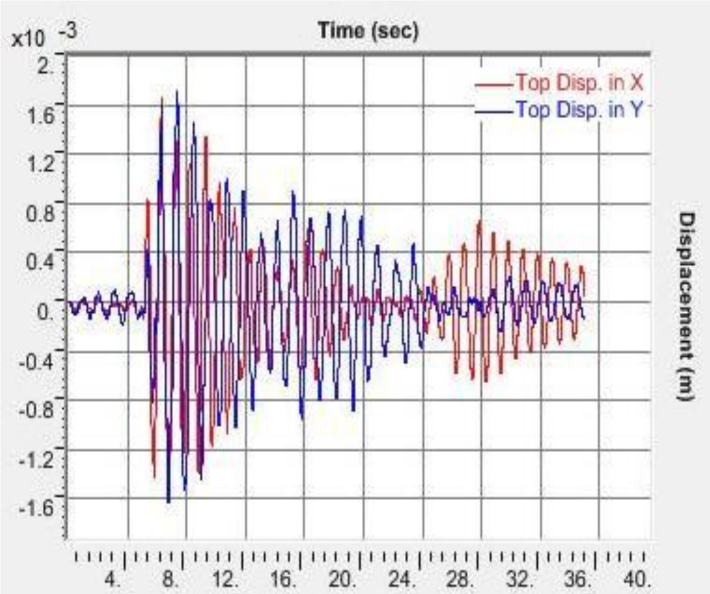

Figure 6. Displacement time histories of the top of the Obelisk during the Marmara Earthquake, Turkey, 1999 (Mw=7.5).

Şekil 6. Türkiye, Marmara 1999 (Mw=7.5) depremi sırasında Dikilitaş'ın tepesinin yer değiştirme zaman kayıtı.

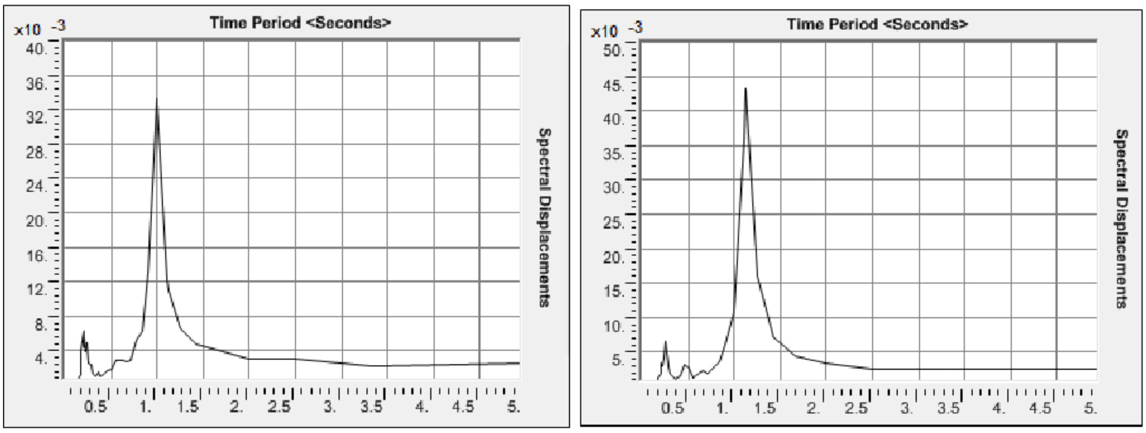

Figure 7. Spectral displacements in X (right) and Y (left) directions at the top of the Obelisk during the 1999 Marmara Earthquake.

Şekil 7. 1999 Marmara Depremi sırasında, Dikilitaş'ın tepesinde X (sağ) ve Y (sol) yönlerinde spektral yer değiştirmeler.

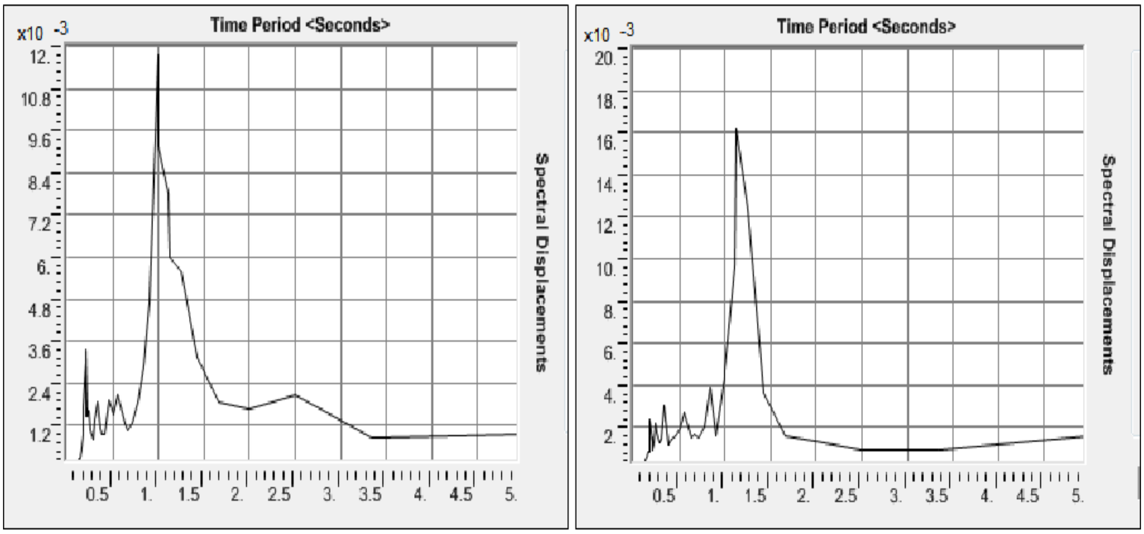

Figure 8. Spectral displacements in X (right) and Y (left) directions at the top of the Obelisk during the 2000 Hendek-Akyazi Earthquake.

Şekil 8. 2000 Hendek-Akyazı Depremi sırasında, Dikilitaş'ın tepesinde X (sağ) ve Y (sol) yönlerinde spektral yer değiştirmeler.

The results of time history analysis are presented in terms of spectral displacement at the top of the Obelisk in orthogonal direction in Figs. 7 and 8. From these figures, it is seen that under the 1999 Marmara Earthquake, the Obelisk experienced maximum displacement of 4.35 cm in the Y direction. Furthermore, it is evident from Fig. 7 that the maximum spectral displacement was observed at a natural period of the numerical model, which is 1.12 sec when the numerical model is subjected to the 2000 Hendek-Akyazi Earthquake, maximum spectral displacement reached 1.61 cm. Although both earthquakes have different moment magnitudes, the ancient structure experienced reasonable displacements. Similar results were obtained from stresses along the Obelisk under seismic loadings. Under the 1999 Marmara Earthquake, the computed stress responses and their variations in time along the Obelisk show that the peak stress, as compression, has a value of 141 kPa, which is relatively small than the ultimate strength of the ancient structure. A similar response was observed for the 2000 Hendek-Akyazi Earthquake, the value of peak stress was 44 kPa.

DISCUSSION AND CONCLUSION

Numerical analyses were performed to show the effects of real earthquakes on the Obelisk of Theodosius. The 3-D numerical model was constructed for the Obelisk using the finite element method. The natural frequency of the principal mode of vibration of the obelisk obtained from this analysis is 0.886 Hz. The fundamental frequency obtained from modal analysis seems consistent with the frequency obtained from the study of Saygili (2019) which was based on discrete element methodology (DEM). This observation indicates that although discrete element method provides very detailed results in terms of structural behavior under seismic excitation, macro modeling based on the finite approach can provide simplified results, which are consistent with the ones obtained from the discrete approach. Based on this observation, it might be possible to claim that the finite element method is capable to reveal dynamic behavior of the buildings like the DEM. Another important observation from this study is that even though the analyzed seismic events were smaller than Mw 7.6, the constructed numerical model created using the finite element approach provides reasonable results. In addition, the observed fundamental natural frequency of the Obelisk is consistent with the range of the dominant frequencies of the earthquakes (Tedesco et al., 1999; Darwish and Rashwan, 2018). This suggests that it might be possible that under the seismic event greater than Mb 7.5 expected in the Marmara Region, the Obelisk would be experiencing critical damage due to resonance. One of the striking results of this study is that although the Obelisk experienced several devastating earthquakes throughout history, the Obelisk does not have any important inclination and deformation. However, in this region, in general, old structures seriously were destroyed due to devastating earthquakes such as the 1999 Izmit earthquake. For example, the 1470-years old Hagia Sophia Mosque was strongly and repeatedly affected by the earthquakes occurred in the region (Durukal et al., 2003). However, this obelisk strongly remained with a slight deformation during almost two millennia. It might be thought that its strong behavior across to devastating earthquakes is probably associated with its materials. Finally, we can say that the results from this study are strongly evident in how the Obelisk of Theodosius survived from various important earthquakes near to Istanbul for thousands of years.

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