16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1799

Registration Code: S-C1464741935

RESPONSE OF THREE TALL AND SLENDER STRUCTURES IN ISTANBUL TO A LONG-DISTANCE EARTHQUAKE

E. Çaktı[(1)], E. Dar[(2)], E. Şafak[(3)]

[(1)] Professor, Dept. of Earthquake Engineering, Boğaziçi University, Istanbul, Turkey. eser.cakti@boun.edu.tr
[(2)] Ph.D. Student, Dept. of Earthquake Engineering, Boğaziçi University, Istanbul, Turkey. emrullah.dar@boun.edu.tr
[(3)] Professor, Dept. of Earthquake Engineering, Boğaziçi University, Istanbul, Turkey. erdal.safak@boun.edu.tr

Abstract

Large magnitude earthquakes originating from distant sources produce long period waves that potentially travel over long distances without significant attenuation. The resulting ground motions at large distances are long-duration, typically a few minutes minimum and contain waves having long periods. They induce large displacements in high-rise buildings or in structures having similar natural periods of vibration. The 24.05.2014, Mw 6.9 Gokceada earthquake of North Aegean Sea took place at an average distance of 300 km to Istanbul. Among a series instrumented structures and buildings in Istanbul, we take a close look at the response of three tall and slender structures. They are the 62 floor, 238 m high Sapphire Tower, currently probably the tallest building in Europe; the 16th century minaret of the Hagia Sophia Museum, which stands at a height of 73 m; and the 20th century minaret of the Maltepe Mosque, which with its 70 m is the most slender minaret in İstanbul. The displacement response of all of these structures was remarkably long, lasting a few minutes, providing interesting examples of the phenomenon.

Keywords: slender structures; long distance - long period earthquakes; structural response; long period structures

1. Introduction

In recent years, seismic response of long-period structures (e.g., tall buildings, long-span bridges, base-isolated structures) has become an important research subject [1,2,3]. The seismic excitation for such structures is mainly controlled by long period surface waves, which can travel very long distances without much attenuation [4,5]. Consequently, even if they are located in low-seismicity regions, long-period structures can be vulnerable to large earthquakes occurring in far away locations.

We show this by studying the earthquake-induced vibration data from three tall structures in Istanbul, a tall building and two tall minarets, during the Mw 6.9 Gokceada earthquake of 24 April 2014, which was 300 km away.

2. Description of the buildings and monitoring systems

To assist in the reduction of losses in Istanbul, the Department of Earthquake Engineering of Kandilli Observatory and Earthquake Research Institute of Boğaziçi University in Istanbul, Turkey has installed and been operating a large number of structural and strong motion monitoring networks in Istanbul for some time. The structural monitoring systems are installed in a large number of historical structures, critical lifelines crossing the Bosporus, several high-rise buildings, and industrial facilities. Real-time data processing and modal identification software is developed to analyze and interpret the data from the instrumented structures.

Three structures stand out from the instrumented buildings, as being tall and slender. They are the 62 floor, 238 m high Sapphire Tower, currently the tallest building in Europe; the 16th century minaret of the Hagia Sophia Museum, which stands at a height of 73 m; and the 20th century minaret of the Maltepe Mosque, which with its 70 m is the most slender minaret in İstanbul.

The structural health monitoring system in the Sapphire Tower is an accelerometric network with with 30 channels distributed over seven levels. One wind sensor is also operational in the building. Fig. 1 shows the 62-story reinforced concrete Sapphire Building and the sensor layout. It houses the most comprehensive structural monitoring system to date in Turkey.

Three tri-axial accelerometers are installed in the masonry minaret of Hagia Sophia: at the ground level, near the top of the triangular transition segment and at the balcony level (Fig. 2). The sensors in the reinforced concrete minaret of the Maltepe mosque are located at the basement, ground level, and at each one of the three balconies (Fig. 2). The Maltepe minaret is currently the tallest modern minaret in Istanbul.

In all systems three component accelerometers are used. All systems operate in real-time, providing the opportunity to track continuously the dynamic response of these structures under a variety of excitations.

The 24.05.2014, Mw 6.9 Gokceada, North Aegean Sea, earthquake took place at an approximate distance of 300 km from Istanbul. It was felt over a large area in Turkey and Greece. All monitoring networks in Istanbul registered it, as did those in the two minarets and the Sapphire Tower.

3. Data analysis

Standart data analysis involved instrument correction, baseline correction and filtering. Corrected accelerations, velocities and displacements were estimated. Fig. 3 shows accelerations and displacements recorded by the topmost station in the three structures. The topmost station corresponds to station 3 in the balcony of Hagia Sophia (Fig.2); to station 5 on the top balcony of the Maltepe mosque and to the instrument at level G in the Sapphire building. Transfer functions between the top floor and ground floor were calculated. As indicated in Fig. 4 the longest natural period of vibration is that of the Sapphire building. It is in the order of 10s in the short direction. The first natural frequency of vibration of the Maltepe minaret is about 0.5 Hz and that of Hagia Sophia is about 1.2 Hz. The particle motions are estimated using top floor displacements and shown in Fig 5.

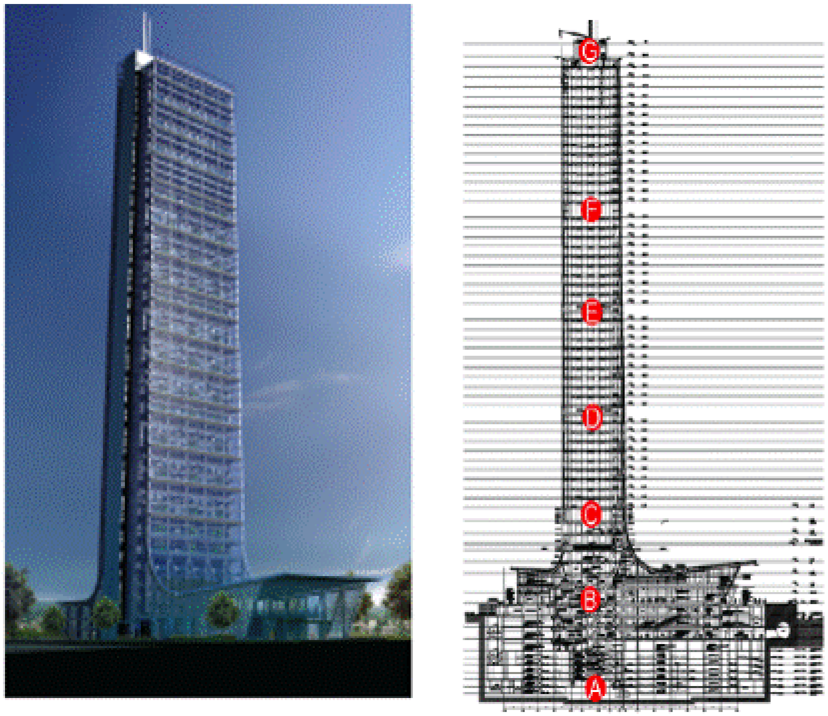


Fig. 1 – 62-story Sapphire tower and the sensor layout

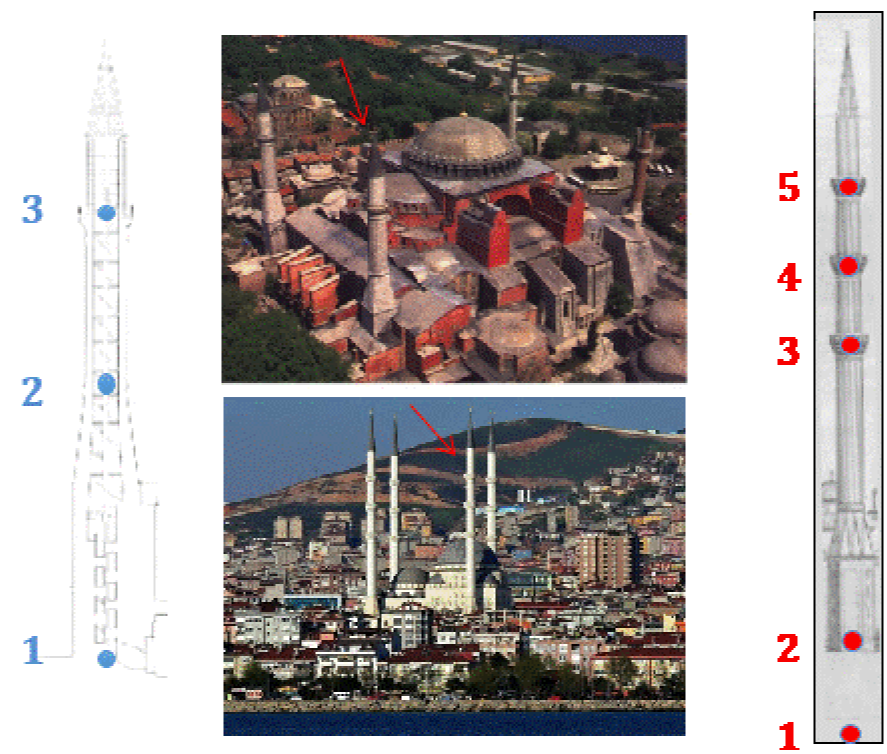


Fig. 2 – Hagia Sophia in Istanbul (middle top) and its instrumented minaret (left). The Maltepe mosque (middle bottom) and its instrumented minaret (right)

The acceleration and displacement response spectra obtained from the ground level stations of three buildings are shown in Fig 6. At periods 4s and longer the large amplitudes in the displacement spectra are striking, which can completely be missed if only acceleration spectra are taken into account. Such spectra are typical for large earthquakes recorded at large distances.

4. Observations

Sapphire building experienced displacements larger than 1 cm for about 5 min in its shorter axis. Overall the structure sustained vibrations that lasted about 10 min. The largest displacements were registered after the strong shaking part, where accelerations were decreasing. They reached 3 cm. The difference between its displacement and acceleration response along its short and long axes was striking (Fig. 3). Sapphire building is the tallest of the three structures.

The Maltepe minaret is about 1/3 of the Sapphire building in height. As a cylindrical structure its response is very similar in two directions (Fig. 3). For about 3 min it experienced displacements in the order of 1 cm.

The Hagia Sophia minaret, although tall, is less slender than the other two. Furthermore the combined length of its boot and the transition segment, which together form a more rigid lower portion, is almost equal to the length of its body (Fig. 2). Its response is therefore less pronounced than the Sapphire building and the Maltepe minaret. Yet the order of maximum displacement experienced (0.6 cm), and the displacements in the order of 0.2 s lasting for almost 2 min after strong shaking has seized are still worth noting.

The particle motions, particularly those from the Sapphire building and Maltepe minaret, display strong directionality, which is a result of structural response in the case of Sapphire and the earthquake characteristics in the case of Maltepe minaret (Fig. 5). Minutes-long, large displacements can be visualized very nicely with the help of particle motions. The Maltepe minaret, during the whole the earthquake responded on an axis in northeast-southwest direction, while the Sapphire was responding purely in its short axis in late parts of the record.

Records from all three structures clearly show that ground motions from distant large earthquakes can excite long-period structures significantly. The main reason for this is the long-period surface waves generated by these earthquakes, which can travel far distances without much attenuation. Such long periods can match the natural periods of tall and slender structures, creating resonant vibrations. The long period energy seen in displacement response spectra of ground motions (Fig. 6) clearly shows that.

In addition to large amplitudes, another main characteristic of such vibrations is their long duration, lasting several minutes. Data from slender structures have shown that these structures also have very low damping, sometimes less than 1%. Low damping is another reason for long-duration vibrations in such structures.

Although the displacements and forces may not be critical from the structural safety point of view, the long duration of vibrations can create panic among the occupants, causing injuries when they all rush to the stairs for escape. This was the case in the Gulf Countries (e.g., United Arab Emirates, Qatar) during the M 7.8 Iran-Pakistan border earthquake of 16 April 2013 that was 900 km away. It was severely felt in several high-rises in Dubai with witness reports suggesting 40s long vibrations (http://www.emsc-csem.org). Some high-rise office buildings were evacuated (http://gulfbusiness.com, http://worldnews.nbcnews.com). The earthquake was felt in Muscat, Oman as well, that is 660 km to the southwest of the epicenter (http://www.emsc-csem.org). Safak et al. [7] present the response of a 74-storey, instrumented, high-rise building in Abu-Dhabi, which is approximately 900 km away from the epicenter. Although the vibration amplitudes were found to be low (2 cm maximum displacement at the top floor), the earthquake caused long duration shaking in the building (10 minutes or more), which caused human discomfort and may eventually lead to low-cycle fatigue [7].

During the 2011 Tohoku earthquake it is known that several high-rise buildings in Japan experienced excessive levels of vibrations. According to Takewaki et al. [8] a 54 story steel building in Shinjuku-Tokyo that had been retrofitted with passive dampers sustained a 50 cm top displacement during the Tohoku earthquake. The duration of experienced vibrations were 13 min. Another building in Osaka, which is 55 stories high and located 800 km away from the epicenter, experienced top story displacements reaching 140 cm over a duration of more than 10 min [8].

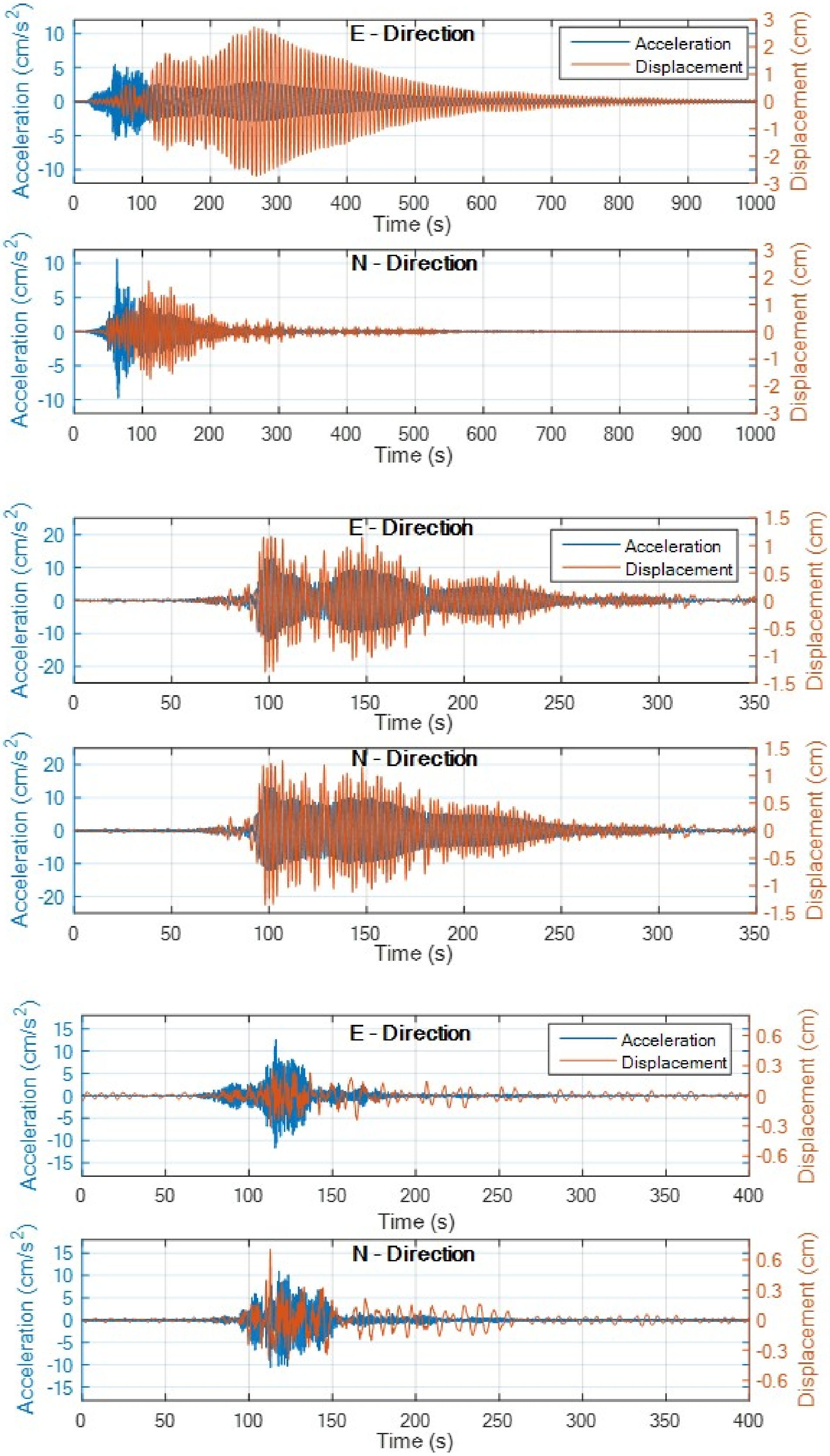


Fig. 3 – Acceleration and displacement responses of the Sapphire building (top), Maltepe minaret (middle) and Hagia Sophia minaret (bottom) filtered between 0.1-2.0 Hz.

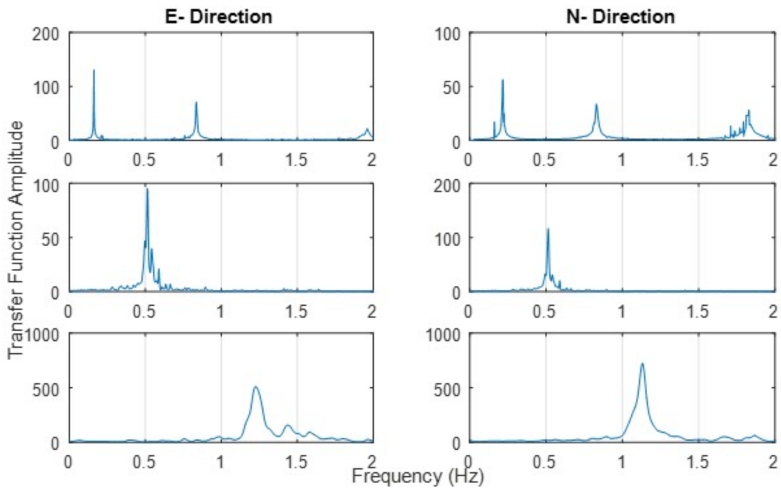


Fig. 4 – Spectral ratios with respect to ground floor accelerations for the Sapphire building (top), Maltepe minaret (middle) and Hagia Sophia minaret (bottom).

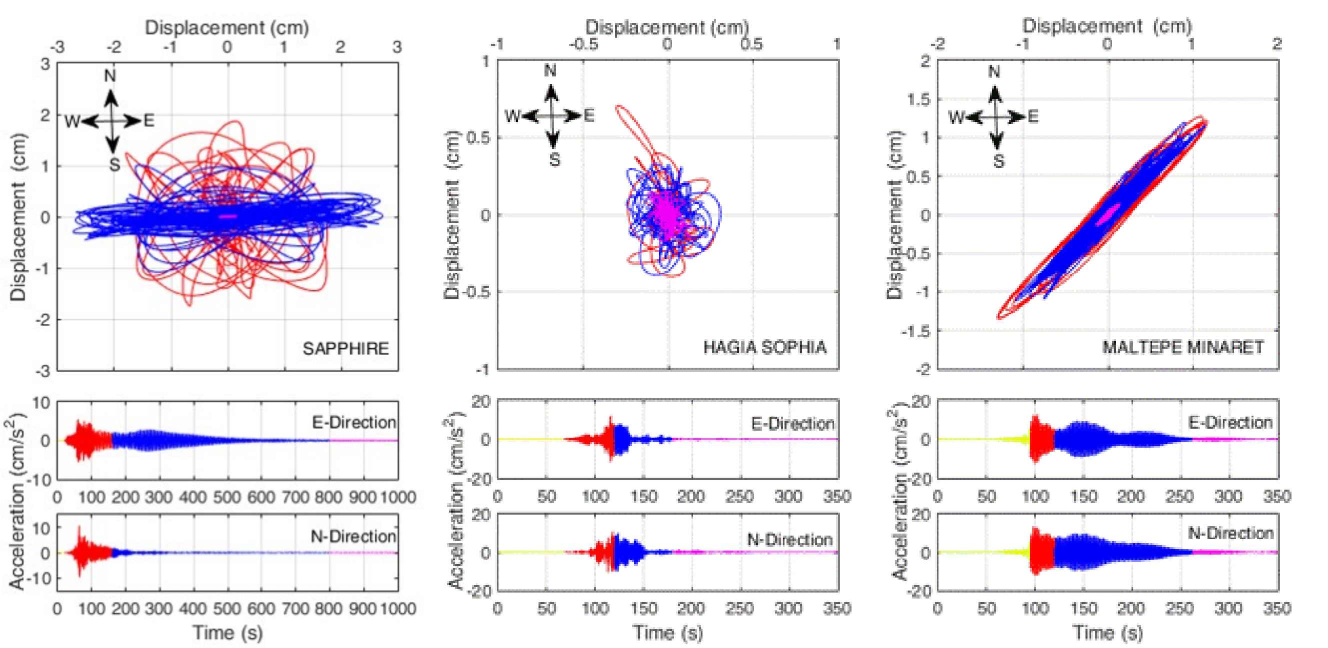
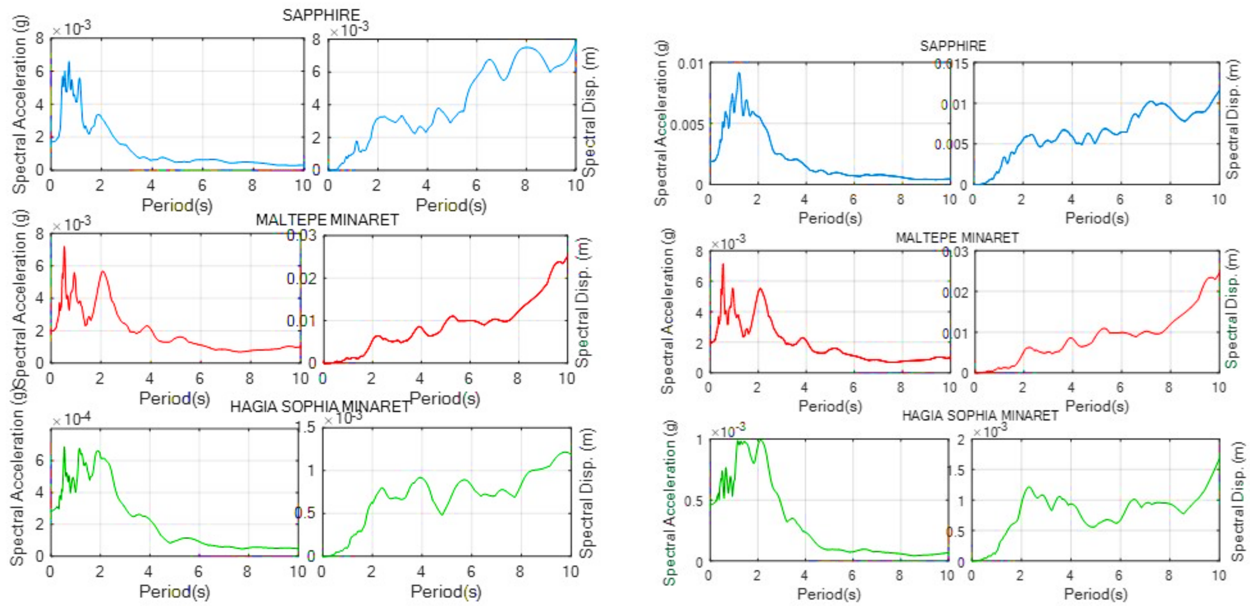


Fig. 5 – Particle motions at the top level co-shown with accelerations recorded at the same level, all filtered between 0.1-2.0 Hz



E-Direction N-Direction

Fig. 6 – 5% damped spectral accelerations and spectral displacements estimated using the ground stations at the three buildings.

5. Conclusion

Distant large earthquakes can create long-period, long-duration ground shaking in far away locations from their epicenters because of surface waves. Surface waves can cause long duration resonant vibrations in tall buildings. The data recorded in three tall structures in Istanbul, a tall building and two tall minarets, during the Mw 6.9 Gokceada earthquake of 24 April 2014, which was 300 km away, clearly confirm this.

Although the vibration amplitudes and forces may not be critical for structural safety, the long duration of shaking can cause panic among the occupants of tall buildings and injuries when they all rush to the stairs. In the event of very large long-distance earthquakes (i.e. >M 8.0) persistent excessive displacements can also lead to damage to non-structural components and contents.

Long duration of shaking may create low-cycle fatigue failures in steel structures. Such effects and distances are not considered in current seismic design codes and GMPE’s.

6. References

[1] Safak E, Kaya Y (2007): Sensitivity of base-isolated systems to ground motion characteristics: A stochastic approach, Proceedings. *10th World Conference on Seismic Isolation, Energy Dissipation and Active Vibrations Control of Structures*, Istanbul, Turkey.

[2] Safak E (2007): Importance of surface waves on base-isolated structures. *Proceedings, 10th World Conference on Seismic Isolation, Energy Dissipation and Active Vibrations Control of Structures*, Istanbul, Turkey.

[3] Celebi M, Sanli A (2002): GPS in pioneering dynamic monitoring of long-period structures. *Earthquake Spectra*, **18** (1), 47–61.

[4] Safak E (2007): Surface waves and seismic response of long period structures. *Proceedings, 4th International Conference on Earthquake Geotechnical Engineering*, Thessaloniki, Greece.

[5] Olsen AH, Aagaard BT, Heaton TH (2008): Long-period building response to earthquakes in the San Francisco Bay area. *Bulletin of the Seismological Society of America*, Vol. **98** (2), 1047–1065.

[6] http://earthquake.usgs.gov/earthquakes/

[7] Safak E, Kaya D, Skolnik M, Ciudad-Real H, Al Mulla A, Megahed (2014): Recorded response of a tall buildings in Abu Dhabi from a distant large earthquake, *10th U.S. National Conference on Earthquake Engineering*, Alaska, USA.

[8] Takewaki I, Fujita K, Yoshitomi S (2013): Uncertainties in long-period ground motion and its impact on building structural design: Case study of the 2011 Tohoku (Japan) earthquake, *Engineering Structures*, **49** , 119-134.