Earthquake ground motion simulation at Zoser pyramid using the stochastic method: A step toward the preservation of an ancient Egyptian heritage

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Abstract Strong ground shaking during earthquakes can greatly affect the ancient monuments and subsequently demolish the human heritage. On October 12th 1992, a moderate earthquake (Ms = 5.8) shocked the greater Cairo area causing widespread damages. Unfortunately, the focus of that earthquake is located about 14 km to the south of Zoser pyramid. After the earthquake, the Egyptian Supreme council of antiquities issued an alarm that Zoser pyramid is partially collapsed and international and national efforts are exerted to restore this important human heritage that was built about 4000 years ago. Engineering and geophysical work is thus needed for the restoration process. The definition of the strong motion parameters is one of the required studies since seismically active zone is recorded in its near vicinity. The present study adopted the stochastic method to determine the peak ground motion (acceleration, velocity and displacement) for the three largest earthquakes recorded in the Egypt's seismological history. These earthquakes are Shedwan earthquake with magnitude Ms = 6.9, Aqaba earthquake with magnitude Mw = 7.2 and Cairo (Dahshour earthquake) with magnitude Ms = 5.8. The former two major earthquakes took place few hundred kilometers away. It is logic to have the predominant effects from the epicentral location of the Cairo earthquake; however, the authors wanted to test also the long period effects of the large distance earthquakes expected from the other two earthquakes under consideration. In addition, the dynamic site response was studied using the Horizontal to vertical spectral ratio (HVSR) technique. HVSR can provide information about the fundamental frequency successfully; however, the ampli-

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fication estimation is not accepted. The result represented as either peak ground motion parameters or response spectra indicates that the effects from Cairo earthquake epicenter are the largest for all periods considered in the present study. The level of strong motion as indicated by peak ground acceleration reaches the value of 250 gals which is considerably high. At the end, it is worth to mention that the information resulted from the present work may be useful for the planned restoration decision of the Zoser pyramid site.

1. Introduction

Monumental sites are considered as a very important human heritage. In Egypt, valuable human heritages are widespread all over the Nile valley which extended back in history to thousands of years. Unfortunately, some of these monuments suffer from bad conditions under the effects of natural and manmade factors. The present area is near to relatively active earthquake area to the southwest of downtown Cairo. In that area, the most destructive event in recent history of Egypt took place in October 12th, 1992. The epicentral distance is only about 14 km. Damage report after that earthquake showed that Zoser pyramid was severely damaged, and few years later a restoration plan was inaugurated to save the pyramid from total collapse.

One of the most important decisions in carrying out proper design is to select a design earthquake that adequately represents the ground motion expected at a particular site and in particular the motion that would drive the structure to its critical response, resulting in highest damage potential. The quantification of such ground motion is not easy, it requires a good understanding of the ground parameters that characterize the severity and the damage potential of the earthquakes' ground motion and seismological, geological, and topographic factors that affect them. As a result, evaluation of the expected earthquake ground motion becomes a must for retrofitting against possible future large earthquake. Strong ground motion evaluation requires definition of both the most effecting earthquake source on the area and the dynamic site response that sometimes becomes more effective than the original ground motion.

This research is focusing on the application of stochastic method to simulate the ground motion time history during Cairo 1992 earthquake at Zoser pyramid. Accordingly, Simulation of the effective strong ground motion is conducted using the stochastic simulation method (e.g., Boore, 1983; Boore and Joyner, 1984; Boore and Atkinson, 1987; Boore et al., 1992; Atkinson and Boore, 1995; Roumelioti et al., 2000; Boore, 2003; Boore and Thompson, 2015), and the method is used due to its effective low computational efforts and short time consumption with reliable simulation results when applied to engineering applications. Determination of the site effect was used based on a previous work of the authors (Khalil and Abdel Hafiez, 2016), they determine response characterization of the site using HVSR technique (Nakamura, 1989), and the results of this work are so important in the future understanding of the area behavior during earthquakes taken into consideration the importance of this heritage area for national income.

## 2. Location and description of Zoser pyramid

Saqqara (Zoser) pyramid is located to the south of Cairo at a distance of about 20 km (Fig. 1). It is the first Egyptian step pyramid consisted of six Mastabas (of decreasing size) built atop one another in what were clearly revisions and developments of the original plan. The pyramid originally stood 62 m (203 ft) tall, with a base of 109 m × 125 m (358 ft × 410 ft) and was clad in polished white limestone (Fig. 2).

Despite the general belief that ancient Egyptians were skilled in selecting stable areas for their monuments, the present location is near moderately seismic active region. An active region that produced the October 12th, 1992 earthquake lies at about 14 km only. Earthquake monitor of the area shows that moderate earthquakes of magnitudes less than 5 are continuously recorded there. Considering that the area may be capable of producing earthquakes of magnitude like that of 1992 every 70 years, the pyramid may have witnessed 60 earthquakes of magnitudes around 6.0. If the proposition is true, the pyramid can be seen as a successful example of earthquake resistant structure. The damage encountered after the 1992 earthquakes might be a cumulative effect of the past earthquakes.

3. Seismicity and seismotectonics

The seismic activity in Egypt is concentrated in the northeastern part at gulfs of Aqaba and Suez, and most of the largest earthquakes were recorded there. In the gulf of Suez, the largest event took place near its entrance on 31st March 1969. The magnitude of such event was Ms = 6.9. It was the largest instrumental earthquake until 22nd November 1995, when an earthquake with magnitude Mw = 7.2 took place in the gulf of Aqaba. Numerous microearthquakes are recorded at both gulfs each year. In addition to these seismic sources, several other sources of low to moderate activities are observed. The border between the stable and unstable shelfs of Egypt exhibits earthquake activity of low to moderate sizes; geographically, this zone is known as Cairo-Suez district. East Beni Suef zone was discovered after the operation of the Egyptian National Seismological Network. This zone lies to the south of the Cairo Suez district zone.

In addition, other earthquake activities are observed at east Cairo, Abu Rawwash and Dahshour areas. Dahshour seismic zone constitutes the epicenter of the 12th October 1992 Cairo earthquake, and other seismic activity area produced earthquakes with magnitudes seldom reaching a magnitude of 5. However, due to their proximity from the dense population
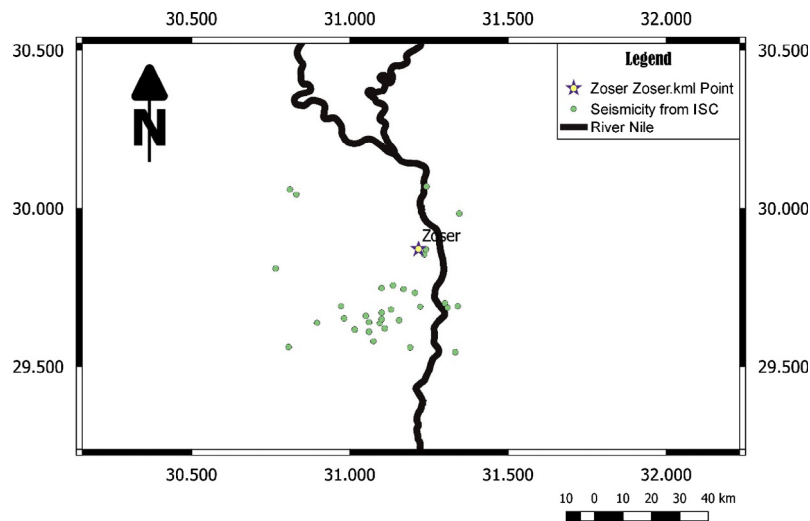
Figure 1 Location map of Zoser pyramid and the earthquake activities in its vicinity (data obtained from International Seismological Centre (2013)).
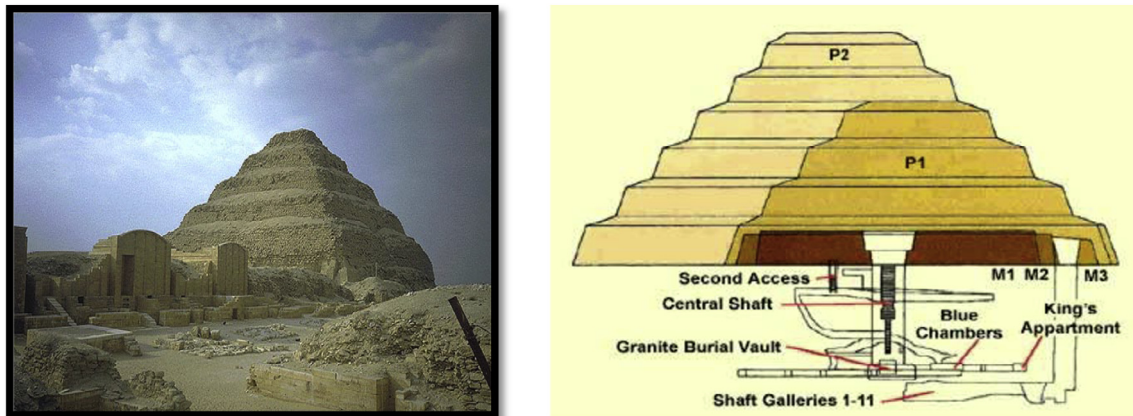
Figure 2 The Saqqara Pyramid view together with the internal structure.

Cairo metropolitan, such earthquakes were widely felt in greater Cairo area. The seismic zone at Dahshour is only few kilometers from Zoser pyramid. The epicentral distance between Cairo earthquake and Zoser pyramid is 14 km only. This proximity indicates that Dahshour seismic zone might have the highest effect especially at short periods. In the present study, simulation will be carried out for the source parameters of Cairo earthquake. In addition, simulation due to both Gulf of Suez and Gulf of Aqaba earthquakes will also be conducted. Seismicity of the Egyptian territories and its surroundings (recorded by the Egyptian National Seismological Network for the period 1997–2015), are presented in Fig. 3 in addition to the largest recorded earthquakes that are used for the stochastic simulation in the present study.

4. Stochastic simulation method

Stochastic strong motion simulation technique is considered as fast and efficient method for producing synthetic time series whose spectrum has on average, similar spectral features as those of the desired ground motion spectrum. The stochastic

method is based on the work of Hanks and McGuire, who through series of research papers combined seismological representation of the ground motion spectral amplitude with the engineering belief that high-frequency ground motions are basically random (e.g. Hanks, 1979; Hanks and McGuire, 1981). They derived a simple relationship to predict peak acceleration assuming that the spectral ground acceleration on a half space is band-limited, finite duration, white Gaussian noise, and the source spectra are represented by a single corner frequency model whose corner frequency be governed by the size of earthquake following (Brune, 1970) scaling. The essential ingredient for the stochastic method is the spectrum of the ground motion, and this is the actual representation of earthquake process and wave propagation effects, usually encapsulated and put into the form of simple equations.

In the present work, strong ground motion was simulated for three earthquakes only. These earthquakes are Shedwan 31st March 1969, Cairo 12th October 1992, and Aqaba 22nd November 1995. The source parameters have been studied more extensively because of the availability of digital waveforms. Shedwan earthquake is relatively old. Hence, limited

source information is currently available. The surface wave magnitude of Shedwan event was 6.9. The other parameters like corner frequency might be determined using empirical relations between surface wave magnitude and seismic moment, and then seismic moment and corner frequency. The other two events are studied by many authors. Hussein (1999) studied the source parameters of Cairo 12th October 1992. The source parameters obtained are seismic moment of 7.2×10^{17} N m, stress drop 1.85 MPa, radius 5.5 km, area 99 km^2, and dislocation 0.245 m. The source parameters of

Aqaba 22nd November 1995 earthquake are taken from the work of Hussein and Abo-Elenean (2008). The source parameters are seismic moment of 13.77×10^{18} N m, stress drop of 1.49 MPa, radius of 36.6 km, and dislocation of 0.53 m.

5. Characterization of local site effect

The response of the site to ground motion vibration is proven to have the highest effect on the shape and characteristics of ground motion at the site (Reiter, 1990). The effects of the site are usually represented in both natural frequency and amplification factor. The site effects for the present study is taken from the work of Khalil and Abdel Hafiez (2016) that employed the HVSR method in the vicinity of Zoser pyramid. Fig. 10, shows the natural frequency at the area to be about 0.4 Hz. with the amplitude of the peak up to value of 8.

6. Conclusion and discussion

Thorough consideration of the possible effects of the natural hazards on human heritage is required for both restoration and preservation plans. Zoser pyramids experienced considerable damage after the Cairo earthquake on October 12th 1992 (Ms = 5.8). Consequently, the Egyptian Supreme Council of Antiquities started a restoration project for the pyramid. The effect of ground shaking parameters due earthquakes is needed since the area is witnessing earthquake activities few kilometers away.

Stochastic simulation method is used for determining the ground motion adopting deterministic strategy. In this strategy, the largest earthquakes from various sources inside the Egyptian territories were used for the simulation at the Zoser
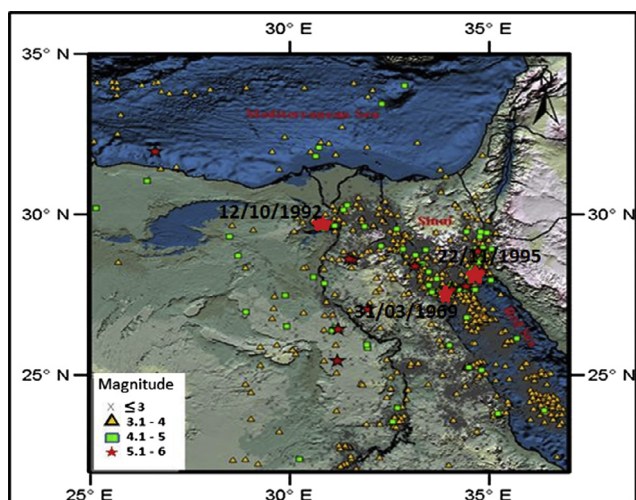
Figure 3 Largest earthquakes recorded in Egypt with the seismicity in the period from 1997 to 2015 as recorded by the Egyptian National Seismological Network.
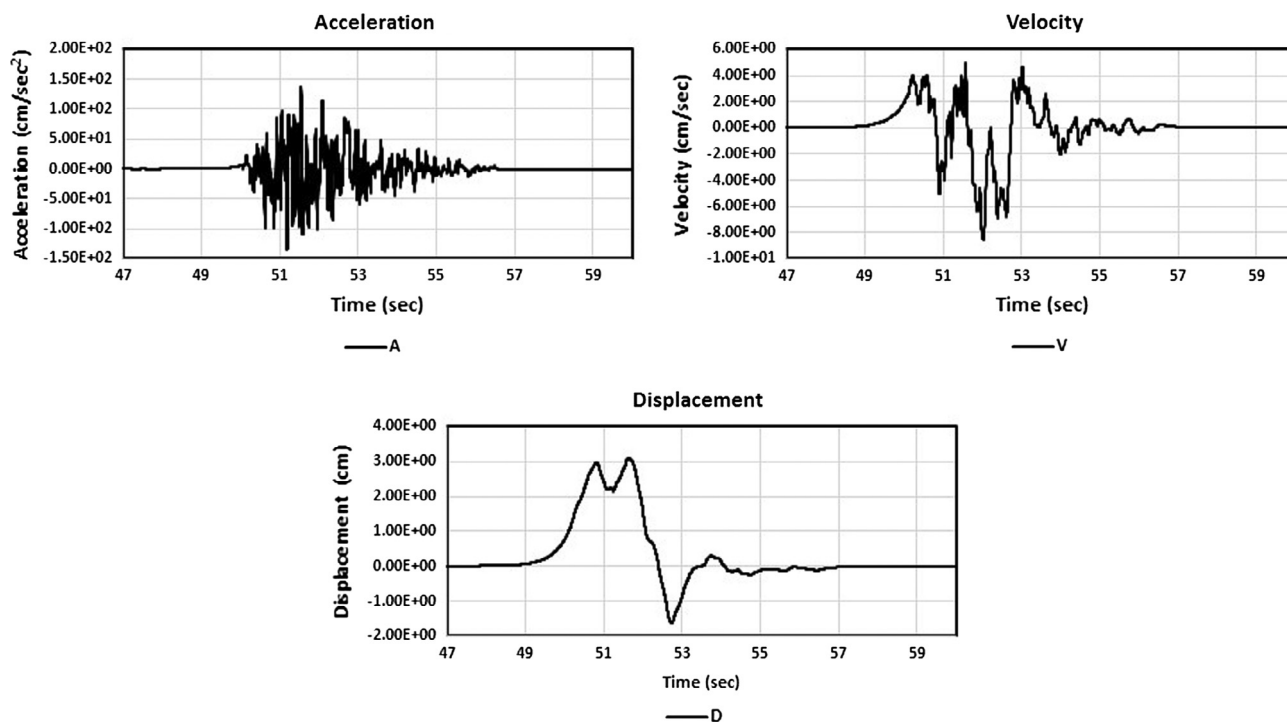
Figure 4 Ground motion time history simulation at Zoser pyramid during Cairo 12th October 1992 earthquake.

pyramid site. Based on this strategy, three events are considered for ground motion simulations. These earthquakes are the Cairo (Dahshour) earthquake on 12th October 1992, Shedwan earthquake on 31st March 1969 and the Aqaba earthquake on 22nd November 1995 arranged according to proximity of the site under investigation. The last two are considered as the largest recorded earthquakes of Egypt's instrumental seismicity history. However, the distances to both are few hundred km from Zoser pyramid. The Size of
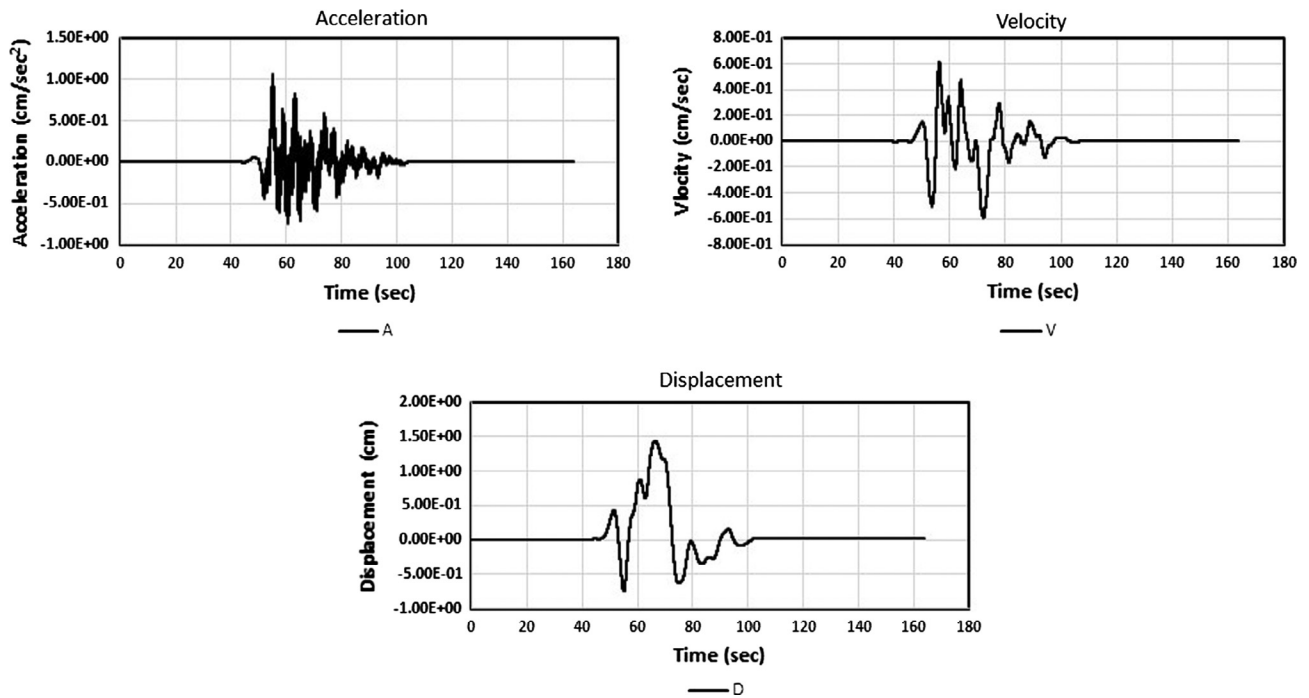

Figure 5   Ground motion time history simulation at Zoser pyramid during Shedwan 31st March 1969 earthquake.
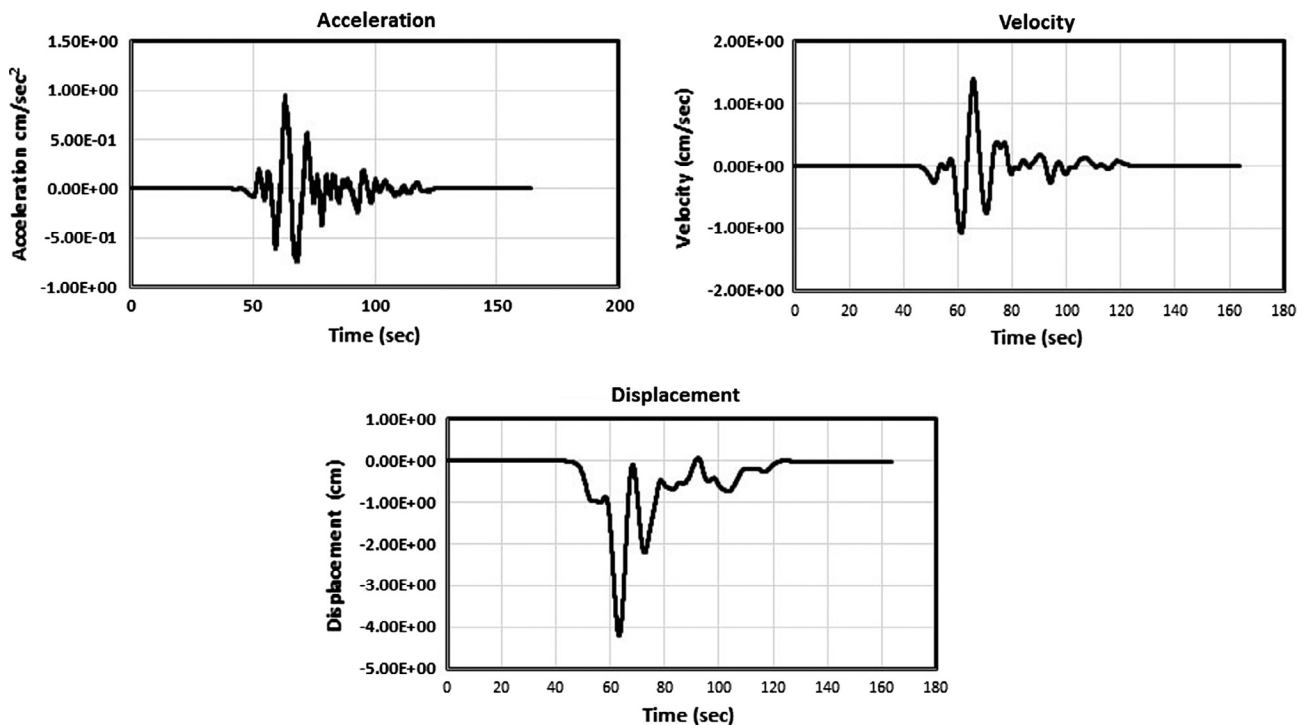

Figure 6   Ground motion time history simulation at Zoser pyramid during Aqaba 22nd November, 1995 earthquake.

these earthquakes is Ms = 5.8, Ms = 6.9 and Mw = 7.2 respectively.

Numerous other earthquakes are present in the vicinity of greater Cairo area; however, their magnitudes are less than Cairo earthquake and their epicentral distances are relatively longer than those of Cairo earthquake. Hence, it is assumed that their effect is lower than that of Cairo earthquake. Despite the relative larger sizes of both Shedwan and Aqaba earthquakes, the reported damage was remarkably lower than that of Cairo earthquake. The main reason is their remoteness from the dense population areas in the Egyptian territories. Aqaba Earthquakes produced considerable damages to neighboring countries such as Saudi Arabia and Jordan.

The simulation technique relies on certain seismological parameters representing the earthquake source. Based on the size and proximity of the focus the source can be modeled as point or extended source. For the present situation, the sources for the three used earthquakes are modeled as point source since the size of Cairo earthquake is moderate and distance to the other two earthquakes is long.
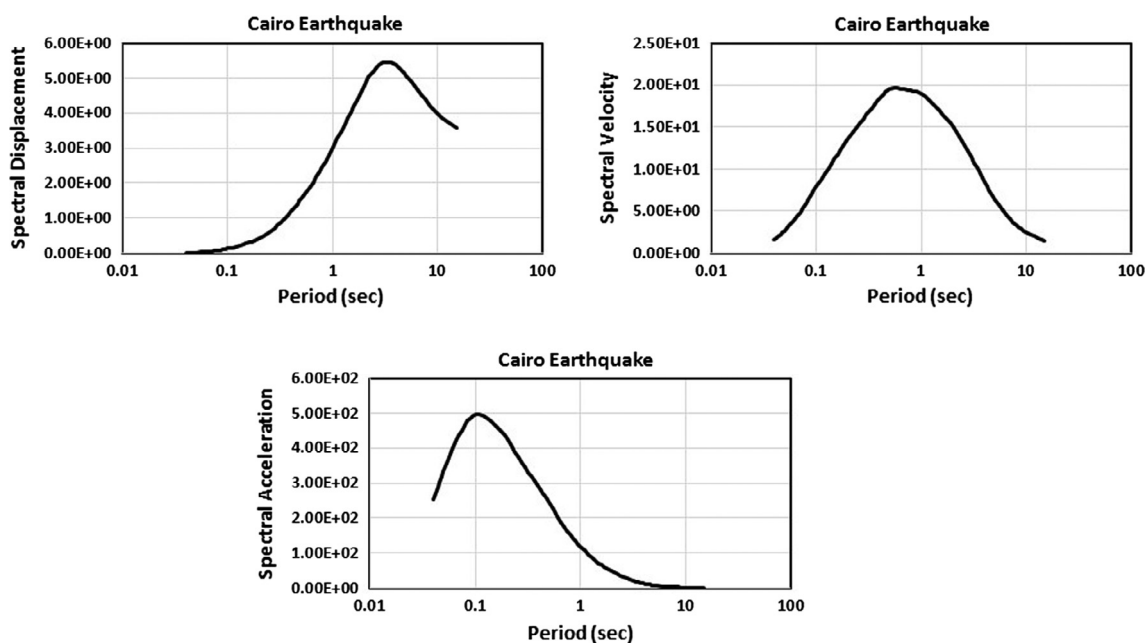

Figure 7   Simulated ground motion response spectra due to Cairo earthquake. Damping factor is 5%.
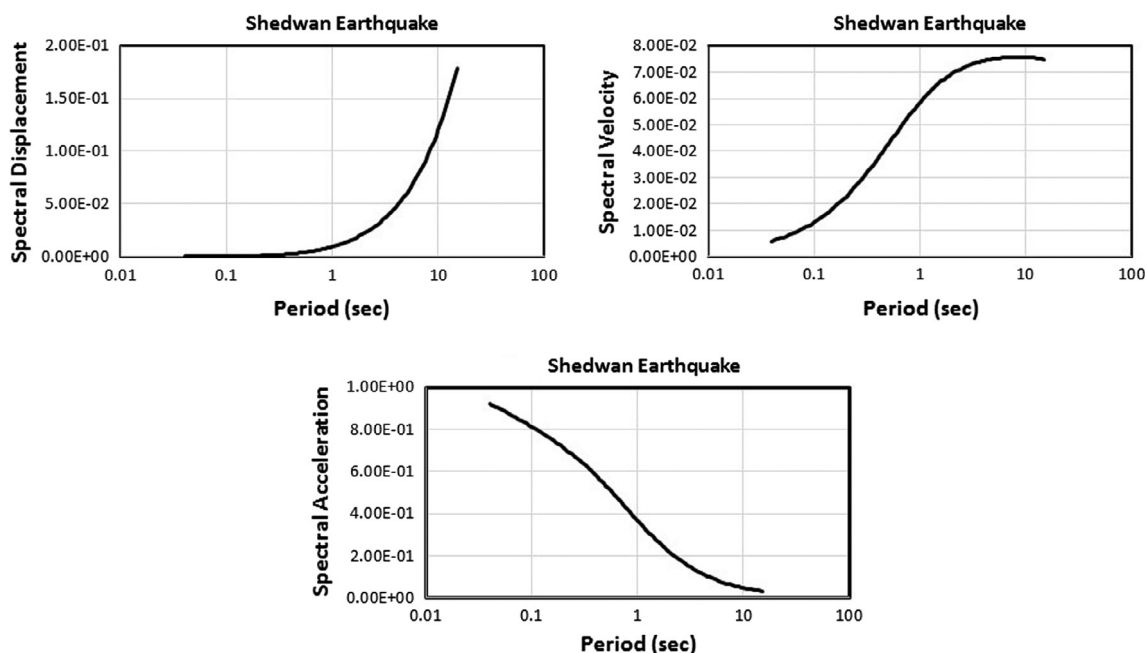

Figure 8   Simulated ground motion response spectra due to Shedwan earthquake. Damping factor is 5%.

The simulation results are presented in Figs. 4–6. Ground motion time series of the aforementioned events were carried out based on source parameters taken from the work of Hussein (1999) and Abou Elenean et al. (2009). Other parameters for path effects were taken from the work of El-Aal (2010), and from the simulation, we can see that the peak ground acceleration for Cairo, Shedwan and Aqaba earthquakes is 140, 1.0, and 1.0 cm/s^2 respectively. The PGV values for the corresponding earthquakes are 50, 0.6 and 1.5 cm/s respectively, whereas the PGD obtained are 3.0, 1.5 and 2.2 cm. These values indicate that Cairo earthquake has the highest impact on the site which conforms to the work of Deif and Khalil (2002). On the other hand, response spectra of the three earthquakes at a damping of 5% are also shown in Figs. 7–9. The response spectra too confirmed the dominance of Cairo earthquake impact on the site. In addition, the site response is delineated using the HVSR technique with data partly analyzed in previous paper (Khalil and Abdel Hafiez, 2016). The cumulative analysis using the whole dataset is shown in Fig. 10. The average value for the natural frequency is found to be 0.4 Hz, whereas the average peak amplitude is close to 8. The peak amplitude obtained from the HVSR technique underestimates the amplification of the soil. Hence, it can be used as lower boundary for site amplifications.

Ground motion parameters obtained from the current study show that the expected ground motion from the focus area of Cairo earthquake is high. Henceforth, special
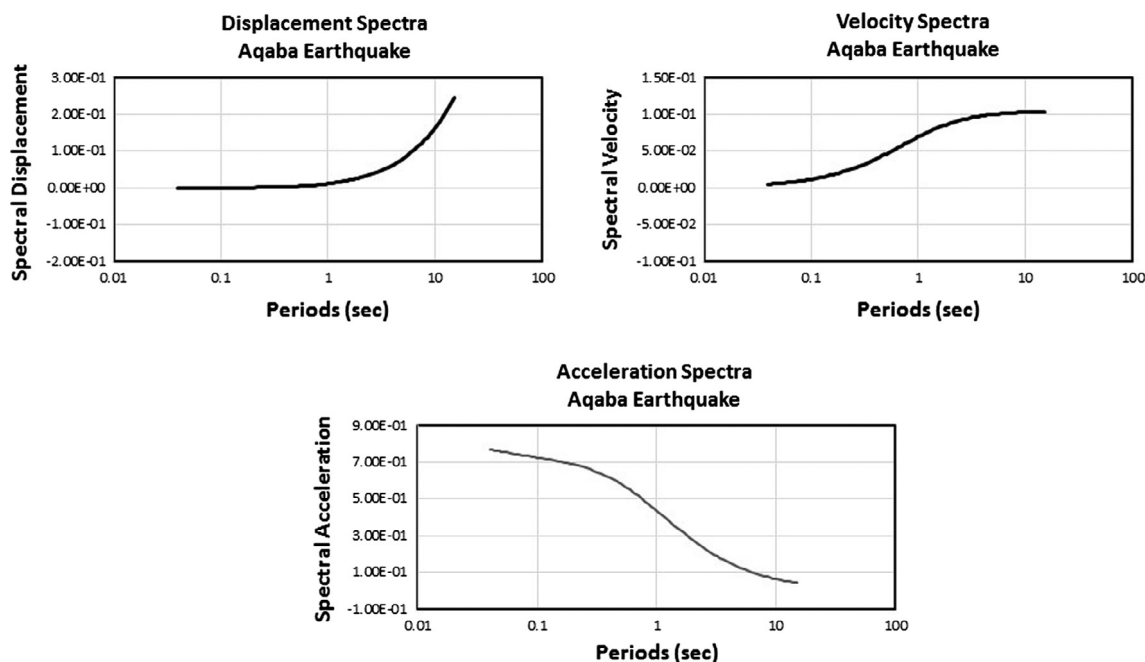

Figure 9   Simulated ground motion response spectra due to Aqaba earthquake. Damping factor is 5%.
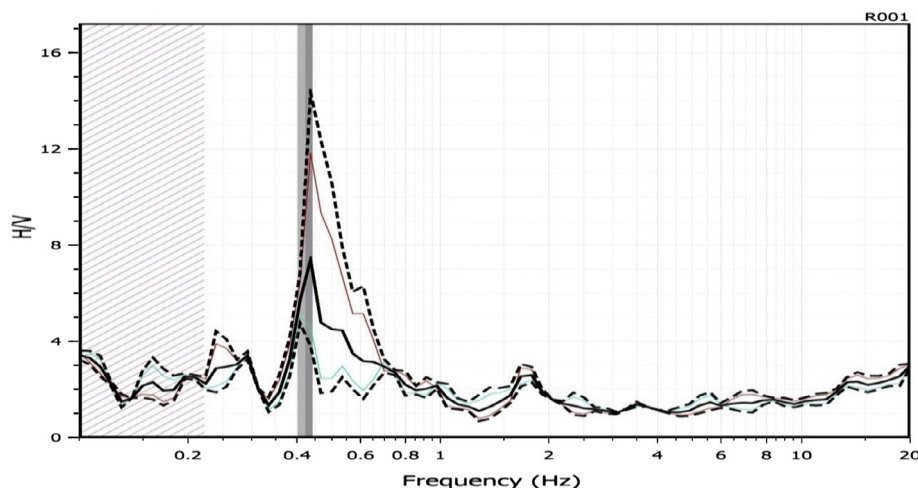

Figure 10   Natural frequency and amplitude of the studied area (Khalil and Abdel Hafiez, 2016).

consideration must be followed for the restoration of both the subsurface tunnels and shaft ceiling.

Acknowledgment

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