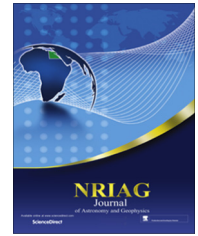




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Simulation of strong ground motion parameters of the 1 June 2013 Gulf of Suez earthquake, Egypt



Mostafa Toni *

*Geology Department, Faculty of Science, Helwan University, Cairo, Egypt
North African Group for Earthquakes and Tsunami Studies (NAGET), Egypt*

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PSA

Abstract This article aims to simulate the ground motion parameters of the moderate magnitude (M_L 5.1) June 1, 2013 Gulf of Suez earthquake, which represents the largest instrumental earthquake to be recorded in the middle part of the Gulf of Suez up to now. This event was felt in all cities located on both sides of the Gulf of Suez, with minor damage to property near the epicenter; however, no casualties were observed. The stochastic technique with the site-dependent spectral model is used to simulate the strong ground motion parameters of this earthquake in the cities located at the western side of the Gulf of Suez and north Red Sea namely: Suez, Ain Sokhna, Zafarana, Ras Gharib, and Hurghada. The presence of many tourist resorts and the increase in land use planning in the considered cities represent the motivation of the current study. The simulated parameters comprise the Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Peak Ground Displacement (PGD), in addition to Pseudo Spectral Acceleration (PSA). The model developed for ground motion simulation is validated by using the recordings of three accelerographs installed around the epicenter of the investigated earthquake. Depending on the site effect that has been determined in the investigated areas by using geotechnical data (e.g., shear wave velocities and microtremor recordings), the investigated areas are classified into two zones (A and B). Zone A is characterized by higher site amplification than Zone B. The ground motion parameters are simulated at each zone in the considered areas.

The results reveal that the highest values of PGA, PGV, and PGD are observed at Ras Gharib city (epicentral distance ~ 11 km) as 67 cm/s^2 , 2.53 cm/s , and 0.45 cm respectively for Zone A, and as 26.5 cm/s^2 , 1.0 cm/s , and 0.2 cm respectively for Zone B, while the lowest values of PGA, PGV, and PGD are observed at Suez city (epicentral distance ~ 190 km) as 3.0 cm/s^2 , 0.2 cm/s , and 0.05 cm respectively for Zone A, and as 1.3 cm/s^2 , 0.1 cm/s , and 0.024 cm respectively for Zone B. Also the highest PSA values are observed in Ras Gharib city as 200 cm/s^2 and 78 cm/s^2 for Zone A and Zone B respectively, while the lowest PSA values are observed in Suez city as 7 cm/s^2 and

* Address: Geology Department, Faculty of Science, Helwan University, Cairo, Egypt.

E-mail address: mostafa.toni@hq.helwan.edu.eg.

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3 cm/s² for Zone A and Zone B respectively. These results show a good agreement with the earthquake magnitude, epicentral distances, and site characterizations as well.

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1. Introduction

The 1 June 2013 earthquake was recorded in the middle part of the Gulf of Suez which is considered as one of the active seismic source zones in Egypt (Fig. 1). The Egyptian National Seismological Network (ENSN) recorded this earthquake and estimated its magnitude as (M_L 5.1) and its focal depth as 21 km. It is worth mentioning that this event is the largest instrumental earthquake to be recorded in middle and northern parts of Gulf of Suez after the M_L 4.8 earthquake of 12 June 1983 (Morsy et al., 2011). No casualties were caused by the 1 June 2013 earthquake; however, minor damage to prop-

erty was observed near the epicenter. Toni et al. (2016b) studied the source mechanisms and parameters of the 1 June 2013 earthquake by using the moment tensor inversion and the first motion polarities of P- and S-waves methods. They concluded that this event had a normal faulting mechanism with strike-slip components. They estimated the source parameters of this earthquake as stress drop (2.1 MPa), seismic moment ($6.30E + 22$ dyne cm), and moment magnitude (M_W 4.6).

The requirements of seismic design, estimation of seismic losses and seismic risk management dictate the necessity of seismic hazard assessment in terms of various parameters of ground motion in the investigated areas, which include from

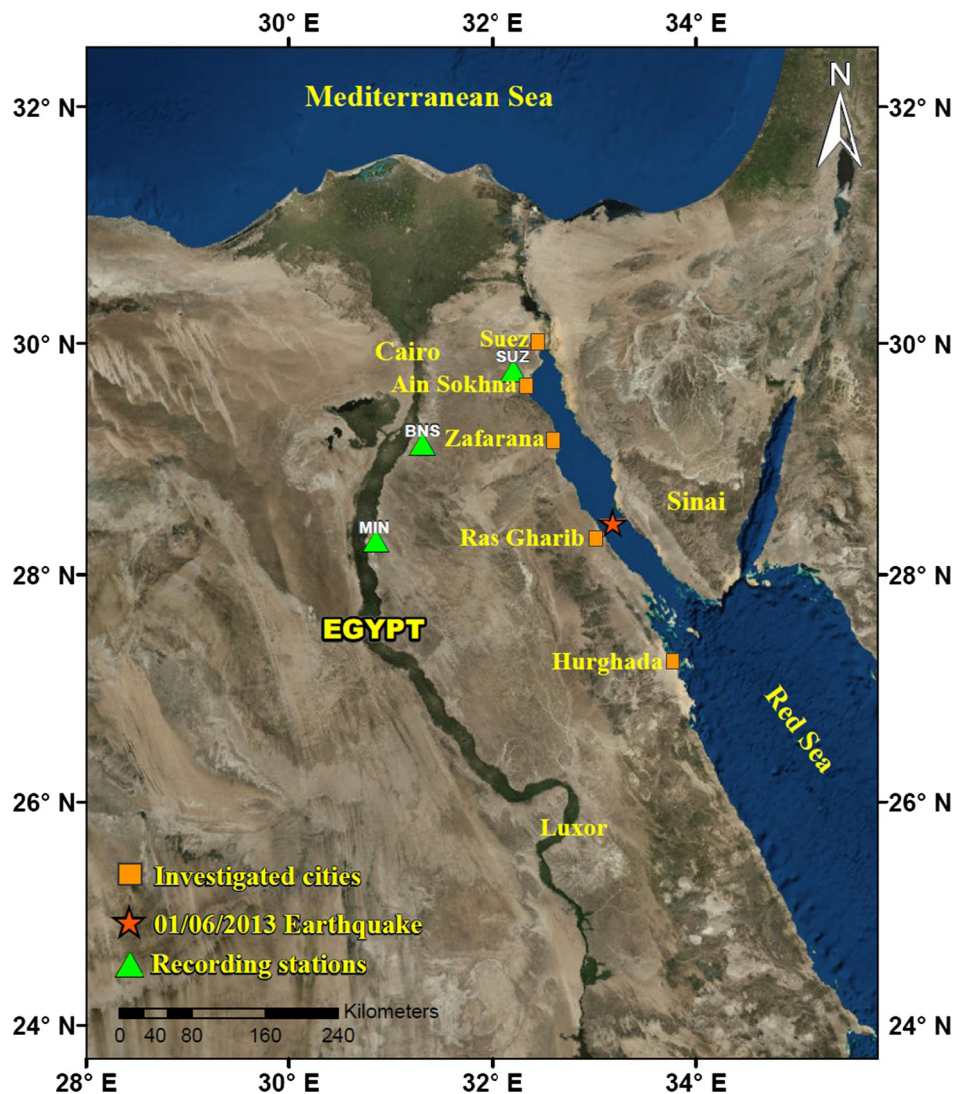


Fig. 1 Map of Egypt showing locations of the investigated cities, epicenter of the 1 June 2013 earthquake, and locations of the recording stations: Suez (SUZ), Beni Suef (BNS), and Minya (MIN).

north to south: Suez, Ain Sokhna, Zafarana, Ras Gharib, and Hurghada cities (Fig. 1). Some of these cities are characterized by high population density like Hurghada city (the capital of the Red Sea Governorate and the main tourist center on the Red Sea coast) and Suez city (the capital of the Suez Governorate). The considered areas cover the western side of the Gulf of Suez and north Red Sea, which are characterized by the presence of many tourist resorts and the increase in land use planning; therefore, it is prime of interest to perform the current study.

The ground motion parameters in terms of peak amplitudes of ground acceleration (PGA), velocity (PGV), displacement (PGD), and response spectra/pseudo-spectral acceleration (PSA) are estimated in the investigated areas. The stochastic technique of Boore (2003) with the site-dependent spectral model is used for this purpose. The goal of modeling is to examine the possibility of application of the technique that is based on the models of radiated spectra, the stochastic models, and the semi-empirical modeling of site response.

The site response is estimated in the studied areas by using microtremor data that have been collected from Ain Sokhna and Ras Gharib. For Hurghada, Zafarana, and Suez, geotechnical information used in site effect estimation is taken from Toni et al. (2016a), Abd el-aal et al. (2016), and Mohamed et al. (2016) respectively. According to site response, the investigated areas are classified into two zones: *Zone A* and *Zone B*, where *Zone A* is characterized by higher site amplification than *Zone B*.

The 1 June 2013 earthquake was also recorded by three accelerographs installed by the ENSN in Suez (SUZ), Beni Suef (BNS), and Minya (MIN) (Fig. 1). As shown in Fig. 1, the azimuthal distribution of these stations covers the western and northern directions of the considered earthquake. The seismic data observed at these three accelerographs are used for validating the spectral model developed for ground motion simulation in the current study.

2. Methodology

The stochastic method (Boore, 2003) is one of the most frequently used approaches in earthquake ground motion simulation. This technique is useful for simulating earthquake ground motion for engineering applications. It is also used for ground motion prediction especially in regions of low to moderate earthquake activities where recordings of strong ground motion from large earthquakes are not available (Boore, 1983; 2003).

The model of Fourier acceleration spectrum A at frequency f with considering the site response is given by

$$A(f) = (2\pi f)^2 cs(f)D(R,f)I(f) \quad (1)$$

where C is the scaling factor, $S(f)$ is the source spectrum, $D(R,f)$ is the attenuation effect, and $I(f)$ is the frequency-dependent.

The scaling factor C is calculated as

$$C = ([R_{\theta\theta}]FV)/(4\pi\rho\beta^3 R) \quad (2)$$

where $R_{\theta\theta}$ is the radiation coefficient, F is the free surface amplification, V is the partitions of vector into the horizontal components, β is the shear wave velocity and ρ is the density at earthquake source region, and R represents the source-site propagation path (i.e. hypocentral distance).

The source function $S(f)$ in Brune single-corner-frequency model (Brune, 1970) is

$$S(f) = M_0/[1 + (f/f_c)^2] \quad (3)$$

The corner frequency f_c can be calculated as

$$f_c = 4.9 \times 10^6 \beta (\Delta\sigma/M_0)^{1/3} \quad (4)$$

Here $\Delta\sigma$ is the stress parameter in bars, M_0 is seismic moment in dyne-cm, and β is the shear wave velocity (km/s) in the source region.

The function $D(R,f)$ accounts for frequency-dependent attenuation that modifies the spectral shape. It depends on the hypocentral distance R , crustal material characteristics, and the quality factor Q that represents an elastic attenuation. These effects are represented by

$$D(R,f) = \exp[-\pi f R / Q(f)\beta] P(f, f_{max}) \quad (5)$$

where $P(f, f_{max})$ is high-cut filter.

The high-frequency amplitudes can be reduced by kappa (k) operator (Anderson and Hough, 1984), by multiplying the spectrum by the factor $P(f)$

$$P(f) = \exp(-\pi k f) \quad (6)$$

where k is a region-dependent parameter.

A simplified scheme of the stochastic approach applied in this study is shown in Fig. 2.

3. Ground motion simulation

Simulation of ground motion parameters comprises four main stages: evaluation of site effect at the investigated areas, development of site-dependent spectral model, validation of the developed model, and application of the verified model in ground motion simulation. Here is a description of each stage:

3.1. Site effect evaluation

During this stage, the site amplification function is estimated. According to the geological setting, the five investigated cities are classified into two main zones, i.e. *Zone A* and *Zone B* (Fig. 3).

Zone A represents the plain of coastal zone between the Gulf of Suez/Red Sea in the east and mountain chains in the west. This zone is covered mainly by Quaternary deposits, Sabkha deposits (fine sand, silt, evaporates), and recent Wadi (Valley) deposits (detritals of sand, silt, and gravel) (EGSMA, 1981; Conoco, 1987; Said, 1990). At Hurghada, Zafarana, and Suez, the site amplification has been calculated by using shear wave velocity profiles obtained in Hurghada by Toni et al. (2016a), in Zafarana by Abd el-aal et al. (2016), and in Suez by Mohamed et al. (2016). An example of the shear wave velocity profiles used in the determination of site amplification in the current study is depicted in Fig. 4. At Ras Gharib and Ain Sokhna areas, a field survey of microtremor single station has been carried out. The recorded seismic signals are analyzed using the H/V method of Nakamura (1989). Then the site effect is taken from the resulted spectral ratio curves (Fig. 5). The site effect estimated by this method is represented by the site fundamental frequency (f_0) and its corresponding amplitude of ground motion (A_0). However, it is necessary to note that A_0 is not the real site amplification;

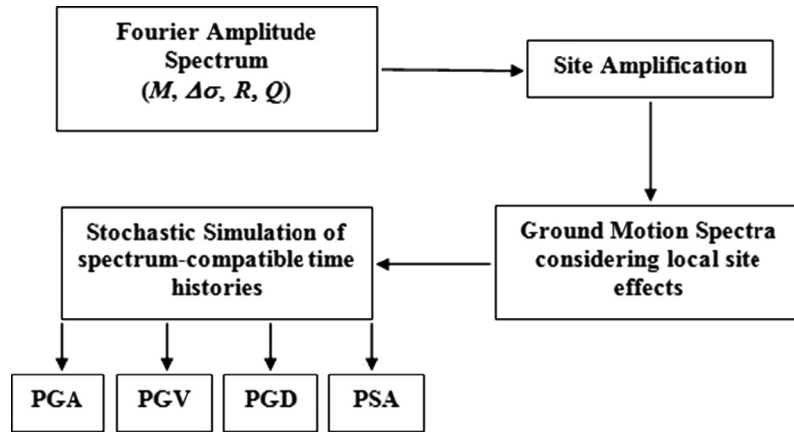


Fig. 2 Scheme of ground motion modeling based on the Fourier amplitude spectrum and stochastic simulation applied in this study.

it is still controversial (Mucciarelli, 1998; Horike et al., 2001; Mucciarelli and Gallipoli, 2004; Mukhopadhyay and Bormann, 2004; SESAME, 2004). Therefore the site effect estimated here should be considered as preliminary.

At areas where the shear wave velocity profiles are available (i.e. Zafarana, Hurghada, and Suez), the site amplification is estimated by applying the relations between the average shear wave velocity (AVS_{depth}) and amplification factor (A_f) obtained by regression analysis of attenuation law of ground motion indices (Tamura et al., 2000). The relationship between AVS_{depth} and A_f of ground motion is obtained as follows:

$$\log(A_f) = -0.734 * \log(AVS_{depth}) + 1.98 \quad (7)$$

The average shear wave velocity (AVS_{depth}) at the sediments over a hard rock is here calculated by the following expression (CEN, 2004):

$$AVS(depth) = \frac{d}{\sum_{i=1,N} \frac{h_i}{V_i}} \quad (8)$$

where h_i denote the thickness (in meters), d being the depth, and V_i is shear wave velocity of the i -th layer, in a total of N , existing in depth.

Zone B is rock sites, and in most of the investigated areas, it is very close to the Red Sea Mountains which composed of igneous and metamorphic rocks. In Suez city, Zone B is covered by Cretaceous limestone (Mohamed, 2016). The rock units at Zone B have approximately similar characteristics of the hard rock/half-space. Consequently, the site amplification at Zone B is assumed to be unity.

3.2. Development of the spectral model

During this stage the Fourier amplitude spectrum (FAS) source scaling, attenuation model, and site amplification function are used for constructing the site-dependent spectral model (Boore, 2003). Parameters of the spectral model considered in this study are listed in Table 1.

3.3. Validation of the developed spectral model

Validation of the spectral model parameters is an important step that should be done before using it in ground motion simulation. As mentioned before, the 1 June 2013 Gulf of Suez

earthquake was recorded by three accelerographs that have been installed by ENSN in Suez (SUZ), Beni Suef (BNS), and Minya (MIN) (see Fig. 1). These stations cover the western and northern directions of the earthquake's epicenter. The observed recordings at these three accelerographs are used for validation of the developed spectral model which is used for simulating ground motions (i.e. acceleration, velocity, displacement). Figs. 6-8 show a comparison between the observed and the simulated ground motions at Suez (SUZ), Beni Suef (BNS), and Minya (MIN) respectively. This correlation shows a good agreement between the observed and the simulated ground motions at all the three locations. However the observed ground motion reveals relatively higher PGA, PGV, and PGD values than the simulated ones (but still in the accepted range). This can be regarded as the local site effect at locations of the accelerographs, in addition to the effect of the recording system (i.e. instrument effect). Also, the simulated ground motions used in this comparison have been simulated without considering any site effect. In conclusion, the observed data proved the validity of the developed spectral model to be used honestly in ground motion simulation at the investigated areas.

3.4. Application of the verified model in ground motion simulation

After verifying the developed spectral model considering the local site effect, the stochastic technique software package (http://www.daveboore.com/software_online.html) is here used for estimation of Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak Ground Displacement (PGD), and Pseudo Spectral Acceleration (PSA). A set of twenty synthetic acceleration time series are generated using the spectral model. A value of duration $\tau=0.9$, for which it is assumed that most of the spectral energy (90%) is spread over this duration of the accelerogram, is taken as 10 s. The PGA, PGV, and PGD are obtained as the average values from those calculations using simulated acceleration time functions. Peak Ground Velocity (PGV) and Peak Ground Displacement (PGD) are evaluated by integration of the synthetic accelerograms after high-pass filtering with the cut-off frequency of 0.2 Hz. Such type of filtering is a standard procedure when processing the empirical strong ground motion recordings. The response spectra (PSA) are here calculated at 0.05 damping ratio.

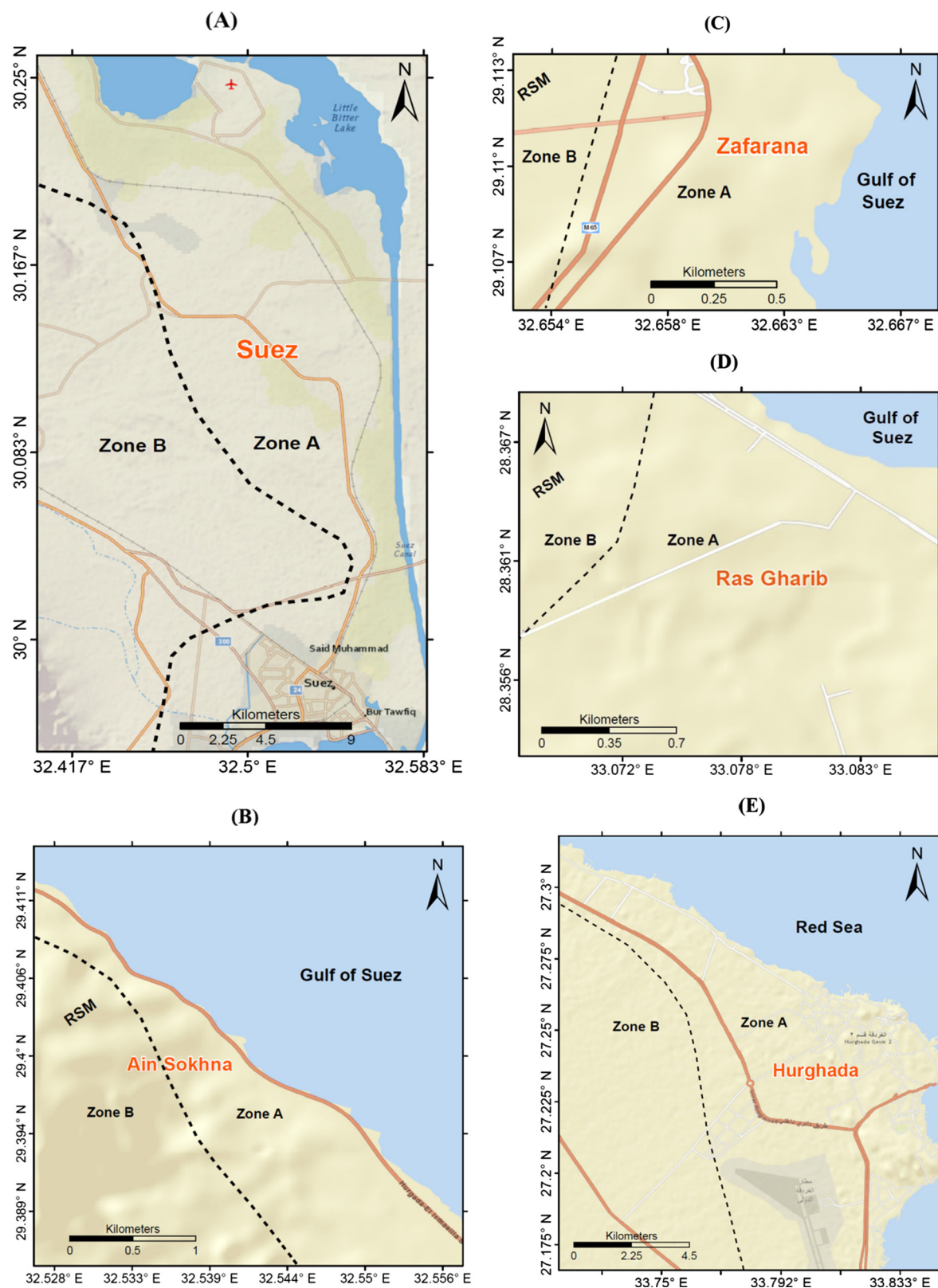


Fig. 3 Location Maps of the investigated areas: (A) Suez, (B) Ain Sokhna, (C) Zafarana, (D) Ras Gharib, (E) Hurghada. The black dashed line represents the boundary between Zone A and Zone B. The acronym RSM refers to the Red Sea Mountains.

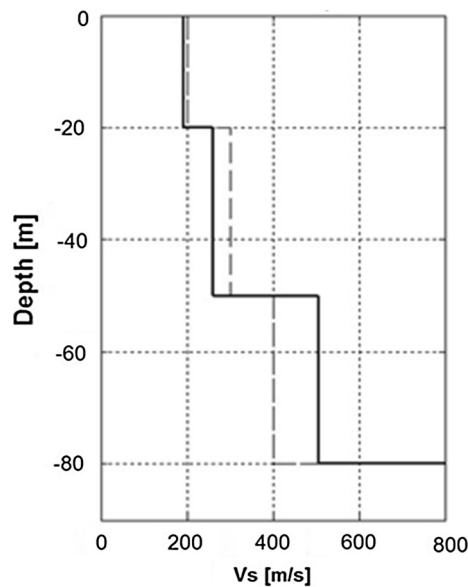


Fig. 4 Shear wave velocity profile used in determination of site amplification at Zone A in Hurghada city (after Toni et al., 2016a). The solid black line is the observed and the dashed gray line is the theoretical one.

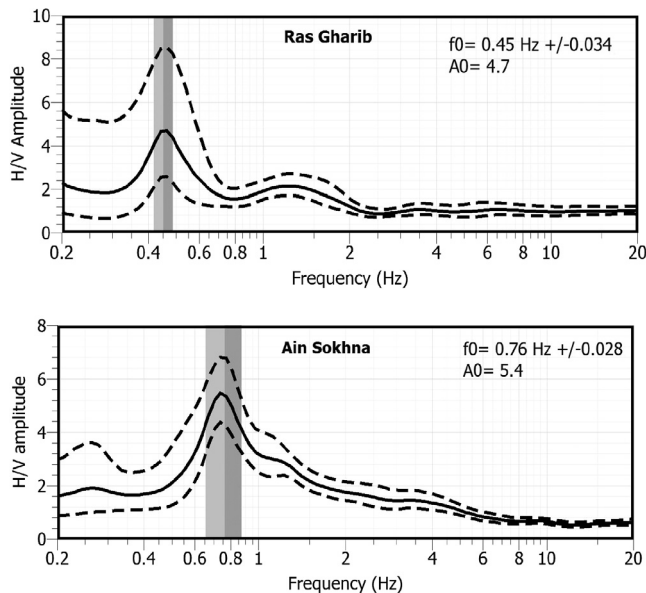


Fig. 5 H/V spectral ratio curves obtained at Zone A in Ras Garib and Ain Sokhna. Acronyms f_0 and A_0 are the site fundamental frequency and its corresponding amplitude of ground motion respectively. The black line represents the main spectral ratio curve; the dashed lines are \pm standard deviation of spectral ratios.

4. Results

The Fourier amplitude spectra of ground motion during the 1 June 2013 Gulf of Suez earthquake were calculated using the developed spectral model with the site amplification functions estimated for the considered areas (Suez, Ain Sokhna, Zafar-

Table 1 Parameters of the spectral model of 1 June 2013 Gulf of Suez earthquake considered in the present study.

Parameter	Description
Location	28.433°N 33.153°E (ENSN)
Magnitude	$M_w = 4.6$ (Toni et al., 2016b)
Focal depth	21 km (ENSN)
Stress parameter $\Delta\sigma$	21 bars (Toni et al., 2016b)
Seismic moment M_0	$6.30E+22$ dyne.cm (Toni et al., 2016b)
Corner frequency f_c	3.1 Hz (Toni et al., 2016b)
Density ρ	2.7 gm/cm ³ (Marzouk, 1987)
Shear velocity β	3.46 km/s (Marzouk, 1987)
Path attenuation	$Q(f) = 320 f^{0.49}$ (Girgis, 2010)
High-frequency filter $P(f)$	$P(f) = \exp(-\pi \kappa f)$ (Anderson and Hough, 1984)
Site attenuation, κ (sec)	$\kappa = 0.005$

ana, Ras Gharib, and Hurghada). The simulated time histories (acceleration, velocity, displacement) at Zones A and B in the considered areas are depicted in Fig. 9. Table 2 summarizes the results of ground motion parameters obtained at Zone A and Zone B in the five investigated areas.

The results reveal that the highest PGA, PGV, and PGD values are observed in Ras Gharib city, i.e. the closest area to the earthquake's epicenter. The lowest values of PGA, PGV, and PGD are observed in Suez and Hurghada cities, i.e. the farthest areas to the epicenter (see Table 2).

The response spectra (PSA), which represent the most important characteristics of ground motion in earthquake engineering, were calculated in the present study. Fig. 10 shows the calculated PSA at Zone A and Zone B in the considered areas. As shown in Fig. 10 the PSA has the highest amplitudes in Ras Gharib city as 200 cm/s² and 78 cm/s² for Zone A and Zone B respectively, while the lowest PSA values are reported in Suez city as 7 cm/s² and 3 cm/s² for Zone A and Zone B respectively.

In general, the results demonstrate the following: a) in all investigated areas, Zone A is characterized by higher values of ground motion than Zone B due to the site amplification in this zone and b) the simulated ground motions show a good agreement with earthquake magnitude (M_w 4.6) and epicentral distances (i.e. the smaller distances the higher ground motion values, and vice versa).

5. Discussion and conclusion

On the first of June 2013, a moderate earthquake with local magnitude (M_L 5.1) struck the middle part of the Gulf of Suez at latitude 28.433°N, longitude 33.153°E, and depth of 21 km. According to Toni et al. (2016b) this earthquake originated from oblique fault (normal fault with strike-slip components). The quake was felt in various locations around the epicenter. Some people felt this earthquake in Cairo at distance of about 190 km. The 1 June 2013 earthquake is the largest instrumental earthquake to be occurred in the middle Gulf of Suez up to now. This article aims to simulate the ground motion parameters of the 1 June 2013 Gulf of Suez earthquake at Suez, Ain Sokhna, Zafarana, Ras Gharib, and Hurghada cities, for the purposes of seismic hazard assessment and risk management. The considered areas represent the main cites on the Gulf of Suez and north Red Sea coast. The increase in

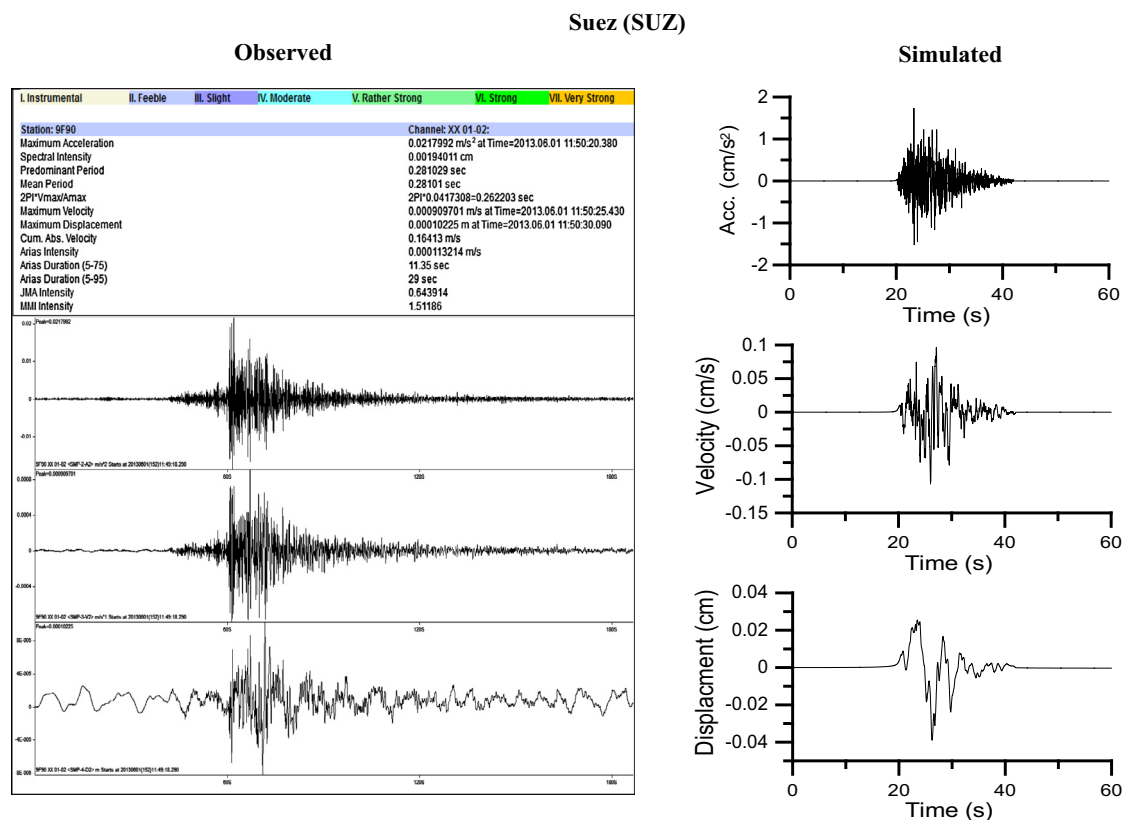


Fig. 6 Comparison between observed and simulated ground motion (acceleration, velocity, displacement) at SUZ station (epicentral distance 174 km).

urbanization and the presence of many tourist resorts in this region represent the motivation of this study.

The stochastic technique (Boore, 2003) has been used for simulating ground motions of the 1 June 2013 earthquake at the investigated areas. This technique requires information about earthquake's source, propagation path, and site response. In the current study, parameters of the earthquake source in terms of moment magnitude, stress drop, seismic moment, density and shear velocity of the source region were taken from Toni et al. (2016b) and Marzouk (1987). The path effect (path attenuation) was taken as $Q(f) = 320 f^{0.49}$ (Girgis, 2010). The site amplification functions were determined from the shear wave velocity- site amplification relationship (Tamura et al., 2000). The shear wave velocity is taken from the previous work in Hurgada (Toni et al., 2016a), Zafarana (Abd el-aal et al., 2016), and Suez (Mohamed et al., 2016). In Ras Gharib and Ain Sokhna, a field survey of micro-tremor single station has been carried out to estimate the site effect using H/V spectral ratio method (Nakamura, 1989). Depending on the geological setting and the determined site effect, the five investigated areas were classified into two zones (A and B). Zone A lays in the coastal plain between the Gulf of Suez/Red Sea coast in the east and hard rocks of the Red Sea Mountains in the west. It is characterized by site amplification due to the presence of thick layers of unconsolidated deposits. Zone B is covered by rock sites that have approximately similar characteristics of the hard rock/half-space. Consequently, the site amplification at Zone B is assumed to be unity.

Validation of the spectral model parameters is an important step that should be done before using it in ground motion simulation. Therefore, the developed model was validated using seismic waveforms that have been recorded by three accelerographs installed by ENSN in Suez, Beni Suef, and Minya (Figs. 1, 6, 7, and 8).

After validating the site-dependent spectral model, time histories of ground motion (acceleration, velocity, and displacement) were simulated. Then the peak amplitudes of ground acceleration (PGA), velocity (PGV), and displacement (PGD) were estimated. The response spectra (PSA), which are considered as one of the most important characteristics of ground motion in earthquake engineering, were calculated at each zone in the studied areas.

The results reveal that Ras Gharib city which is the closest city to the epicenter, has the highest value of ground motions, while the lowest values of ground motions were observed at the farthest cities to the epicenter (i.e. Suez and Hurgada).

The results of the present study indicate that, the joint influence of factors related to earthquake source, path, and local geological conditions during the 1 June 2013 Gulf of Suez earthquake resulted in a maximum $PGA = 67 \text{ cm/s}^2$ at Zone A in Ras Gharib city (epicentral distance $\sim 11 \text{ km}$), which was not strong to cause structural damage. However it was enough to cause the minor damage to property that has been observed after this event. Besides that, construction issues such as building designs, quality of building materials, and age of building may play an important role in the damage caused

Beni Suef (BNS)

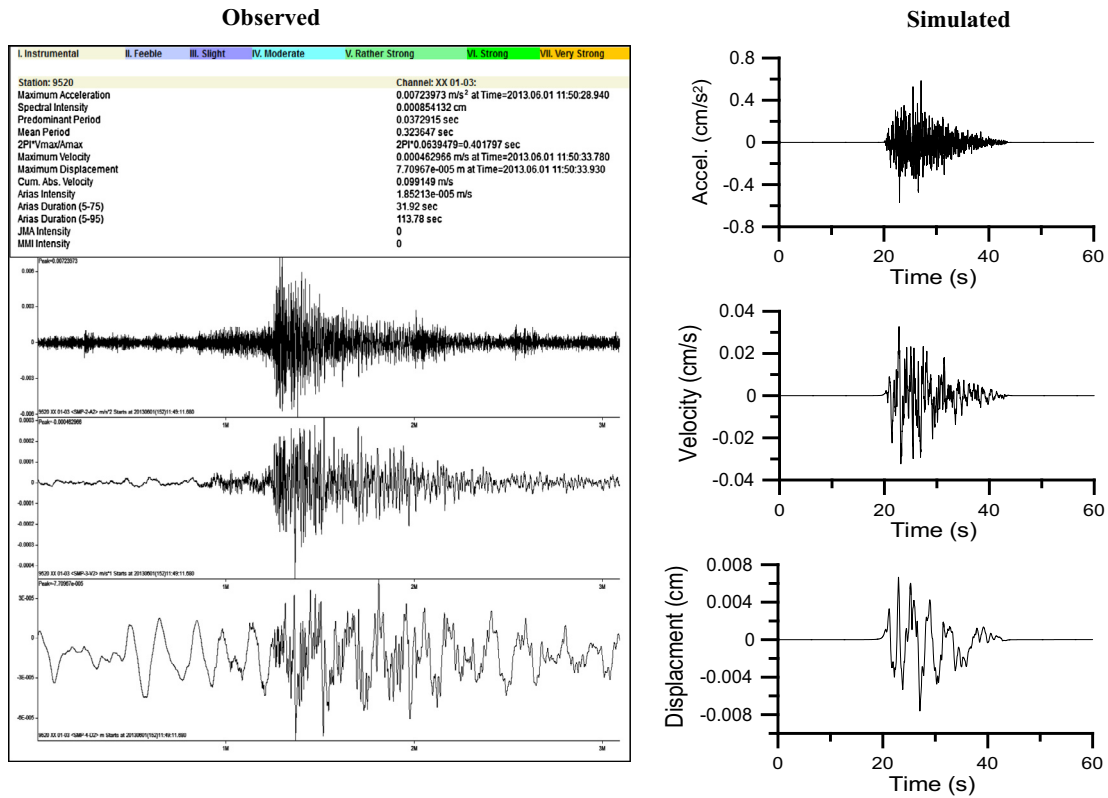


Fig. 7 Comparison between observed and simulated ground motion (acceleration, velocity, displacement) at BNS station (epicentral distance 196 km).

Minya (MIN)

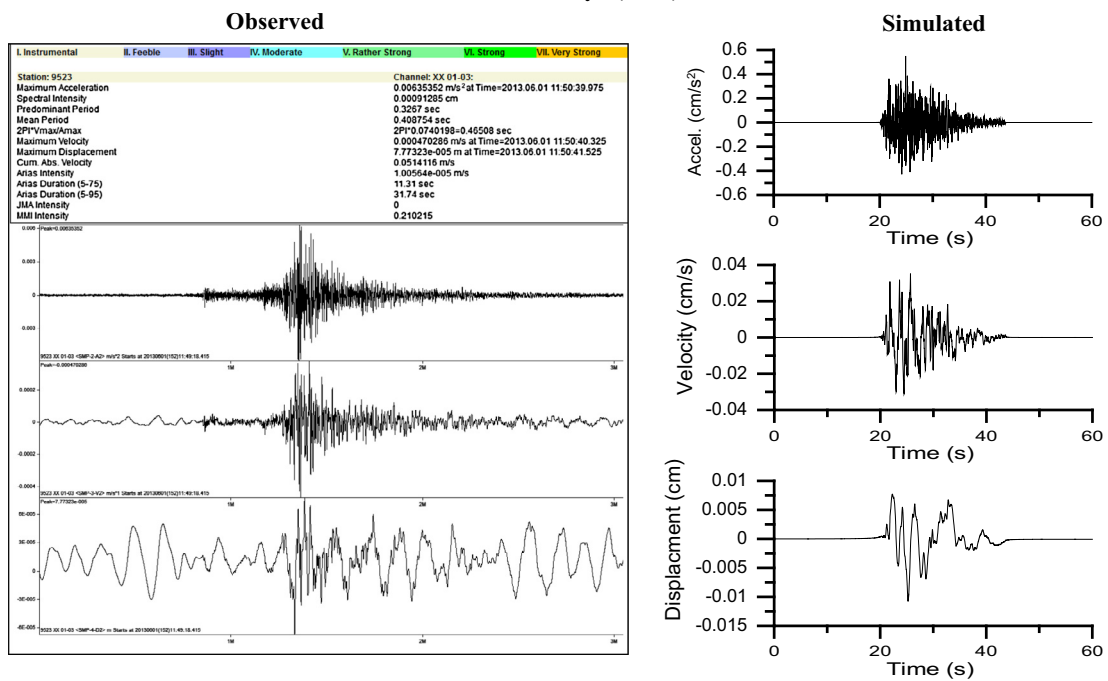


Fig. 8 Comparison between observed and simulated ground motion (acceleration, velocity, displacement) at MIN station (epicentral distance 225 km).

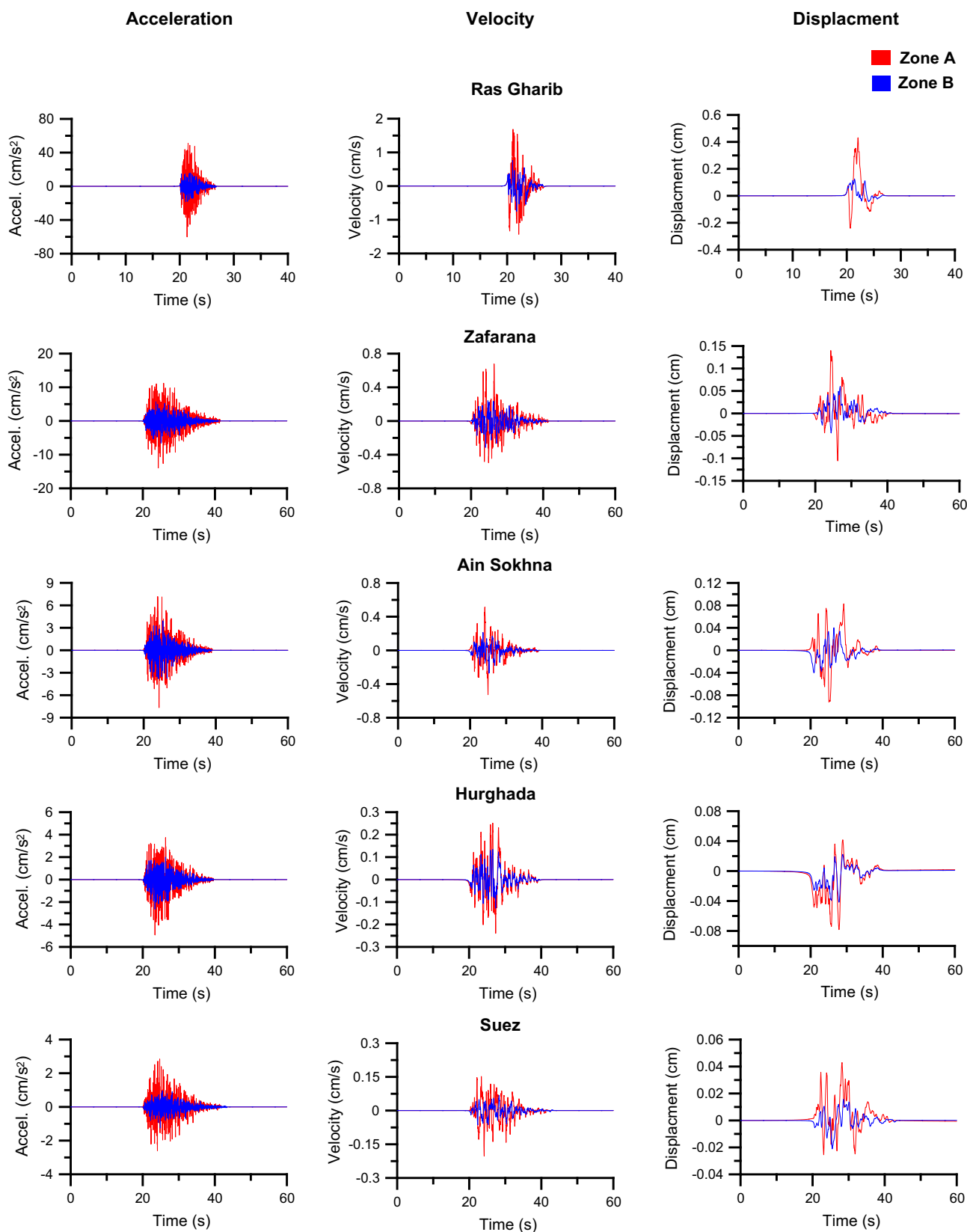


Fig. 9 Simulated time histories of ground motion at Zone A and Zone B in the investigated areas.

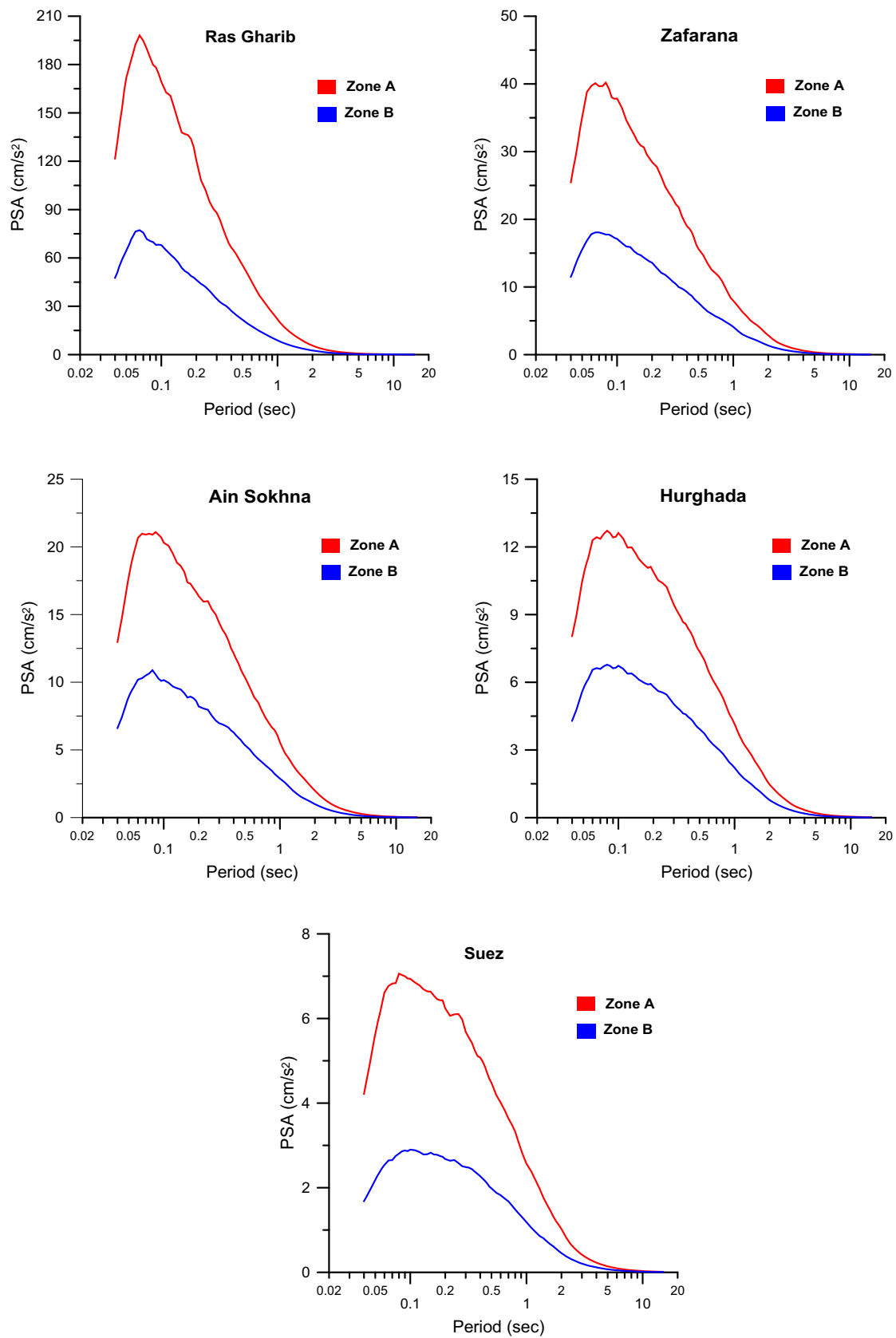


Fig. 10 Calculated response spectra (PSA) at Zone A and Zone B in the investigated areas. The spectra were calculated at 5% damping ratio.

Table 2 Results of ground motion parameters of the 1 June 2013 Gulf of Suez earthquake obtained in this study.

Investigated area\Ground motion	Zone A			Zone B		
	PGA (cm/s ²)	PGV (cm/s)	PGD (cm)	PGA (cm/s ²)	PGV (cm/s)	PGD (cm)
Ras Garib (epicentral distance ~ 11 km)	67	2.53	0.45	26.5	1.0	0.2
Zafarana (epicentral distance ~ 90 km)	14.7	0.7	0.15	6.8	0.33	0.08
Ain Sokhna (epicentral distance ~ 122 km)	8.2	0.5	0.12	4.1	0.24	0.06
Hurghada (epicentral distance ~ 145 km)	5.3	0.31	0.09	2.8	0.18	0.042
Suez (epicentral distance ~ 190 km)	3.0	0.2	0.05	1.3	0.1	0.024

by earthquakes, even in the case of small events as previously reported by Polat et al. (2009) and Gok et al. (2014).

Also, the ground motion parameters obtained in this study showed that the 1 June 2013 earthquake had a very small effect on Zafarana and Ain Sokhna areas, and no perceptible effect on the cities located far away from the epicenter like Suez and Hurghada.

The stochastic approach based on regional seismological models of radiated spectra and local geological and geotechnical data reveals a good ability to predict the strong ground motions in the investigated areas. The approach may be successfully used, together with other techniques of strong ground motion prediction, for the goals of deterministic and probabilistic seismic hazard assessment.

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