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Modeling of strong ground motion during the 1992 Cairo earthquake in the urban area northern Greater of Cairo, Egypt

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Abstract The 1992 Cairo earthquake originated from Dahshour seismic zone at an epicentral distance of about 25 km southwest of Cairo. Regardless of its relatively moderate magnitude (Mb = 5.8), it caused extensive property damage besides injuries and loss of lives. The significant damage of this earthquake was probably associated with amplification of seismic waves due to local site effects. Liquefaction was observed at many sites near the epicenter. There are no records of strong ground motion at the damaged area during this earthquake. The main shock was recorded only by the local Kattamya station (KEG) constructed in limestone rock site at about 46–48 km east of Cairo. In the present work, the strong ground motion during 1992 Cairo earthquake was analyzed and the possible causes of damage and structural failure were discussed. The study area is located at the southern part of Cairo city, holding heavy population and many public structures and strategic buildings. The ground motion parameters in terms of peak ground acceleration (PGA), peak ground velocity (PGV), and pseudo-spectral acceleration (PSA) were estimated for each site in the study area and in the KEG site. The site-dependent spectral models together with the stochastic technique were applied for this purpose, using the Fourier amplitude spectrum (FAS) source scaling, attenuation model, and the site amplification functions. The peak ground acceleration of the studied area, comprising 89 sites in northern great of Cairo (Qalyoub city) was calculated. The calculated peak ground acceleration values indicate the sites of high values of peak ground acceleration which are also characterized by high ground motion amplification factors. The ground motion, which is presented in this study, is highly amplified by the soil layer covering

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the area. Otherwise, the surface layer must be totally removed before construction of the buildings to avoid its large amplification to the ground motion.

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1. Introduction

The ever increasing urbanization and construction of specific installations that have marked the recent decades in Egypt require heightened sensitivity toward danger, generally represented by natural phenomena, particularly earthquakes. Occurrence of large-magnitude earthquake near an unprepared city of specific geological environment causes disaster. Hence, seismologists and civil engineers in seismic countries work on a seismic design structure and its resistance to strong ground motion. The ground motion relationships describe peak ground motions and response as a function of earthquake magnitude and distance. Thus, they are of paramount importance in the assessment of earthquake hazard to engineered structures. The response spectrum is the best representation of ground motion because it is based on natural frequencies of structures.

In the present study, the stochastic technique proposed by (Boore, 2003) is used to simulate the peak ground acceleration (PGA), and the acceleration time-histories expected from a significant earthquake that could have the greatest effect on the study area of Qalyoub city. The stochastic method is useful for simulating the higher-frequency ground motions ($f > 0.1$ Hz), which are interesting to engineers. This frequency range is widely used to predict ground motions due to potentially damaging earthquakes in regions of lack of strong ground motion records.

2. General geology of the study area and its surrounding

The Study area lies at the northeastern part of Greater Cairo (Qalyoub city) as shown in Fig. 1 and is located between latitudes 30.16 and 30.20N and longitudes 31.19 and 31.23E (Fig. 2). Most part of the geological units in the study area be-

longs to the Quaternary, Middle Miocene and Oligocene deposits. The Quaternary deposits are represented by different formations such as sand sheets which are located at the eastern part of the area. Inshas formation occupying the northern and eastern parts of the study area consists of cross-bedded sand, intercalated with Nile mud and silt. Bilbies formation is located at the central and eastern parts of the area and is made up of medium to coarse-grained and cross-bedded sands with plant roots and carbonate pockets. El Debba formation, in the southern part of the area, consists of coarse-grained sands intercalated with flint. The Middle Miocene is represented by Hommath formation, which is located at the central part of the survey area and made up of interbedded yellow sandy limestone, sandstone and sandy marl. The Oligocene deposits are represented by Gabal Ahmar Formation, which is composed of sand and sandstone according to EGSMA (1998). Fig. 2 shows the subsurface stratigraphy as described from a 202 m deep borehole drilled at the eastern part of the survey area by EGSMA (1998). The stratigraphic column consists of Quaternary, Middle Miocene and Oligocene deposits. The Quaternary deposits are represented by sand sheet and the Middle Miocene is represented by the Hommath formation.
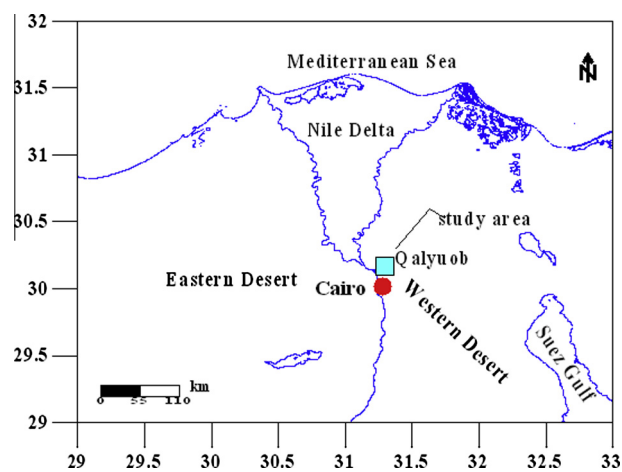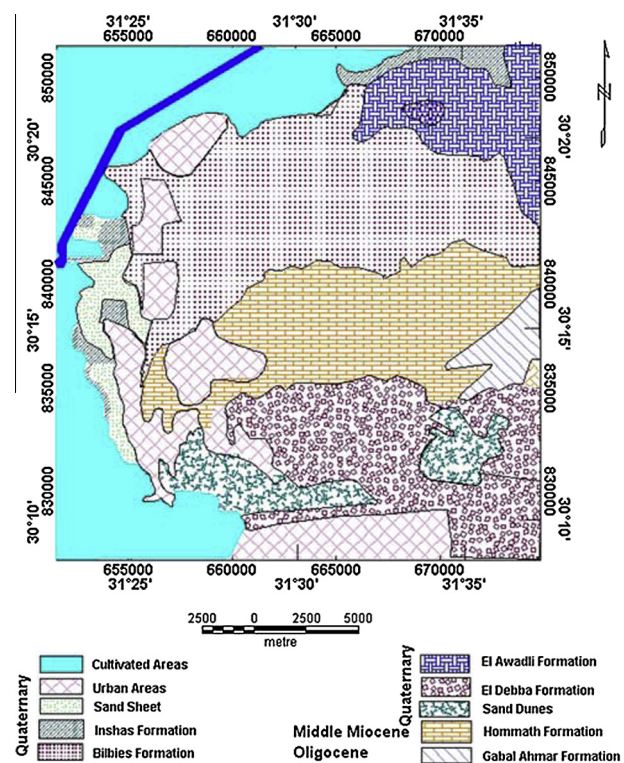

Fig. 1 Location map of the case study area.

Fig. 2 Geological map of the study area and surrounding area (modified after EGSMA, 1998).

The Oligocene deposits are represented by Gabal Ahmar Formation (sand and sandstone) and by a Basaltic sheet lying between 113.5 m (top) and 162.2 m (bottom) depths. And there are about 10 boreholes drilled at in the Qalyuob area.

The present study is intended to improve our understanding of the relationship between the shallow geological structure and microtremors, the experiments consisted of microtremor measurements at different points.

3. Outline of the method

Aki (1967) derived the first expression based on the spectrum of seismic waves radiated from complex faulting and determined the seismic moment of earthquake. Hanks and McGuire (1981) presented a simple theoretical model that predicts accurately the peak acceleration a max for California earthquakes and corroborated the scaling of motions with magnitude that had been derived empirically. The model treats ground motion as a band-limited finite-duration Gaussian white noise, with an amplitude spectrum given by Brune's model (1970 and 1971) for shear radiation. The source spectra are described by a single corner frequency that depends on earthquake size. Boore (1983) and McGuire et al. (1984) extended the model to predict the peak velocity vmax and the pseudo relative velocity spectra (PSV).

The assessment of seismic hazard in terms of acceleration and response spectra is the fundamental base of ground motion prediction. The radiated energy is assumed to be evenly distributed over a specified duration. Andrews (1986) stated that the shear-wave spectrum, $Y(f)$, for source i and site j is decomposed as:

$$Yij(f) = Ei(f) \ Pij(f) \ Gj(f), \tag{1}$$

where $E(f)$ is the source spectrum, $P(f)$ is the path spectrum, and $G(f)$ is the site spectrum.

Eq. (1) assumes that the directional effects of the source are averaged out by observations at different azimuths. The path spectrum is represented by geometrical spreading and whole-path attenuation $Q(f)$ as:

$$P(f) = r - y \ e(-\pi f t) \ Q(f), \tag{2}$$

where y is set to 1.0, consistent with body waves in uniform medium, t is the travel time, and r is the hypocentral distance.

Taking the natural logarithm, Eq. (1) becomes:

$$\ln Yij(f) = \ln Ei(f) + \ln Pij(f) + \ln Gj(f). \tag{3}$$

This linear expression often forms the basis for attempts to separate the source, path, and the site effects.

Boore (2003) employed a stochastic time-domain simulation method and used general equations from random process theory. He broke the total spectrum of the motion at a site into contributions of the earthquake source, path, site, and instrument. By separating the spectrum into these components, the models based on the stochastic method can be easily modified to consider both the specific situations and/or improved information about any particular aspects of the model.

Input parameters of the stochastic simulation method involve all the terms in the following equation:

$$Y(Mo, R, f) = E(Mo, f) \ P(R, f) \ G(f) \ I(f). \tag{4}$$

The method begins by specifying the Fourier amplitude spectrum of ground acceleration as a function of seismic moment and distance, $Y(Mo, R, f)$. The term $E(Mo, f)$ is the earth-quake source spectrum of a specific seismic moment (i.e., Fourier spectrum of the ground acceleration at a distance of 1 km) and $P(R, f)$ is the path effect that models the geometric spreading and an elastic attenuation of the spectrum as a function of hypocentral distance, R, and frequency, f. The term $G(f)$ is the site effect and the term $I(f)$ is the instrument effect or filter used to shape the spectrum to correspond to the particular ground motion measure of interest.

4. Methodology

Simulation of peak ground velocity (PGV), peak ground acceleration (PGA), peak ground displacement (PGD) is made for different soil conditions of Qalyoub city. The stochastic simulation method is done using the computer code SMSIM FORTRAN Programs for Simulating Ground Motions version 2.3 (Boore, 2008). This program version has major modifications of ground motion in Qalyoub city.

The method begins, as described in detail in the last text with specification of the furrier amplitude spectrum of ground acceleration as a function of earthquake size (moment or moment magnitude) and distance and frequency $Y(Mo, R, f)$, which can be represented as shown in Eq. (5):

$$Y(Mo, R, f) = E(Mo, f) \ P(R, f) \ G(f) \ I(f) \tag{5}$$

where E, P, G and I factors are the earthquake source, path, site, and instrument or type of motion respectively.

4.1. Input parameters

The input parameters for the method include all terms of Eq. (4), and the duration of motion, the simulation will apply to the random horizontal component of the shear wave of ground motion for the earthquake source of Dahshour seismic zone that represents the main disastrous and devastating source for Cairo.

The earthquake source spectrum $E(Mo, f)$ adopted here is Brune source model (Brune, 1970, 1971) given by:

$$E(Mo, f) = CMo/[1 + (f/fo)2], \tag{6}$$

where C is the source scaling factor given by:

$$C = R\theta\phi FV/4\pi\rho\beta3 \tag{7}$$

where $R\theta\phi$ is the average radiation pattern of shear wave (0.55, (Boore and Boatwright, 1984), F is the free-surface amplification ($= 2.0$), V represents the partition of energy from a vector into horizontal component, ρ is the crustal density, and β is the shear wave velocity which are chosen as ($\rho = 2.8$ gm/cm^3, $\beta = 3.7$ km/s), depending on the crustal stricture model for the source area (Samy, 2001), and Mo, fo are the seismic moment and corner frequency respectively. The relation between the two parameters Mo and fo is given by:

$$fo = 4.9 \times 106\beta s(\Delta\sigma/Mo)1/3 \tag{8}$$

where $\Delta\sigma$ is the stress drop parameter in Bar, fo in Hz, β in km/s, and Mo in Dyne-cm (Brune, 1970, 1971). In this study, $\Delta\sigma = 18.5$ bar depending on the study of the source parameters of the main shock of Dahshour earthquake by Hussein (1999), the seismic moment and stress drop of the effective earthquake are estimated based on Hussein (1999), as listed in Table 1.

Table 1 The recorded and simulated PGA for 12 October 1992, earthquake at KOT station.

Station	Coordinates		Recorded PGA (cm/s^2)	Simulated PGA (cm/sec^2)
	Latitude	Longitude		
KOT	29.927	31.829	3.145E+01	2.845E+01

The simulated ground motion of this event using stochastic simulation method is carried out with the following source parameters: stress drop $\Delta\sigma$ is equal 18.5 bars, (Hussein, 1999) as listed in (Table 2).
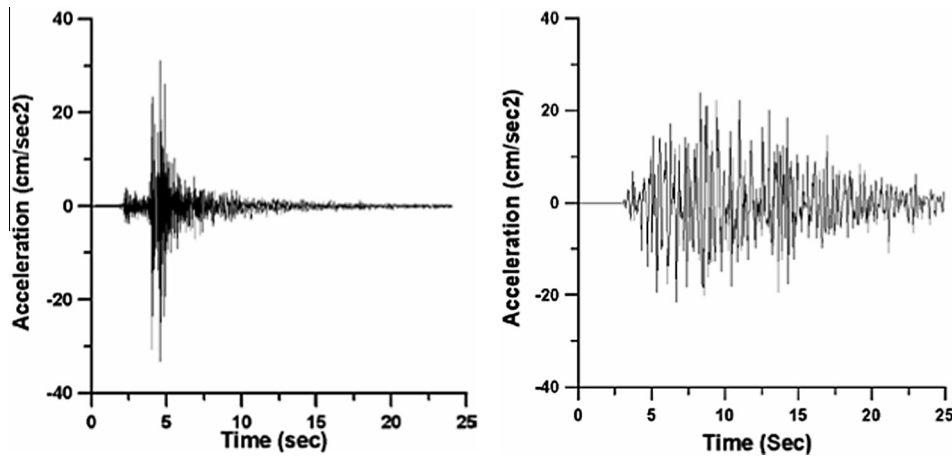
Fig. 3 (a) The recorded PGA at KOT station and (b) the simulated PGA at KOT station.

The path function [P(R, f), duration] can be represented by simple functions that account for geometric spreading function, attenuation (combining intrinsic and scattering attenuation) and path duration.

The geometric spreading attenuation factor, Z, is expressed as:

$$Z(R) = Ro/Rn \qquad (9)$$

where Ro is unit distance (1 km), R is taken as the closest distance to the rupture surface, and the exponent, n, depends on R.

The spectral–amplitude decay due to geometric spreading that is applied in this study, is given by three segment operators (Atkinson and Boore, 1995) for Eastern North America area as follows:

For R > 130, $n = 1$;
70 < R < 130, $n = 0.0$
R > 130, $n = 0.5$.

The main advantage of (Atkinson and Boore, 1995) formula is that the path-dependent part of the duration is not represented by the connected series of straight-line segments with different slopes, but it is modeled as trilinear, using transition distances between 70 and 130 km, which are of consistency with the attenuation model. The slope values have been changed based on the distance variations where the values 0.16, 0.03 and 0.04 are adopted to distance ranges 10–70, 70–130, 130–1000 km, respectively. The slope is assumed to be zero at distances less than 10 km.

The attenuation that includes the intrinsic and scattering attenuation, as described before, depends on the quality factor (Q) of the medium. Where Q is strongly dependent on the fre-

quency (f), in this study for Qalyoub city, the Q function is given by (Mustafa, 2002):

$$Q(f) = 86 \, f \, 0.79 \qquad (10)$$

The distance-dependent duration function has two terms:

$$T = To + bR \qquad (11)$$

where T is the duration of motion in sec, To is the source and bR represents a distance-dependent term that accounts for dispersion. For the source duration, we assume that $To = 1/fo$ (Brune, 1970, 1971), where fo is the corner frequency in source spectrum.

We use the distance-dependent duration of EN America (Atkinson, 1993) that is given by:

$$T = 1/fo + 0.05R \qquad (12)$$

This equation is suitable for north Egypt where it is not a tectonic region as EN America.

The site function (G(f)) can be simplified and used to describe the frequency-dependent modifications of seismic spectrum. It is given by the product the amplification (A(f)) and attenuation (D(f)) as follows:

$$G(f) = A(f) \, D(f) \qquad (13)$$

The site effects are described in detail and estimated in the previous chapter (chapter 3). They are estimated for 41 different sites in Nile Delta and 89 sites in Qalyoub city as part of greater Cairo.

A particular type of ground motion (I(f)), resulting from the simulation is controlled by:

$$I(f) = (2\pi \, \text{fi}) \, n \qquad (14)$$

where $n = 0$, 1, or 2 for ground displacement, velocity, or acceleration respectively. For the response of an oscillator, the response spectra $I(f)$ is given by:

$$I(f) = -Vf2/(f2 - f2r) - (2ffr^{\xi}i) \qquad (15)$$

Table 2 Source parameters of the 1992 Cairo earthquake.

Seismic Moment	Stressdrop (bar)	Radius (km)	Area (km)
9.70×1017 N m	18.5	5.6	99

The density and shear-wave velocity in the vicinity of the source ($\rho s = 2.8$ gm/cm^3, $\beta s = 3.7$ km/s (Samy, 2001).
The simulated peak ground acceleration; velocity and displacement of shear wave are obtained and illustrated in (Table 3) and Fig. 4(A–C) as follow.

Table 3 The simulated peak ground acceleration; velocity and displacement at KOT station due to specific event.

Date	Time	PGA (cm/s^2)	PGV (cm/s)	PGD (cm)
12/10/1992	15:09	2.845E+01	1.45	0.96

For an oscillator with natural frequency fr, damping$^{\xi}$ and V (for computation response spectra $V = 1$).

Concerning the fmax value, (Hanks, 1982) applied a maximum frequency of 15 Hz to the soft surface layers and 25 Hz to the bedrock. Thus, a value fmax = 20 Hz, average of (Hanks, 1982) assumption, is here applied due to the absence of a strong motion record in Egypt. It includes the frequencies vital (up to 10 Hz) and interesting for engineers.

4.2. Model verification

On 12 October 1992 Dahshour earthquake took place at 15:09 local time with a moment magnitude of Mb = 5.9, epicenter of 29.77°N, 31.07°E; and focal depth at 22 km occurring in south Cairo area. It was the largest event during of the last five decades. The earthquake was felt over a large area and caused damage in Cairo big city and several places in north Egypt. The accelerograph recorded this event at Kottamia very broad band station (KOT), which is located at latitude 29.93N and longitude 31.88E. The waveform that is recorded by this station is regarded as velocity, this velocity that is recorded by this station is converted to acceleration by an integration process.
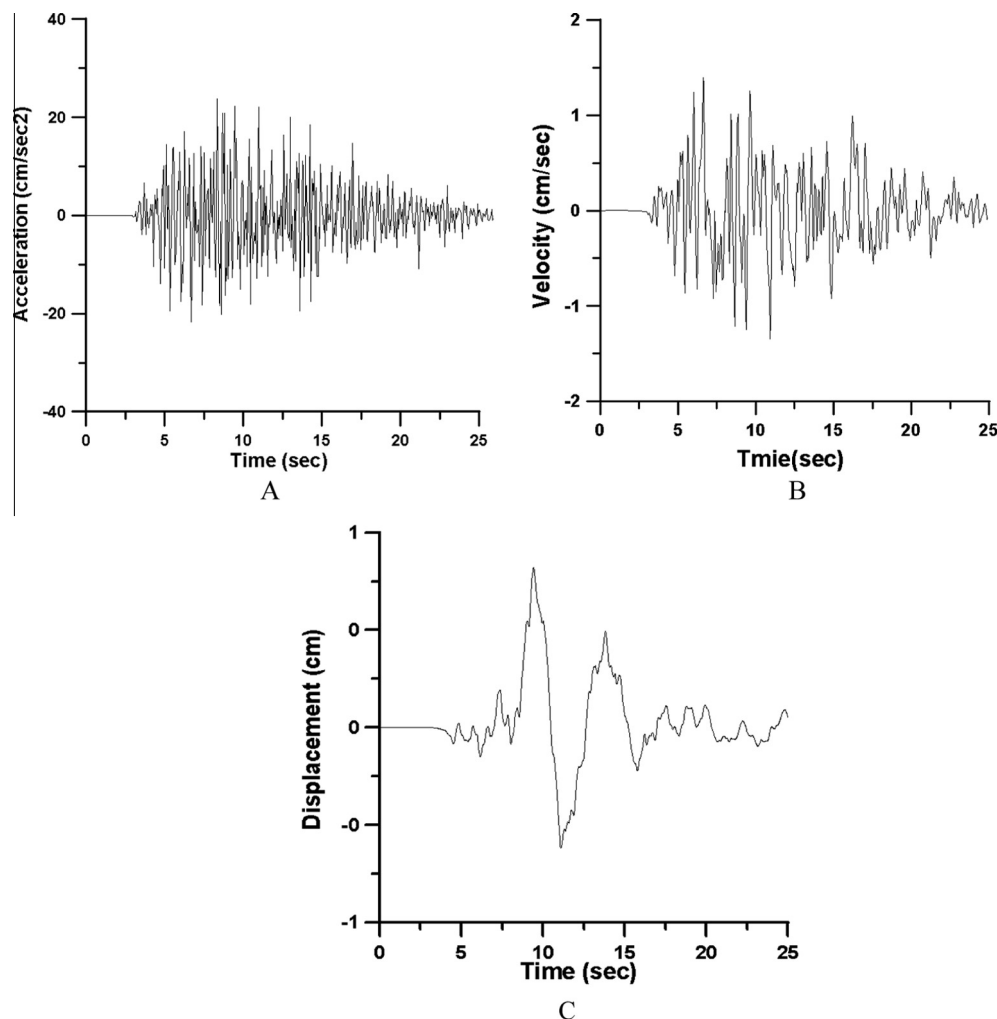
Fig. 4   (A) The simulated PGA, (B) the simulated PGV and (C) the simulated PGD from the October 12, 1992, at KOT station.

Fortunately, this event was recorded by the Kottamia very broad band station (KOT) of about 75 km distance from the epicenter. The synthetic and observed seismogram (Kottamia station) time series acceleration for the main shock of Dahshour earthquake, which is shown in Fig. 3a, was very useful in the comparison with the simulated seismogram at the same KOT location site as illustrated in figure which is shown in Fig. 3b, and Table 1, it has been noted the peak ground accelerations of the observed and synthetic acceleographs are mostly equal and the general waveform is nearly the same.

5. Ground motion simulation at the studied area

In Qalyoub city, we estimated the H/V spectral ratio for each microtremor observation at the fundamental frequency for 89

point that distributes in the grid system passing in all area by spacing 200 and 300 from south to north and east to west, these estimations consider site effect, by meaning Ao and F for each site (89 sites selected), distance each site from earthquake source and in addition to all parameters such as source, path applied in SMSIM FORTRAN Programs for Simulating Ground Motions version 2.3 etc (Boore, 2008).

The stochastic simulation method is applied in the area under investigation in order to predict ground motion of earthquake. The source is used to estimate the ground motion in the area is Dahshour 92 (southwest Cairo) the distance of this source is different from site to site and in the case simulation of ground motion on the bed rock the frequency is one and amplification is one and in case simulation of ground motion on the surface it takes the value of each site from amplification and frequency and the distance of each point or site from the
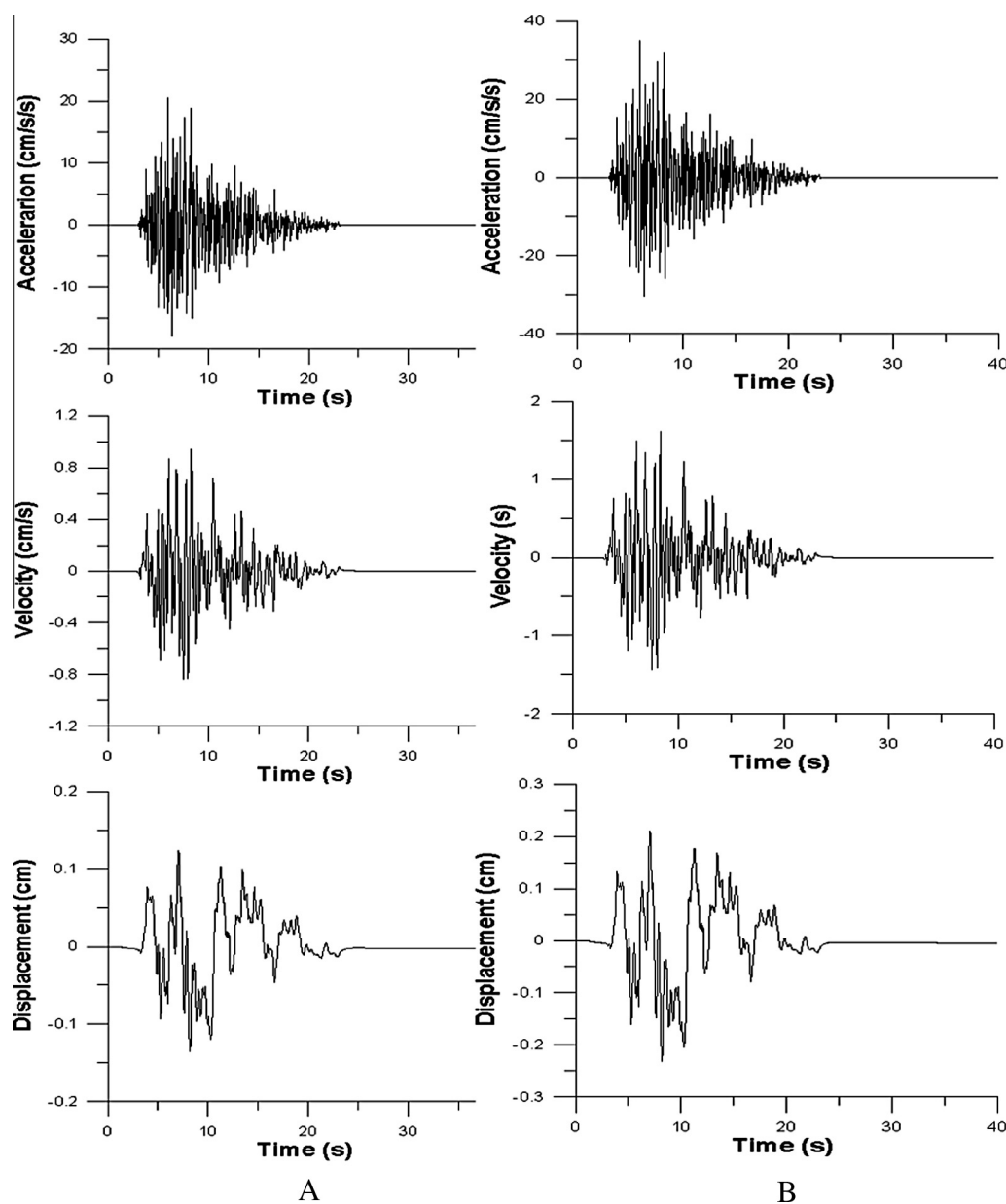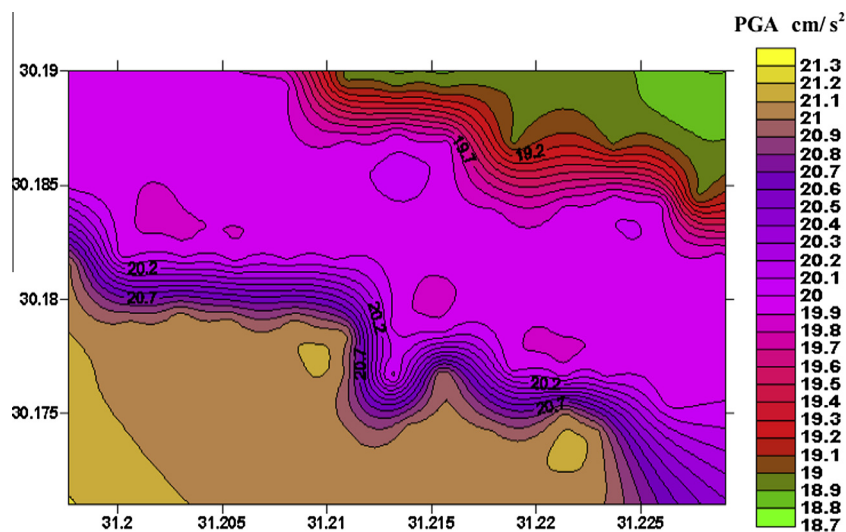

Fig. 5 (A) The simulated time history of October 12, 1992, earthquake at the bedrock in the Nile Qalyoub city, (B) the simulated time history of October 12, 1992, earthquake at the surface in Qalyoub city.
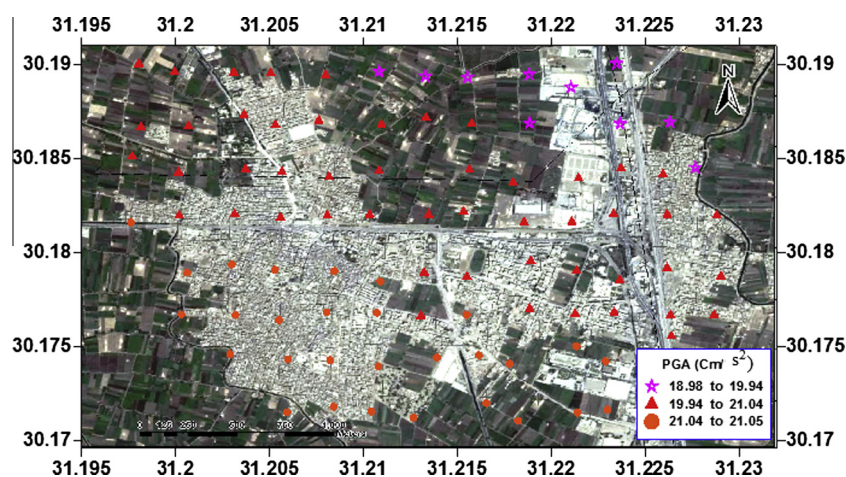
Fig. 6 Simulated peak ground acceleration (PGA) at bedrock at Qalyoub city at the fundamental frequency due to Dahshour 1992 earthquake.
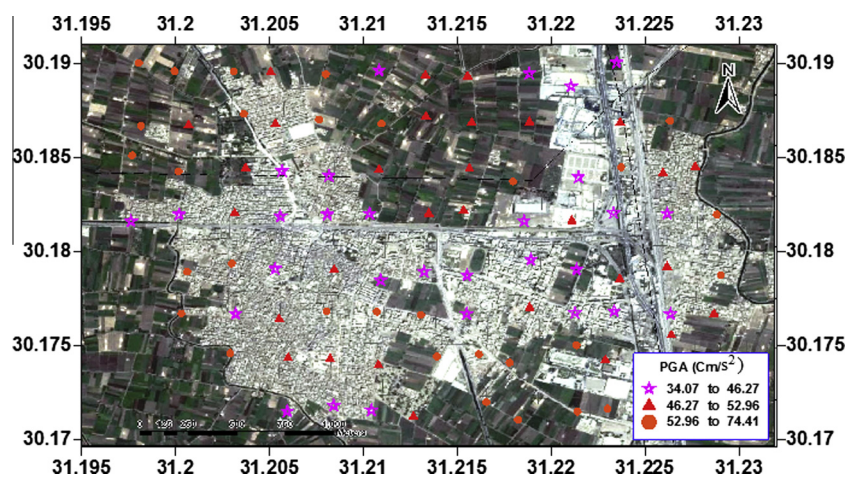
Fig. 7 Simulated peak ground acceleration (PGA) at surface at Qalyoub city at the fundamental frequency due to Dahshour 1992 earthquake.

Fig. 8 Simulated peak ground acceleration (PGA) at bedrock at Qalyoub city at the fundamental frequency due to Dahshour 1992 earthquake.

source The peak ground acceleration, velocity and displacement represent the output parameters, which are obtained by the stochastic simulation method as shown in Fig. 5A and B shows a representative sample of simulated time history at the selected site.

Representative examples of the simulated time history of October 12, 1992, earthquake at the bedrock and surface at the location of selected sites from Qalyoub city are as shown in Fig. 5A and B. The results reflect clearly the effect of local site conditions upon the predicted ground motion, the peak ground acceleration, peak ground velocity and peak ground displacement are calculated at the bedrock and at the surface (at the fundamental frequency) at eighty-nine sites at the studied area by using the stochastic simulation method due to Dahshour 1992 earthquake and the predicted ground motion, and the peak ground acceleration, are calculated at the bedrock and at the surface (at the fundamental frequency) at

eighty-nine sites at the studied area by using the stochastic simulation method due to Dahshour 1992 earthquake as shown in Figs. 6–9.

5.1. Response spectra

The pseudo-spectral acceleration (PSA) is an important characteristic of seismic ground motion in earthquake engineering. Response spectra are defined on the basis of the response of single degree of freedom damped oscillator to the earthquake acceleration (Jennings, 1983). The response spectra of an accelerogram serve a twofold function characterizing the ground motion as a function of frequency and providing a tool for determining earthquake resistant design criteria.

The response spectra are calculated for four selected damping values at two sites characterized by high ground motion
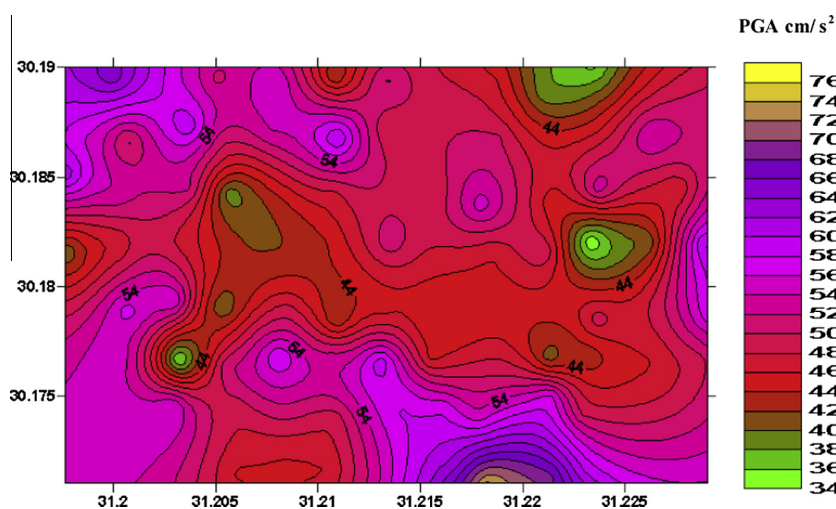

Fig. 9 Simulated peak ground acceleration (PGA) at surface at Qalyoub city at the fundamental frequency due to Dahshour 1992 earthquake.
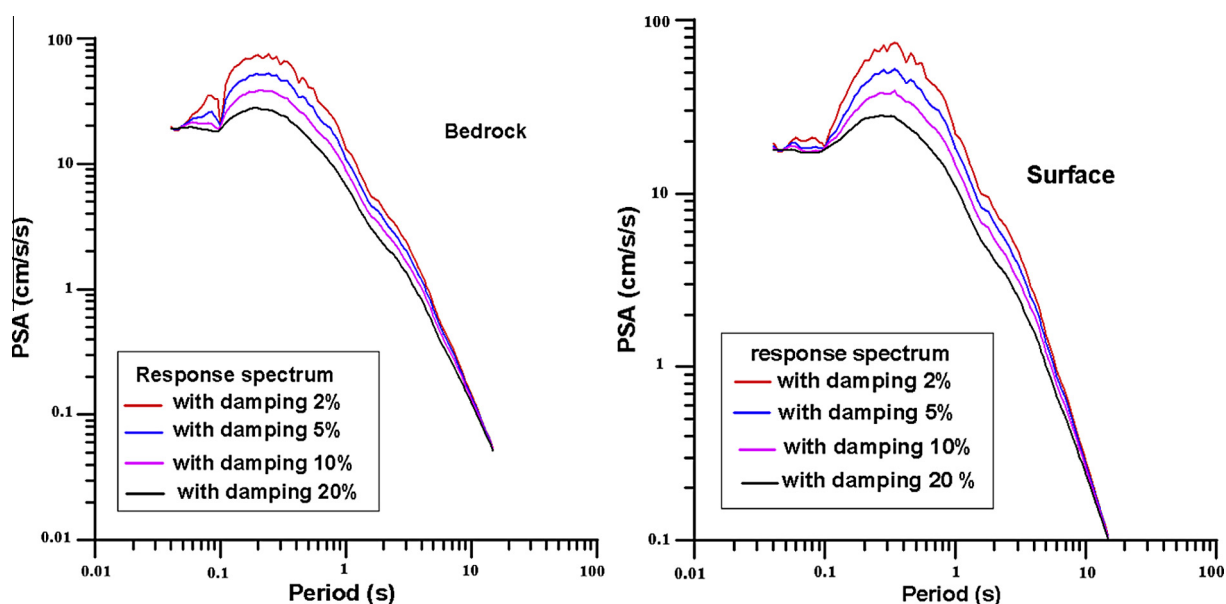

Fig. 10 The pseudo accelerations predicted from October 12, 1992, earthquake, at Qalyoub.

amplification (on surface) and low ground motion (on bedrock), the selected damping values are (2%, 5%, 10% and 20% damped pseudo-acceleration) of the critical damping for frequencies of 0.1 to 25 Hz simulated for October 12, 1992, earthquake for the selected site at the proposed area of Qalyoub City as shown in Fig. 10. The presented results could be used as a basis for designing motion specification of critical structure and for the nonlinear analysis (structural, site response, landslides, and liquefaction).

5.2. Results and conclusion

The current study is one of the trials to simulate the high frequency ground motion produced from the damping earthquakes at any areas where there are no recording instruments. From the engineering point of view the peak ground acceleration and the response spectrum plays a critical role in the construction process.

The stochastic simulation method is used to obtain the acceleration of ground motion at eighty-nine sites in Qalyoub city distributed at the studied area with the following results:

(1) The sites of high acceleration values are characterized by high ground amplification factors.
(2) The maximum PGA was found to be 23.5 Gal on the bed rock and is 79.6 gal on the surface in Nile Delta Basin and is 21 Gal on the bed rock and is 74.4 gal on the surface in Qalyoub city.
(3) The distance is affected on the peak ground acceleration meaning when the distance between the source and site is short the PGA is high but when the distance between the source and site is large the PGA is low.

The proposed area of Qalyoub city is characterized by low to moderate seismic activity and was affected by some felt and damaging historical and instrumental earthquakes. To assess the seismic hazard, I used the stochastic method to simulate the largest damaging earthquake from a possible seismic source to the proposed site of the city.

The stochastic simulation method was used to simulate the October 12, 1992, earthquake at the location of selected sites in the area of Qalyoub city. It was demonstrated that the ground motion will be considerably amplified by the soil Nile Deposits and this must be taken into consideration during the construction of any new buildings in the study area. I concluded that large modifications of seismic waves are due to variations of material properties near the Earth's surface and by both surface and buried topography. It is worth mentioning that some uncertainty of this work is due to the use, after (Atkinson and Boore, 1995), the duration function cutoff frequency and geometrical spreading parameter function. These assumptions were used because of the absence of local strong motion database, necessary for the determination of such functions.

I recommend that the surface layer must be totally removed before the construction of any new building in the study area to avoid the ground motion amplification produced by this Nile deposits. On the other hand, the maximum expected earthquake, Mb = 6.2, from the seismic source closest to the city (the seismic source of October 12, 1992, earthquake) should be taken into consideration before the construction of the city (Mohamed et al., 2002). Finally, I recommend that a more powerful earthquake design for the city be applied.

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