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ORIGINAL ARTICLE

Probabilistic earthquake hazard analysis for Cairo, Egypt

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Abstract Cairo is the capital of Egypt and the largest city in the Arab world and Africa, and the sixteenth largest metropolitan area in the world. It was founded in the tenth century (969 AD) and is 1046 years old. It has long been a center of the region's political and cultural life. Therefore, the earthquake risk assessment for Cairo has a great importance. The present work aims to analysis the earthquake hazard of Cairo as a key input's element for the risk assessment. The regional seismotectonics setting shows that Cairo could be affected by both far- and near-field seismic sources. The seismic hazard of Cairo has been estimated using the probabilistic seismic hazard approach. The logic tree frame work was used during the calculations. Epistemic uncertainties were considered into account by using alternative seismotectonics models and alternative ground motion prediction equations. Seismic hazard values have been estimated within a grid of $0.1° \times 0.1°$ spacing for all of Cairo's districts at different spectral periods and four return periods (224, 615, 1230, and 4745 years). Moreover, the uniform hazard spectra have been calculated at the same return periods. The pattern of the contour maps show that the highest values of the peak ground acceleration is concentrated in the eastern zone's districts (e.g., El Nozha) and the lowest values at the northern and western zone's districts (e.g., El Sharabiya and El Khalifa).

1 Introduction

In the Middle East and North Africa region, the synergy of natural disasters, rapid urbanization, water scarcity, and climate change has emerged as a serious challenge for policy and planning. This synergy has reconfigured risk landscapes by making the region's natural resource base fragile and extremely susceptible to a variety of internal and external factors. Despite the different levels of development, between 1980 and 2010, 81 % of disaster events were concentrated in just six countries: Algeria, Djibouti, Egypt, Iran, Morocco, and Yemen (World Bank Development Report 2014). In the last 30 years, Egypt has faced 23 large natural disaster events, floods, earthquakes, and landslides, causing over US$1.3 billion in damages (PreventionWeb: Egypt Disaster Statistics).

Cairo is arguably the largest city in the Middle East and North Africa is a chaotic megalopolis where life is characterized by extremes, both of tradition and of modernity. Satellite pictures show the city sprawling out in every direction, expanding in the north toward the Nile Delta and encroaching upon its scarce arable land. Since ancient times, the river has been the lifeline of Egyptian society. This is still true, particularly with respect to

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agriculture and water supply. Informal development has been, and continues to be, the dominant mode of urbanization in many developing countries, including Egypt. It occurs especially on the urban fringes, on privately owned agricultural land, rather than in desert areas, which would be considered squatting on state-owned land. In Cairo, these phenomena began just after the Second World War (and later in the following decade for the rest of the country), when migration from Upper Egypt and the Nile Delta caused housing pressures to become critical (Sims and Séjourné 2008). Migrants, attracted by economic development then occurring in Cairo, coincided with the massive industrialization policy launched in the 1950s. The 12 October 1992 (Ms 5.4) event that struck Cairo illustrated the vulnerability of the building stock, especially older structures, due to design, detailing, construction, and maintenance issues. Very little of the ancient city has survived, most of the moments and civic quarters were affected by earthquakes. These factors, when combined with the steadily increasing population density, clearly emphasis the potential significance of an earthquake occurring in or near Cairo.

The major part of the tectonic deformation within Egypt is remote and takes place along three active tectonic margins, the African–Eurasian plate margin, the Red Sea plate margin and the Levant–Dead Sea transform fault, as revealed by the observed seismicity (Fig. 1). Nevertheless, low to moderate seismic activity has occurred along a few E–W to NW–SE faults due to the part transfer of deformation from these boundaries to activate these faults inland or due to the local stress (Badawy 2001, 2005; Abou Elenean and Hussein 2008). Moreover, a historical earthquake shook Cairo in July 1847 and caused remarkable damages (Ambraseys et al. 1994; Badawy 1999).

The aim of this study is the estimation of the earthquake hazard parameters for the Cairo city (Fig. 2) as a first step toward an earthquake-resistant design and seismic safety assessment. Probabilistic seismic hazard assessment (PSHA) is conducted as a widely applicable and seismological most valuable contribution to earthquake hazard assessment (Reiter 1990; Frankel 1995; Woo 1996; Badawy 1998; Giardini et al. 1999; Bommer et al. 2004; Deif et al. 2009; El-Hussain et al. 2010). PSHA is performed utilizing CRISIS 2007 software (Ordaz et al. 2007). CRISIS 2007 accommodates uncertainty in the seismicity parameters and ground motion scaling model, and has a user-friendly interface. It

allows the complete definition of a seismic model for probabilistic hazard assessment and the calculation of stochastic scenarios for risk evaluation. CRISIS 2007 was developed at the Engineering Institute of the National University of Mexico (UNAM) by Ordaz et al. (2007). The PSHA has applied to estimate the peak ground acceleration (PGA) for a return periods 224, 615, 1230, and 4745 years, in addition to six spectral periods (0.2, 0.3, 0.5, 0.8, 1.0, and 2.0 s) to define approximate uniform response spectra at each $0.1° \times 0.1°$ grid nodes.

2 Data and analysis

The assessment of the probabilistic seismic hazard requires all available information on seismicity and geotectonic of the region and on regional attenuation characteristics of the ground motion as well as the adoption of a stochastic model for the forecasting of future occurrence. All procedures applied in seismic hazard assessment presuppose knowledge of the boundaries of the earthquake source regions and the level of activity within these regions, including a definition of the upper threshold magnitude which could be reached in the future. Since the intervals of systematic earthquake observation are usually too short to implement the above-mentioned tasks, various non-seismological approaches are introduced to supplement the observational data base. These approaches are based on simple analogies.

For performing a PSHA following the Cornell–McGuire approach (Cornell 1968; McGuire 1976; Reiter 1990), the required input data and analysis are as follows: (1) An earthquake catalog, which is used to derive recurrence rates and to estimate the maximum possible earthquake for each seismic zone with potential hazard on the site of interest. (2) A seismotectonic source model: this model identifies all the seismic sources that can generate strong ground shaking at the site of interest. These seismic sources are shown as map representations of lines (fault sources), and areal source zones that are defined on the basis of a number of different types of geological, geophysical, and seismological data. (3) The seismicity recurrence characteristics for the seismic sources, where each source is described by an earthquake recurrence relationship. A recurrence relationship indicates the chance of an earthquake of a given size to occur anywhere inside the source zone during a specified period of time. (4) A

Fig. 1 Seismicity of Egypt and its surroundings from 2200 BC to 2013 AD using the compiled earthquake catalog in this study
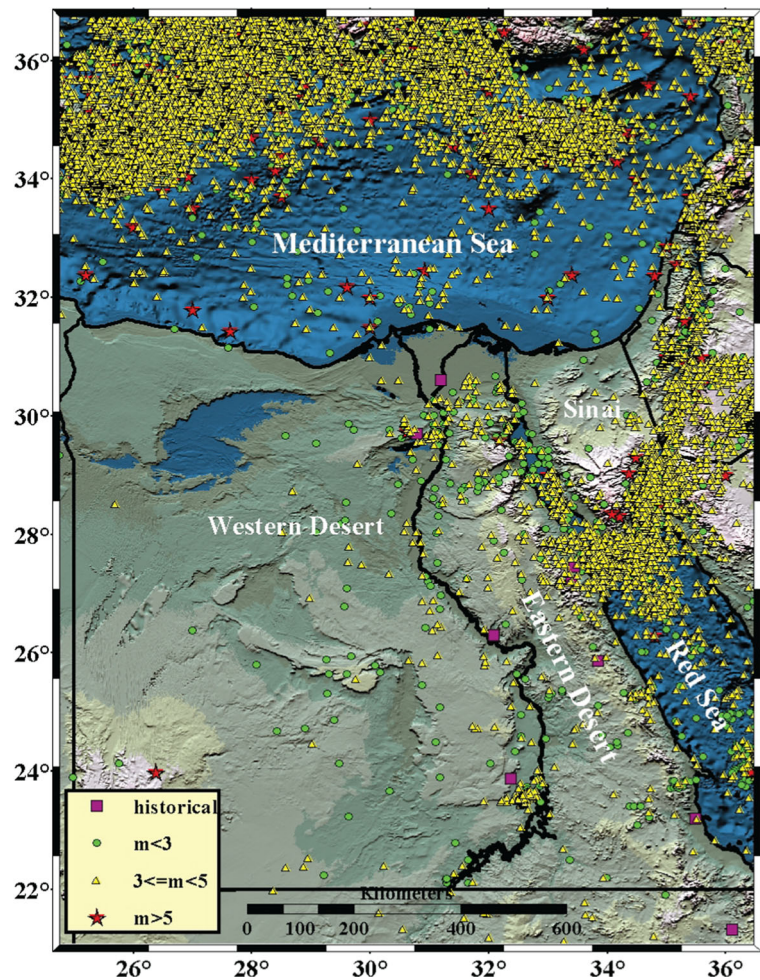
predictive ground motion model, which describes the attenuation of amplitudes of ground motion as a function of distance and magnitude. Different models are constructed for different frequencies and local site conditions. In the following section, we describe how these input parameters were derived for Cairo, Egypt.

2.1 Earthquake catalog

The basic step is to prepare a reliable and homogenous earthquake catalog. The compiled catalog spans periods from 2200 BC up to 2013 AD (Fig. 1) and covers a region spanning 20° to 38° E and 22° to 38° N. Any duplication in the resultant catalog is removed and events with magnitude 3.0 and above on any magnitude scale are included. For the purpose of characterizing the activity rates of the identified seismic sources, a catalog was

compiled using information from several available seismic sources:

- Preliminary determination of epicenters (PDE) provided by the National Earthquake Information Center (NEIC);
- The International Seismological Center (ISC) online bulletin;
- EHB (Engdahl et al. 1998) catalog updated to 2007 from the site of the ISC;
- Centroid Moment Tensor catalog (CMT) provided by Harvard;
- Maamoun et al. (1984);
- Regional catalog of Ambraseys et al. (1994);
- Annual Bulletin of the Egyptian National Seismic Network (ENSN) during the period between 1998 and the end of 2013.

Fig. 2 Location map delineates the 27 Cairo districts for the current study. Three administrative zones are given in *different colors*
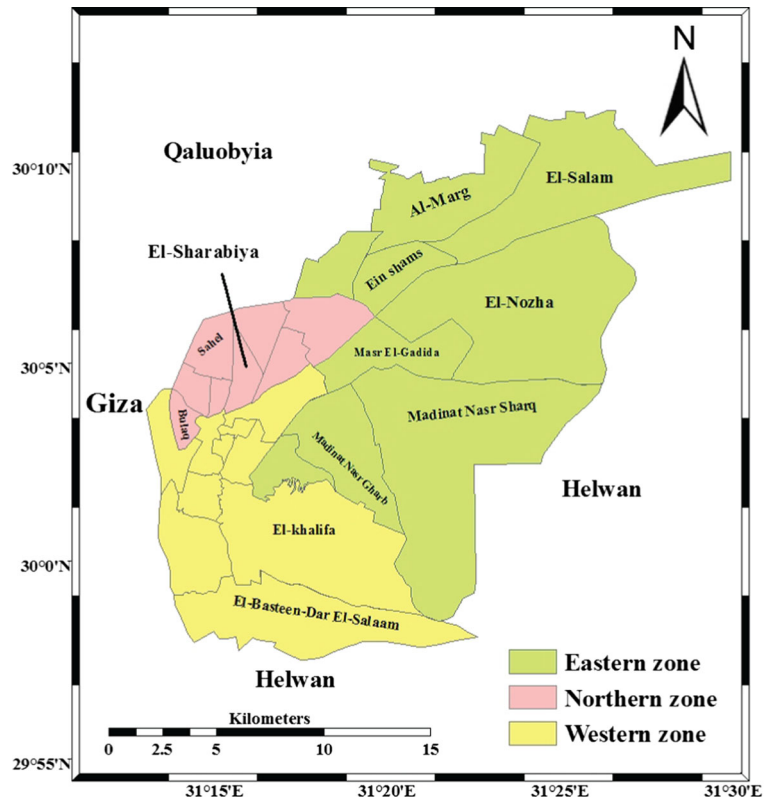
To ensure the homogeneity of the catalog, all events for which moment magnitudes (Mw) were not reported were converted into this scale using El-Hadidy (2008) relationships. Mw was chosen because it is the most reliable magnitude scale. Moreover, most of the ground motion prediction models used in the current study are expressed in terms of this magnitude scale. The catalog was further processed to remove dependent events (catalog declustering) and to identify relative completeness levels. We applied the Gardner and Knopoff (1974) technique using original parameters given in Gardner and Knopoff (1974).

To model the seismicity in each zone, we need knowledge on the magnitude of completeness, M_c, below which only a fraction of all events in a magnitude bin are detected by the network (Kijko and Graham 1999; Rydelek and Sacks 2003; Wiemer and Wyss 2000, 2003).

2.2 Seismotectonics models

Seismic zonation studies are very important not only for theoretical studies, but also for practical applications.

Both seismic hazard assessment and earthquake prediction depends much on the seismic zonation. In the current study, we have used the seismotectonics model that consists of 57 seismic zones by Mohamed et al. (2012). Figure 3 shows the structures and boundaries of the used earthquake source zones. The all seismicity parameters and characteristics of each source zone are also provided in detailed and tabulated by Mohamed et al. (2012)). Based on the compiled earthquake catalog, sets of recurrence parameters (b, a, and M_{max}) are estimated for each seismic zone. Suitable alternatives ground motion scaling relationships for rock are used to produce 10 % damped spectral acceleration values for different spectral (PGA, 0.2, 0.3, 0.5, 0.8, 1.0, and 2.0 s) for different return periods. In addition, uniform hazard spectra for Cairo were calculated at spectral periods and graphed.

2.3 Recurrence parameters

The number of earthquakes is a basic characteristic of the seismic activity of any given region during a specific period of time. The relationship between the number (N)
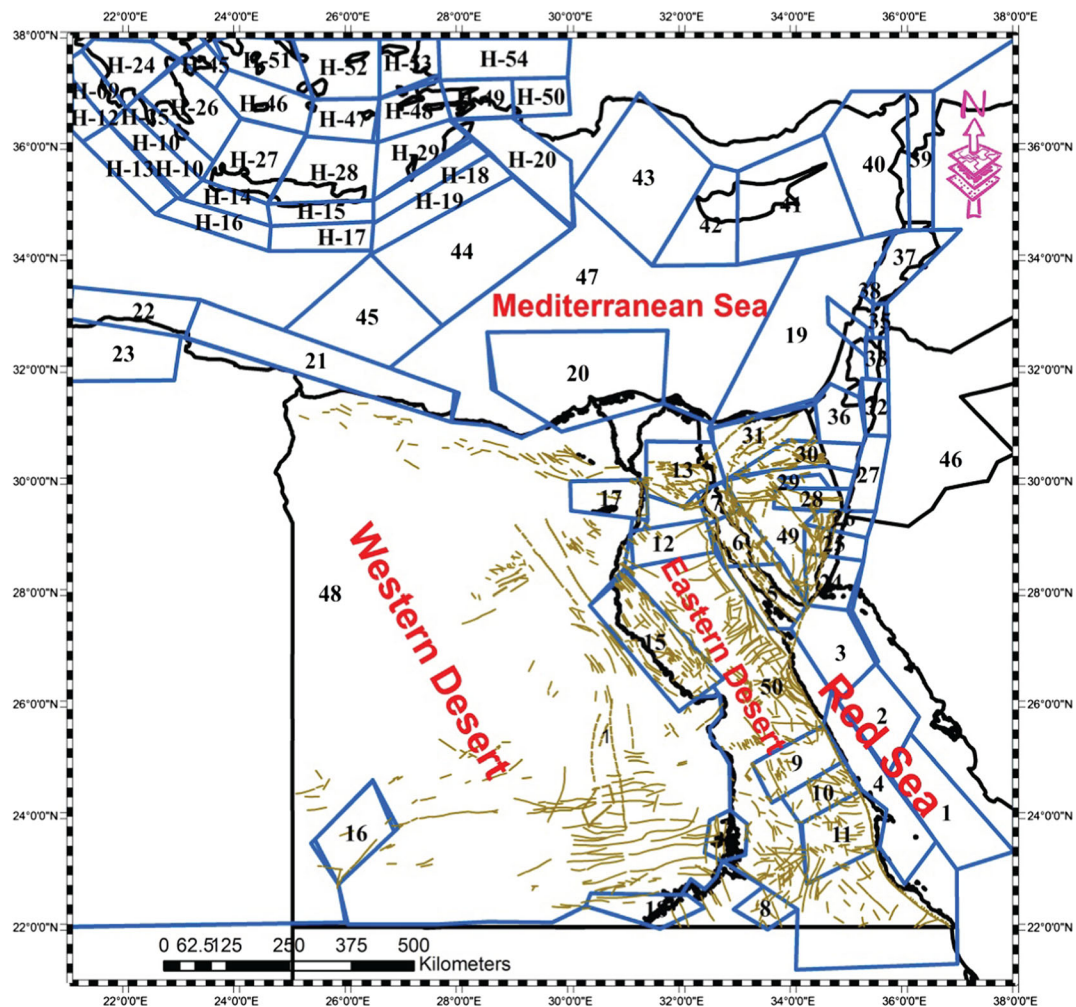
Fig. 3 The earthquakes source zones that used in hazard calculations (after Mohamed et al. 2012)

of earthquakes and their magnitude (*M*) is usually written in the form as proposed by Ishimoto and Iida (1939) and Gutenberg and Richter (1944):

$$\mathrm{Log}\, N = a - bM.$$

It is widely recognized that the *N(M)* relationship is still the basic measure of the seismicity of a particular region because this relationship can be routinely established using seismological information now available.

It is well known that the parameters *a* and *b* have a certain physical significance; *a* is proportional to the level of earthquake activity and can, therefore, be used to quantify seismicity within a region of identical *b*. This possibility is, however, limited to only a small area because *b* varies from

one seismotectonic unit to the other. Laboratory experiments indicate that *b* is influenced mainly by the degree of fracturing or heterogeneity of the material and by the stress rate (Mogi 1963; Scholz 1968). Thus, low value of *b* signify a relatively compact and homogeneous medium, high stress drops, large source dimension, and high stress rate or high confining pressure.

The earthquake catalogs are often biased due to incomplete reporting for smaller magnitude earthquakes at earlier period. Thus, to fit the recurrence relationship to a region, one should choose among using a short sample that is complete in small events or a longer sample that is complete in large events or a combination of the two data sets to complete the deficient data and thereby obtaining a homogeneous data set.

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2.4 Ground motion prediction models

Strong-motion attenuation equations are empirical equations that can be used to estimate the values of strong-motion parameters as functions of independent parameters, which characterize the earthquake and the site of interest (Hasegawa et al. 1981). Alternative ground motion scaling relationships are applied to various tectonic provinces considered in the current study to account for the epistemic uncertainty associated with not knowing the true attenuation characteristics from each seismogenic zones to the sites of Egypt. These models were extensively used in seismic hazard assessment in different places in the world. In the current study, the models of Youngs et al. (1997) were used to model the ground motions from subduction seismic sources such as the sources of the Cyprean and Hellenic arcs. The models of Abrahmson and Silva (1997), Boore et al. (1997), were used with ground motions of earthquakes occurring within the active shallow crust seismogenic zones. The assigned weight for each ground motion prediction equation is shown in the logic tree (Fig. 4).

3 Hazard estimations

Seismic hazard analyses aim at assessing the probability that the ground motion at a site due to earthquakes from potential seismic sources will exceed a certain value in a given time period. The probabilistic seismic hazard models developed by Cornell (1968), Esteva (1970), and Milne and Davenport (1969) are called "point source model" since they are based on the assumption that the energy released during an earthquake is radiated from the focus of the earthquake and the intensity of the site ground motion is a function of the distance to the source. Although this assumptions may be acceptable for certain earthquakes and regions, it would not, however, be valid for large events where the total energy released is distributed along a long rupture zone.

Using the alternative seismic source zonation, recurrence models, that were derived within this study and other models that were derived by Deif et al. (2009, 2011), and attenuation models Ambraseys (1995), (Abrahmson and Silva (1997), Boore et al. (1997), Youngs et al. (1997), are all incorporated into the hazard calculations through the use of logic tree formulation. In the logic tree (Fig. 4), the branch of each stage of the decision-making process is drawn to represent the different options considered. The branches extended from each node are assigned by the weightings in such a way that they sum to unity. The weightings are assigned by the analyst to reflect the relative confidence in each option, so that two equally valid attenuation relationships may be assigned 0.5 each, whereas moderate estimate of the seismic zone model may be assigned 0.8 and extreme estimate 0.2.

In the current study, the parameter values and weights assigned to each of the various alternatives are shown in Fig. 4. The seismic hazard maps for Cairo are produced. The seismic hazard analysis has been computed using the computer program: CRISIS 2007 (Ordaz et al. 2007). The maximum effect of each considered seismic source on each site of the grid points ($0.1° \times 0.1°$) is calculated for a total of 24 points. Then, the expected ground motion acceleration is contoured, for different
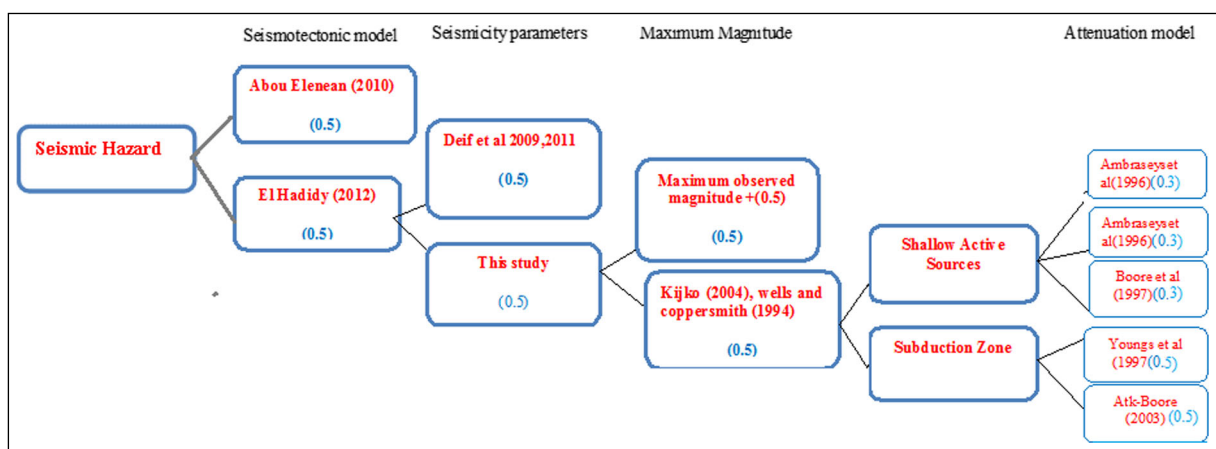

Fig. 4 The logic tree's components used in hazard estimation. The given *real numbers* show the weight of each component

return periods and for different spectral periods of PGA, 0.2, 0.3, 0.5, 0.8, 1, and 2 s. Consequently, the seismic hazard maps of Cairo have been constructed.

4 Results

The construction of seismic hazard maps can be thought as a first step toward taking counter measures against earthquake threats. The aim of seismic hazard maps is twofold: first, to show clearly the variation in seismic hazard within a region, at relative levels. Secondly, they provide guidance to the expected levels of ground motion. For the 27 Cairo districts, the earthquakes hazard values have been calculated over a 0.1°×0.1° grid. Results from the logic tree (Fig. 4) are treated to obtain, at each point, the mean value of the acceleration. Figure 5 displays, the earthquake hazard maps for the 27 Cairo districts as a regional distribution of the peak ground motion (PGA) at rock condition, which correspond to return periods of 224 years (20 % probability in 50 years), 615 years (15 % probability in 100 years), 1230 years (15 % probability in 200 years), and 4745 years (10 % probability in 500 years) according to the Egyptian seismic design criteria (Sobaih 1996).

The eastern zone of Cairo (e.g., El Nozha, El Salam districts) lies at relatively high hazard with PGA varying from 0.1 to 0.3 g in return periods 224 and 4745 years (Fig. 5), respectively. However, both the Cairo's northern zone (e.g., El Khalifa district) and western zone (El Sharabiya district) are shown relatively low earthquake hazard with PGA changing from 0.08 to 0.2 g at the same return periods, respectively.

The expected lifetimes of structures are an important parameter for the chosen level of the hazard analysis at a given site. According to the Egyptian seismic design criteria (Sobaih 1996), structures have been classified into four categories according to their expected lifetimes. Fifty years are assigned as a lifetime to masonry structures, 100 years to reinforced concrete structures, 200 years to civil structures (e.g., bridges and tunnels), and 500 years to major dams and nuclear power plants. To fit these classifications, we have estimated the PGA for four different return periods at 0.2, 0.3, 0.5, 0.8, 1.0, and 2.0 s spectral periods. Table 1 gives the range of mean ground acceleration (g) at these

investigated spectral periods with the same return periods. Figure 6 represents an example of hazard maps at 0.3- and 2.0-s spectral periods. The obtained results (Table 1 and Fig. 6) clearly indicate that the PGA having relatively small values at spectral periods more than 0.5 s. However, the higher values (0.15–0.52 g) have been estimated at spectral periods less than 0.5 s with return periods 224 and 4745 years, respectively.

The uniform hazard spectrum curves (UHS) at the Cairo districts are obtained by computing the hazard at a suite of spectral periods using response spectral attenuation relationships as well. The UHS curves for El Nozha and El Sharabiya districts are shown in Fig. 7. From this figure, it clear that the spectral period 0.5 s represents a critical natural period for constructions in Cairo. This means that the 5-storey buildings and even lower are urgently needs to re-evaluate in the concept of seismic retrofit.

5 Deaggregation

The described PSHA is a very useful tool for assessing the overall hazard posed by earthquakes from all source zones. However, the deaggregation of the earthquake hazard into source zones (and other relevant source parameters such as magnitude) allows identification of high-hazard sources affecting a given site, and these sources can then be studied in more detail with high-resolution modeling.

In this study, the deaggregation of hazard was performed for the curves which were obtained from Mohamed et al. (2012)) model and Abrahmson and Silva (1997) attenuation model branch in the logic tree. The hazard curves were deaggregated to determine the sources which most contribute at hazard levels of 20, 15, 15, and 10 % probability of exceedance in 50, 100, 200, and 500 years corresponding to 224, 615, 123, and 4745 years return period. The results of deaggregation for 5 % damped spectral acceleration at the peak ground acceleration (PGA) are shown in Fig. 8.

For instance, the hazard of El Nozha district is dominated by nearby moderate earthquakes of magnitude 5.4 Mw at short return periods of 224 and 615 years, while the hazard of El Nozha district for the longer return periods of 4745 years is dominated by larger earthquakes of magnitude 6.4 Mw.
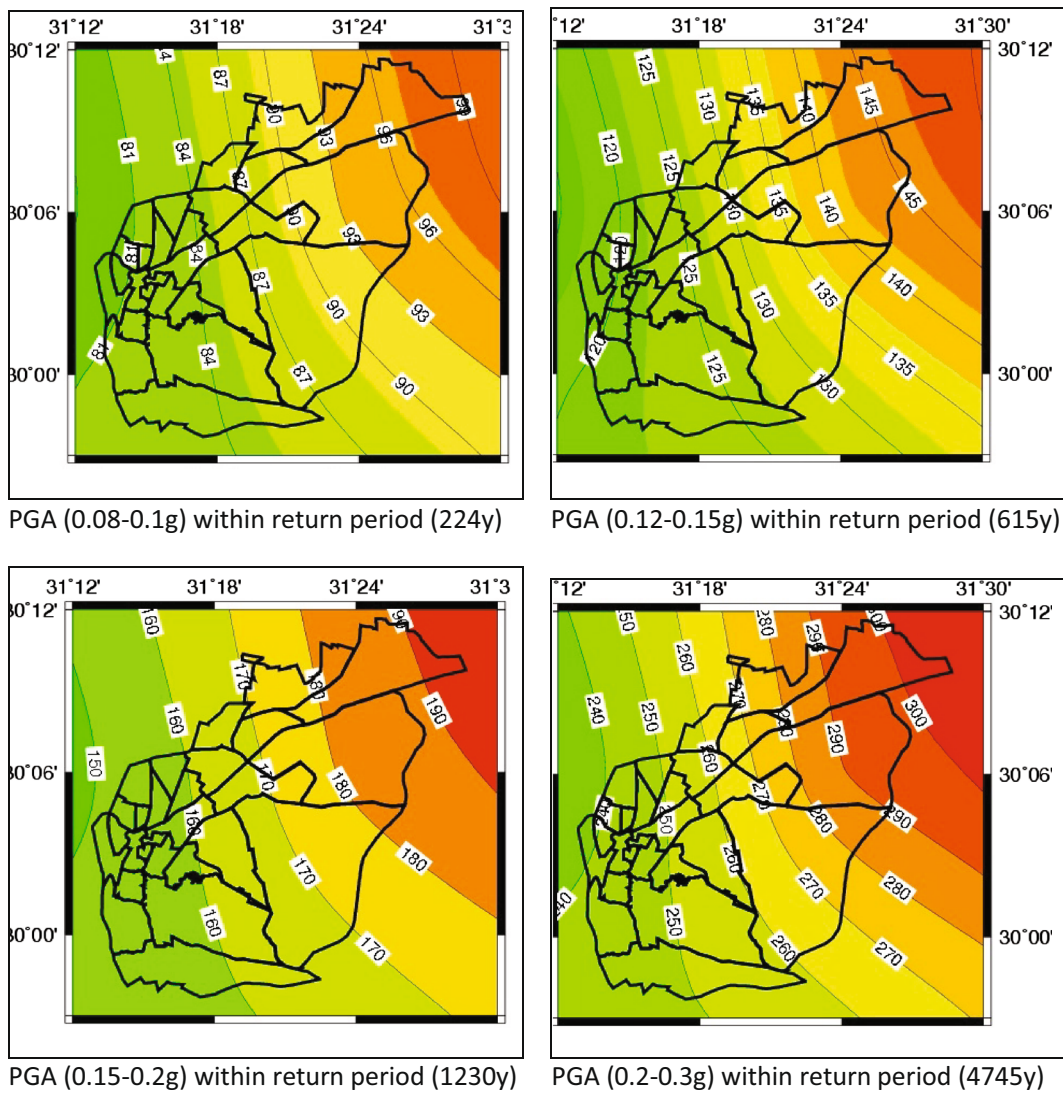
PGA (0.08-0.1g) within return period (224y)   PGA (0.12-0.15g) within return period (615y)

PGA (0.15-0.2g) within return period (1230y)   PGA (0.2-0.3g) within return period (4745y)

Fig. 5 The estimated peak ground accelerations (PGA) for Cairo's districts at the four different return periods: 224, 615, 1230, and 4745 years
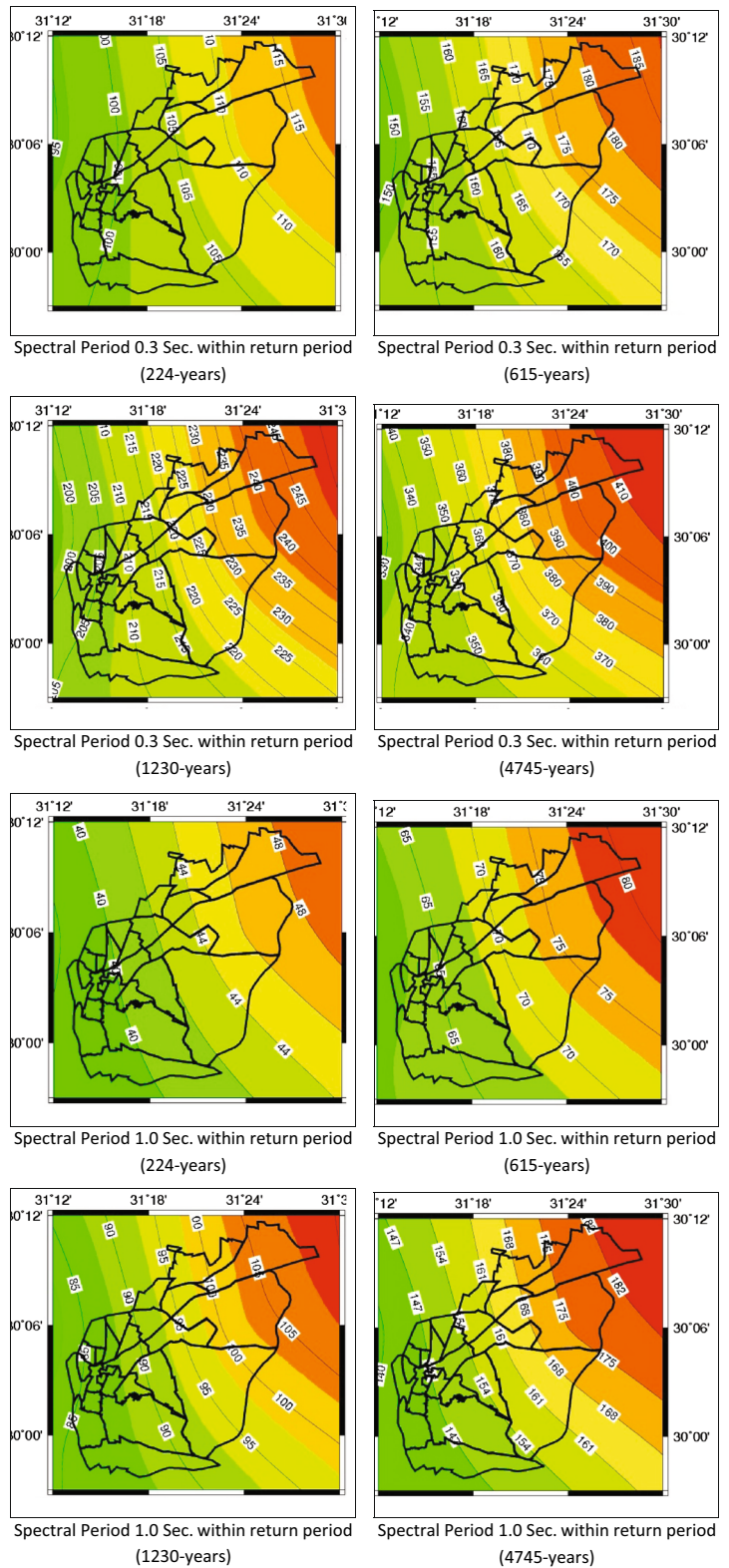
In the case of El Sharabiya district, the hazard is dominated by local earthquakes with magnitude of 5.4 Mw for 224 and 615 years return periods. The hazard level of El Sharabiya district of 1230 years return

Table 1 The range of mean ground acceleration (g) at different four return periods and six investigated spectral periods for Cairo, Egypt

Return period	Spectral periods					
	0.2	0.3	0.5	0.8	1	2
224	0.12–0.15	0.10–0.12	0.06–0.08	0.05–0.06	0.04–0.05	0.03–0.04
615	0.19–0.24	0.15–0.19	0.10–0.12	0.08–0.10	0.07–0.08	0.05–0.07
1230	0.25–0.31	0.20–0.25	0.14–0.17	0.10–0.12	0.09–0.11	0.07–0.10
4745	0.42–0.52	0.33–0.41	0.23–0.28	0.17–0.21	0.14–0.18	0.12–0.16

Fig. 6 Average spectral acceleration at spectral period 0.3 and 2.0 s in the same four return periods: 224, 615, 1230, and 4745 years
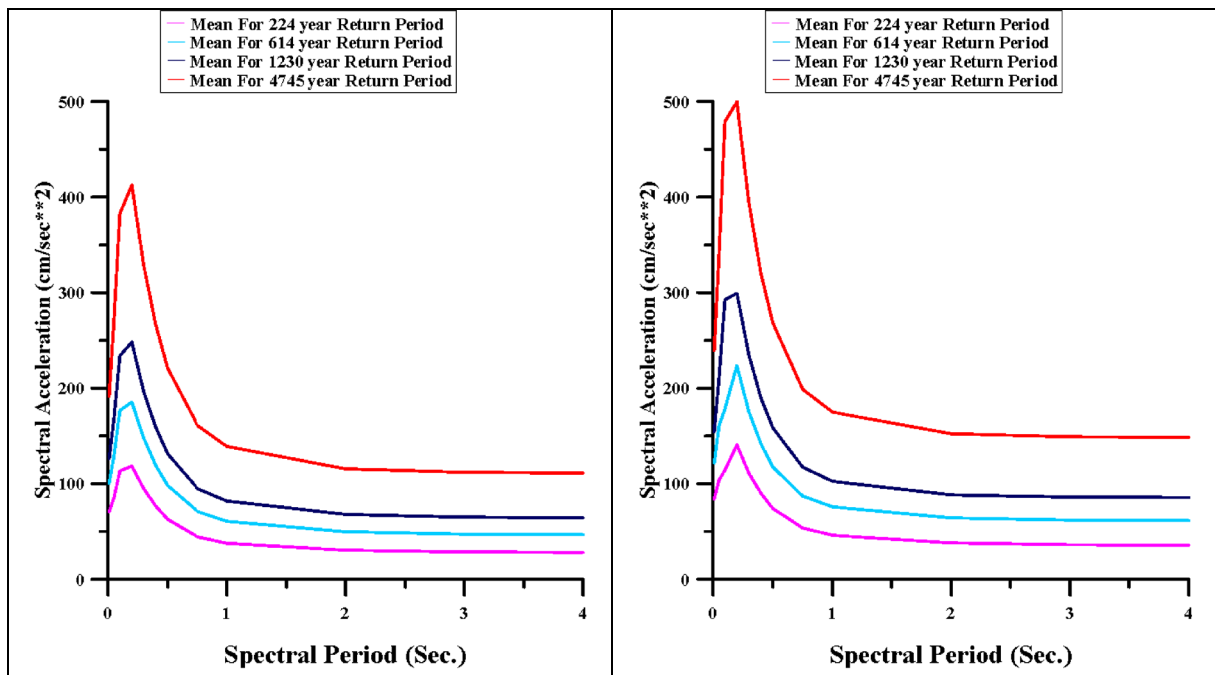

Spectral Period 0.3 Sec. within return period (224-years)

Spectral Period 0.3 Sec. within return period (615-years)

Spectral Period 0.3 Sec. within return period (1230-years)

Spectral Period 0.3 Sec. within return period (4745-years)

Spectral Period 1.0 Sec. within return period (224-years)

Spectral Period 1.0 Sec. within return period (615-years)

Spectral Period 1.0 Sec. within return period (1230-years)

Spectral Period 1.0 Sec. within return period (4745-years)

Fig. 7 The unified hazard curve for El Nozha and El Sharabiya districts at the same return periods: 224, 615, 1230, and 4745 years

period is dominated by nearby earthquakes of magnitude 5.8 Mw, while for the longest return periods of 4745 years, the hazard level of El Sharabiya is dominated by local earthquakes of magnitude 6.0 Mw.

6 Discussion and conclusions

The most important social benefit from earthquake research is the use of that knowledge to reduce the hazard of earthquakes for mankind. These applications may take several forms, which range from the construction of various kinds of seismic hazard maps that permit the prediction (in a probabilistic sense) of the exposure to future ground shaking to the actual prediction of specific earthquakes. The potential damage caused by earthquakes to human settlements and lives in Egypt will certainly increase steeply as the country becomes more populated and industrialized. Earthquakes such as occurred in Shadawn (31 March 1969), southwest Cairo (12 October 1992), and Gulf of Aqaba (22 November 1995) can serve as an upper limit to possible destructiveness in the region.

The high exposure of people's livelihood assets to a range of natural hazards, coupled with the vulnerability and community resilience, is likely to lead to further

losses of life and livelihoods. Resilience is now at the heart of development thinking, natural hazard mitigations, and humanitarian policy. In this study, we have analyzed the earthquakes hazard for the 27 Cairo districts using the probabilistic seismic hazard assessment (PSHA) approach. Indeed, Cairo had been severely affected by earthquakes although Egypt as a whole classified as a relatively low to moderate seismic activity region.

Cairo has been participated at the cities resilience campaigns of the UNISDR in 2010. The city's profile reveals that many natural hazards (earthquakes, floods, sand storms, and droughts) have affected with huge socio-economic impacts. Therefore, the hazard identification and evaluation are important step to reduce the consequent risks. In this study, the earthquake hazard has been estimated for the 27 Cairo districts using the probabilistic hazard approach (PSHA). Our result clearly indicates that Cairo city has relatively moderate suffered from earthquakes with PGA varies from 0.08–0.2 to 0.1–0.3 g at return periods 224 and 4745 years, respectively. These results are consistence with the previous results (Badawy 1998; El-Sayed et al. 2001; Mohamed et al. 2012). The seismic hazards maps (Figs. 5 and 6) have shown that the eastern zone from Cairo relatively possess higher PGA values than the
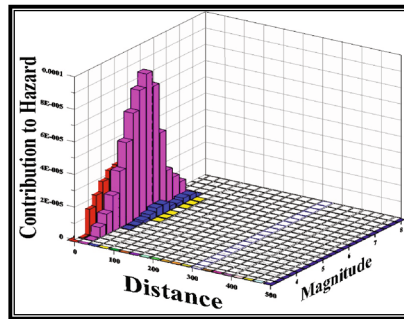
Fig. 8 Deaggregation results for El Nozha and El Sharabiya districts at the same return periods: 224, 615, 1230, and 4745 years
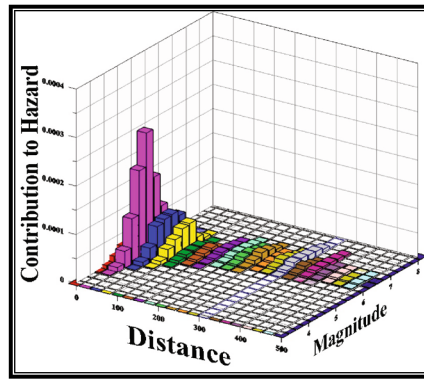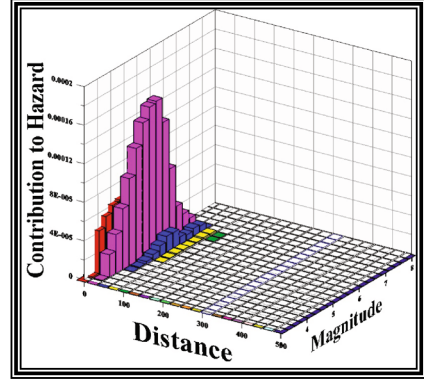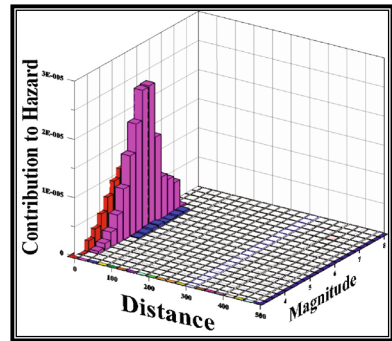
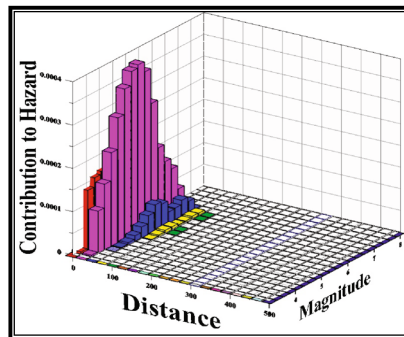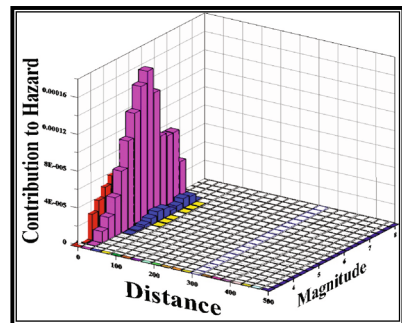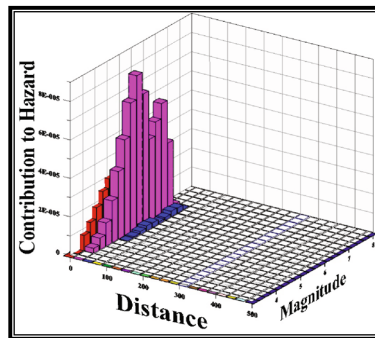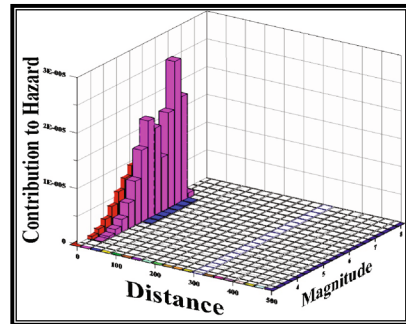northern and western zones. This means that the north-east earthquake dislocations (e.g., Cairo–Suez district) may have more contribution to the hazards than the southwestern (e.g., Dahshour dislocations).

For engineering purposes, the PGA at specific periods are essential. These spectral periods are mainly controlled by the number of stories of the buildings. Our results (Table 1 and Figs. 6 and 7) show that many constructions of five stories or less have relatively higher PGA values more than the higher ones. With this concern, these constructions need to be re-evaluated in order to decide the appropriate process for the required seismic retrofits. Moreover, the deaggregation results clearly defined the contribution of both near-field (first order) and far-field (second order) seismic source around Cairo city. The lateral effect of soil from the western zone (El Sharabiya district) to the eastern zone (El Nozha district) has been notified from these results (Fig. 8a).

Finally, it is worth to note that the inland earthquakes (12 October 1992, 11 October 1999, 28 December 1999, 24 August 2002, and 8 November 2006) ring an alarm for the future urban strategy in Egypt. To mitigate the effects of similar future disastrous earthquakes, seismic risk factors should be considered.

References

Abou Elenean KM, Hussein HM (2008) The October 11, 1999 and November 08, 2006 beni suef earthquakes, Egypt. Pure Appl Geophys 165:1391–1410

Abrahmson NA, Silva WJ (1997) Empirical response spectra attenuation relations for shallow crustal earthquakes. Seismol Res Lett 68:94–127

Ambraseys NN (1995) The prediction of earthquake peak ground acceleration in Europe. Earthquake Eng Struct Dyn 24:467–490

Ambraseys NN, Melville CP, Adams RD (1994) The seismicity of Egypt, Arabia and Red Sea. Cambridge Univ. Press

Badawy A (1998) Earthquake hazard analysis in northern Egypt. Acta Geod Geophys Hung 33(2–4):341–357

Badawy A (1999) Historical seismicity of Egypt. Acta Geod Geophys Hung 34(1–2):119–135

Badawy A (2001) Status of the crustal stress in Egypt as inferred from earthquake focal mechanisms and borehole breakout. Tectonophysics 343(1–2):49–61

Badawy A (2005) Seismicity of Egypt. Seismol Res Lett 76(2): 149–160

Bommer JJ, Abrahamson NA, Strasser FO, Pecker A, Bard P-Y H, Cotton F, Fäh D, Sabetta F, Scherbaum F, Studer J (2004) The challenge of defining upper bounds on earthquake ground motions. Seismol Res Lett 75:82–95

Boore DM, Joyner WB, Fumal TE (1997) Equations for estimating horizontal response spectra and peak acceleration from Western North American earthquakes: a summary of recent work. Seismol Res Lett 68:128–153

Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc Am 18:1583–1606

Deif A, Abou Elenean K, El Hadidy M, Tealeb A, Mohamed A (2009) Probabilistic seismic hazard maps for Sinai Peninsula, Egypt J. Geophys Eng 6:288–297

Deif A, Hamed H, Ibrahim HA, Abou Elenean K, El-Amin E (2011) Seismic hazard assessment in Aswan Egypt. J Geoph Eng 8(2011):531–548

El Hadidy M (2008) Seismotectonics and seismic hazard studies for Sinai Peninsula, Egypt, M. Sc. Thesis. Ain Shams Univ

El-Hussain I, Deif A, Al-Jabry K, Al-Hashmi S, Al-Toubi K, Al-Shijby Y, Al-Saify M (2010) Probabilistic and deterministic seismic hazard assessment for Sultanate of Oman (Phase I) Project #22409017, submitted to Sultan Qaboos Univeristy, Oman 202 pp

El-Sayed A, Vaccari F, Panza G (2001) Deterministic seismic hazard in Egypt. Geophys J Int 144:555–567

Engdahl ER, Van Der Hilst R, Buland R (1998) Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Bull Seismol Soc Am 88:722–743

Esteva L (1970) Seismic risk and seismic design decision. In: Hansen RY (ed) Seismic design for nuclear power plants. Mass. Inst. Techn, Cambridge, pp 142–182

Frankel A (1995) Mapping seismic hazard in the central and eastern United States. Seismol Res Lett 66:8–21

Gardner JK, Knopoff L (1974) Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? Bull Seismol Soc Am 64:1363–1367

Giardini D, Grünthal G, Shedlock KM, Zhang PZ (1999) The GSHAP global seismic hazard map. Ann Geofis 42:1225–1230

Gutenberg B, Richter CF (1944) Seismicity of the earth and associated phenomena. Princeton University Press, Princeton, p 310

Hasegawa HS, Basham PW, Berry MJ (1981) Attenuation relations for strong seismic ground motion in Canada. Bull Seismol Soc Am 71:1943–1962

Ishimoto M, Iida K (1939) Observations sur les seims euregistré par le microseisograph construite dernierment (I). Bull Earthq Res Inst, Univ Tokyo 17:443–478

Kijko A, Graham G (1999) Parametric-historic' procedure for probabilistic seismic hazard analysis—part II: assessment of seismic hazard at specified site. Pure Appl Geophys 154:1–22

Maamoun M, Megahed A, Allam A (1984) Seismicity of Egypt. Bull Helwan Inst Astron Geophys 4:109–162

McGuire RK (1976) FORTRAN computer programs for seismic risk analysis. US Geol Survey Open-File Report No 76–67

Milne WC, Davenport AG (1969) Distribution of the earthquakes risk in Canada. Bull Seismol Soc Am 59:729–759

Mogi K (1963) The fracture of a semi-infinite body caused by a inner stress origin and its relation to the earthquake phenomena (Second Paper). Bull Earthquake Res Inst 41:595–614

Mohamed AA, El-hadidy M, Deif A, AbouElenean K (2012) Seismic hazard studies in Egypt. NRIAG J Astron Geophys 1:119–140

Ordaz M, Aguilar A, Arboleda J (2007) CRISIS 2007. Institute of Engineering, UNAM, Mexico

Reiter L (1990) Earthquake hazard analysis. Columbia University Press, Columbia, 254 p

Rydelek PA, Sacks IS (2003) Comment on 'minimum magnitude of completeness in earthquake catalogs: examples from Alaska, the western United States, and Japan', by StefanWiemer and Max Wyss Bull. Seismol Soc Am 93:1862–1867

Scholz C (1968) The frequency-magnitude relation of micro-fracturing in rock and its relation to earthquakes. Bull Seismol Soc Am 58:399–415

Sims D, Séjourné M (2008) The dynamics of peri-urban areas around greater Cairo: a preliminary reconnaissance. World Bank, Washington

Sobaih M (1996) Seismic design criteria for Egypt, 11th World Conference on the Earthquake Engineering. Paper No. 2158, 7pp

Wiemer S, Wyss M (2000) Minimum magnitude of complete reporting in earthquake catalogs: examples from Alaska, the Western United States, and Japan. Bull Seismol Soc Am 90:859–869

Wiemer S, Wyss M (2003) Reply to 'Comment on "minimum magnitude of completeness in earthquake catalogs: examples from Alaska, the western United States, and Japan" by Stefan Wiemer and Max Wyss' by Paul A Rydelek and I S Sacks. Bull Seismol Soc Am 93:1868–1871

Woo G (1996) Kernel estimation methods for seismic hazard area source modeling. Bull Seismol Soc Am 86:353–362

World Bank Development Report (2014) Risk and opportunity: managing risk for development. http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/EXTWDRS/EXTNWDR2013/0,,contentMDK:23459971~pagePK:8261309~piPK:8258028~theSitePK:8258025,00.html. Accessed 15 Aug 2015

Youngs RR, Chiou SJ, Silva WJ, Humphery JR (1997) Strong ground motion attenuation relationships for subduction zone earthquakes. Seismol Res Lett 68:58–73