Insight on seismic hazard studies for Egypt

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ABSTRACT

The seismic hazard studies for Egypt have been initiated a long time ago aiming to predict the ground motion parameters at different geographical scales; their review process had been routinely performed due to the increase of available instrumental observations rather than from methodological advances.
For the comprehensive understanding of the development of seismic hazard assessment (SHA) studies in Egypt, we properly collect and test the existing SHA maps, computed at different geographic scales, against the available observations, data quality, physical assumptions and adopted methodology. Most of these SHA studies are probabilistic and the mapped ground motion acceleration values have been often largely exceeded by the observed values due to earthquakes occurred after their publication. For each study, we discuss and evaluate the input data, methodology and the results obtained in order to understand the reasons behind the bad performance of the available seismic hazard maps and to avoid such shortcomings in future seismic hazard assessment. Finally, we formulate suggestions that could be considered before new seismic hazard maps are released and then adopted, for the real benefit of society.

1. Introduction

The main aim of seismic hazard assessment (SHA) is the reliable characterization of the possible effects, and their geographical distribution, from local and regional earthquakes and to present them in a form, useful for practical and effective reduction of seismic risk.

It is clear that the most important input parameters for seismic hazard computation, whatever approach is considered, are: the seismotectonic sources, the set of controlling earthquakes (e.g. Maximum Credible Earthquake (MCE)), the ground motion prediction equation (GMPE) in the case of Probabilistic Seismic Hazard Analysis (PSHA) or DSHA (Deterministic Seismic Hazard Analysis) and lithosphere structure in the case of Neo-Deterministic Seismic Hazard Analysis (NDSHA). The first two sets of parameters (seismotectonic sources and the earthquake potential) are not easy to define, especially for intraplate regions, where the earthquake generation process is poorly understood and occasionally there is a poor correlation between the observed seismicity and the geologic structures or active faults (e.g. Egypt). Moreover, the identification of the controlling earthquake for these regions (i.e. intraplate regions) is

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not a handy way because of the limited seismicity record, very variable length of occurrence time interval, lack of our understanding about earthquake generating process and characteristics of seismotectonic earthquake: the subsurface active faults “blind faults” in mid-continental regions are a good example of the active seimotectonic structure that is capable to produce strong earthquakes, despite it is not characterized properly (e.g. Western Australia; Cairo-Suez shear zone in Egypt). Therefore, the incorporation of all available information from different multidisciplines e.g. Morphostructural Zonation (MZ), paleoseismological, geodesy investigations, will be necessary in the proper identification and characterization of active seismic sources, since using the available instrumental and historical earthquake records alone can incorrectly define (underestimate) the hazard level in the studied area. Moreover, the available strong motion databank for regions of scarce seismicity (e.g. Northeast Africa; Arabian Peninsula) and low occurrence rate for large earthquakes is not sufficient to establish or explore a proper GMPE for the prediction of the ground motion parameters. Consequently, it is better to resort to scenario-based techniques (e.g. NDSHA) or to use a GMPE that is developed from reliable source and propagation modeling and then validated using the available ground motion data instead of using imported ones.

In fact, there is the crucial need for a formal procedure for the proper collection and rigorous testing of newly developed seismic hazard maps before they can be accepted and then adopted, so that the society may benefit from such scientific studies and will not be deceived by the existing incorrect SHA results (Kossobokov and Nekrasova, 2012; Panza et al., 2012).

This work aims at giving a detailed insight on the available seismic hazard studies carried out at different geographic scales in Egypt, and finally to come out with some suggestions, comments and conclusions that could help in improving and enhancing the effectiveness of the future studies. To do this, we will start by showing shortly the performance of seismic hazard maps on global scale and an explanation about the SHA methods, their shortcomings and the alternatives; then we will focus on the existing seismic hazard studies for Egypt, describing the approaches that have been used, the input data and models, the dispersion in the obtained results, the testing of the results against the available macroseismic data and discussing the possible shortcomings. In Egypt the available seismological data is not sufficient for a sophisticated testing, but the result of the current testing cannot be overlooked.

2. SHA performance, advances and shortcomings

After the recent destructive earthquakes, e.g. Sumatra 2004, Wench China 2008, Haiti 2010 and Japan 2011, that took by surprise the global existing maps (see Kossobokov and Nekrasova, 2012; Panza et al., 2014), there is the urge to identify the causes of such failures and to improve the procedure of seismic hazard analysis, so that hazard maps possess, at the time they are published, some reliable predictive content and do not need to be revised after each major earthquakes occurrence, as it often happened till now. Stein et al. (2012) studied the causes of the failure of seismic hazard maps related with the Tohoku 2011 (March 11, M ~ 9.0) event and identified four overlapping factors that can cause a hazard map to fail: bad physics, bad assumptions, bad data and bad luck, and introduced suggestions that could improve the performance of such a map.

Intensive debate and criticisms on the traditional PSHA method and its global performance in the last decades has demonstrated the fallacy of its estimates (e.g. Molchan et al., 1997; Castaños and Lomnitz, 2002; Klügel, 2007a,b; Geller et al., 2015). These authors evidenced substantial limits in both theoretical and practical bases of PSHA, including their dangerous effects on seismic codes. Traditional PSHA-based seismic hazard maps are: (1) strongly dependent on the length, completeness and the quality of earthquake database being used; (2) do not adequately consider the seismic source process, seismic wave propagation model and local site condition; (3) do not appropriately consider the temporal properties of earthquakes occurrence, since they are based on the assumption of random occurrence of earthquakes, that implies the independent occurrence of earthquakes in both time and space; this means that the probability of occurrence of two events at the same time and space is about zero, contrary to what sometime observed; (4) do not adequately consider the available information from paleoseismological, morphostructural and GPS based studies. In fact, the number of records of large earthquakes is too limited to attempt to describe the probability of occurrence and ground motion particularly for mid-continental regions. So far, there is no a formal approach that allows for the use of this kind of aforementioned data (item 4) in the computation of the Gutenberg-Richter (GR) relation (Gutenberg and Richter 1956) that is at the base of any traditional PSHA estimate.

The modern PSHA approach (for the complete description see e.g. Petersen et al., 2008; Atkinson and Goda, 2011) could implement data about active sources and has some improvements relative to the traditional one, as: a) the adoption of active fault databases; b) point and finite source modeling can be frequently used in developing a GMPE and generating the time histories from a control fault for structural dynamic analysis; c) Morpho-tectonic and paleoseismological studies, as well as GPS and InSAR measurements are used in the determination of fault segmentation, attitude, depth, and slip-rates of fault sources; d) to characterize the distribution of earthquake magnitudes, GR relationship was commonly used for a relatively big regional sources in PSHA, but for small sources it resort to Characteristic Earthquake (CE) model which refers to the characteristic magnitude occurs more often than predicted by the GR models proposed above; e) weights in a logic tree are commonly determined by a large group of experts instead of “the author's experience and judgment”; f) residuals in GMPEs are decomposed into epistemic uncertainty and aleatory uncertainty. Only aleatory uncertainty was included in the integration for annual rates of exceedance. Epistemic uncertainty is moved to the logic tree; g) Seismotectonics and crustal structures as well as seismicity were commonly used in delineating the regional source zones and focal depth distribution function. Basin depth and Vs30 were used in developing the GMPE; h) Output ground-motion level is not a single value, but a spectrum covering 0 s to 10 s. PGV, PGD, and Arias intensity may also be included.

According to the Multiscale Seismicity (MS) model (Molchan et al., 1997), the GR relation is valid as a law only for the earthquakes that have a linear dimension of the surface rupture small compared to the dimensions of the analyzed region, i.e. in the point source approximation. When focusing on a relatively small site, the point source approximation may no longer be valid and therefore GR is not applicable as a law. For example, an event with $M \geq 7$, whose rupture length can be estimated around 50 km (Wells and Coppersmith, 1994), can be considered a point only if the studied seismogenic zone has linear dimensions larger than 500 km (Panza et al., 2014). The use of small areas has given rise to the CE model (Schwartz and Coppersmith, 1984), but this model has been strongly questioned by several authors (e.g. Molchan et al., 1997; Geller et al., 2015) which cast severe doubts on the CE model reliability.

In view of the theoretical and practical limits and errors in basic assumption of traditional PSHA estimates, it appears urgent to resort to a scenario-based approach to SHA. NDSHA approach is a scenario-based method for seismic hazard analysis, where realistic synthetic seismograms are used to construct earthquake scenarios. NDSHA is best suited to compute the ground motion parameters at 1 and 10 Hz cut-off frequencies for different geographic scale studies. The two frequency thresholds are chosen depending upon the quality of the available input data; cutoff frequency increases with increasing quality. Starting from the available knowledge about the mechanical properties of the Earth's structure, seismic sources and seismicity of the study region, it is possible to realistically compute the synthetic seismograms from which quantify peak values of acceleration, velocity and displacement or any other ground motion parameter relevant to seismic engineering, e.g. design ground acceleration. In the framework of NDSHA procedure, the studied region is usually covered by a regular grid (usually 0.2° × 0.2°). The earthquake sources are centered in the grid cells that fall within the adopted seismogenic zones, while the computation sites are placed at the nodes of a grid that is staggered by 0.1° with respect to the sources' grid. A smoothing procedure for the definition of earthquakes location and magnitude, M, is then applied to account for spatial uncertainty and for source extension. After smoothing, only the cells (earthquake sources) that are located within the seismogenic zones are retained. The smoothing process makes NDSHA robust and prevents it from the possible uncertainties in the earthquake catalog, which is not required to be complete for $M < 5$. A double-couple point source is placed at the centre of each cell, with a representative focal mechanism which is consistent with the present-day dominant tectonic regime of the corresponding seismogenic zone. Source depth is taken into consideration as a function of magnitude. A complete description of the NDSHA methodology can be found in Panza et al. (2001), and its updates and validations in Panza et al. (2012) and Magrin et al. (2016).

If necessary, NDSHA permits to account for earthquake recurrence rate (Peresan et al., 2013 and references therein), performing the characterization of the frequency-magnitude relation for earthquake activity according to the multi-scale seismicity model (Molchan et al., 1997) and associating the estimated recurrence to each of the modeled sources. Thus, the temporal meaning is intentionally addressed in a different way than in the PSHA approach, where the "return period" is one over the annual rate at which a ground motion level is exceeded at a site.

The DSHA and NDSHA agree in: a) considering the MCE not necessarily coincident with Maximum Historical Earthquake (MHE); b) accommodating any reliable information from paleoseismological, MZ investigations or similar studies; c) not using the GR relation or CE model, and differing in the step that is common to standard DSHA and PSHA: the use of GMPE, or attenuation relations, in the ground motion estimation.

In fact, from the basic principles of continuum mechanics (e.g. Aki and Richards, 2002), the ground motion generated by a seismic (point) source can be expressed as the tensor product of the seismic moment tensor and the derivative of the Green's function of the medium, the extension to finite-dimension sources being straightforward. Since GMPEs are scalar, they cannot adequately describe this tensor nature of the ground motion.

The performance of any hazard map can be tested reliably against the available observed intensity and/or recorded ground motion values, and this test may help the adoption of procedures to differentiate between reliable and unreliable hazard assessments. This may lead to the improvement of the physics, data and assumptions on which seismic hazard maps are based and eventually improve their reliability. Moreover, the reliable assessment and clear communication of possible uncertainties associated with SHA to potential users is one of the main elements that could help in improving the performance of resultant map and help different users to decide how much credence to place on this map.

3. Seismic hazard studies for Egypt

As it is the case of global studies and although many lesson learned through the time, most of the seismic hazard maps for Egypt and nearby regions failed to predict the ground motion parameters, which is evidenced in this paper by simply comparing the predicted ground motion parameters by different studies with the macroseismic intensity. The failure may be due to the fact that, to identify the location and characteristics of seismotectonic sources for Egypt, only seismological observations (about 100 years) have been considered, while paleoseismological and MZ investigations or similar studies that are suitable to identify seismotectonic sources that may be active over a time scale that is larger than the instrumental data base time span have been ignored or unappreciated.

For example, the estimated PGA for Gulf of Aqaba region was ranging between 30 and 40 gals computed by Ibrahim and Hattori (1982) with 90% probability of non-exceedance in 50 years and 100–125 gals with 90% probability of non-exceedance in 100 years computed by Sobaih et al. (1992). These values were proven severely wrong (underestimated) by the occurrence of Aqaba earthquake on November 22, 1995 with M_w7.2 when the observed intensity for the Egyptian coast from this event is VIII on MSK (Medvedev-Sponheuer-Karník) scale which equal to 0.2 g, the low intensity for this strong event could be due to the very low population density and the location of event in offshore of the gulf. Also, the observed PGA values on the vertical component "which is generally less affected by site effects" for Eilat (EIL) (located on an alluvial fan of about 50 m thick overlying granite at about 93 km epicentral distance) and Shivta (SVT) (which is located on consolidated chalk with almost no site effect at 244.1 km epicentral distance) strong motion stations were about 113.6 and 38 gals, respectively (Gitterman, 1999, unpublished report). Therefore, the formal procedure for the reliable identification of the location, configuration (fault geometry and orientation) and the potential (maximum magnitude) of earthquake sources becomes a necessary step for sound seismic hazard and risk mitigation.

Egypt is well defined as a relatively low seismicity country and has experienced strong earthquake effects through history from regional (Hellenic arc, Cyprean arc and Dead Sea fault system) and local tectonic sources (e.g. North Red Sea, Gulf of Aqaba, Gulf of Suez, South-West Cairo (Dahshur Zone) and the continental margin of Egypt). The reasons behind the strong risk from modest seismic hazard are the high population density, the proximity of seismic sources to urban cities, profound effect of the path and local geology and the poor design and construction practice. According to the historical reports about earthquake impacts, the 365 Crete, 1303 Rhodes, 1969 Shadwan Island (entrance of the Gulf of Suez) and 1992 Cairo (Dahshur) events are the most devastating ones. These events caused a relatively strong damage to different areas in Egypt and thus recall for the necessity of reliable seismic hazard assessment to mitigate the possible losses in the future.

The seismic hazard studies for Egypt started long time ago with the aim to predict the ground motion parameters and to mitigate the risk (see Tables 1–3). The review of the previous seismic hazard studies in Egypt (e.g. Sawires et al., 2016a) was routinely stimulated by the increase of instrumental observations rather than by methodological advances or the release of a new data about the active faults.

This paper, aims to give an insight into the development of seismic hazard studies achieved so far in Egypt and to show how the seismic zoning maps have been changing with the progresses both in seismological theory and observational practice (the improvement of observation requires to wait for events, while theoretical steps forward can be done at any time).

Although the importance of the new developments in SHA, it is worth to mention that, most of the available SHA maps for Egypt are based on the traditional approaches (DSHA and PSHA) and have not implemented the aforementioned improvements in their computations, so far. About 80% of all SHA studies conducted until now about Egypt at different geographic scales are based on the traditional PSHA and despite of the presence of theoretical and practical limitations and poor performance of these approaches, as demonstrated by Panza et al. (2014) and references therein, it is still in use in the construction of newly developed SHA maps at different scales (e.g. EzzElarab et al., 2016; Sawires et al., 2016b) upon which the current Egyptian Building Code is dangerously based. The different studies adopting the traditional PSHA method contribute to the development of the collection and revision of input data rather than to the critical revision and improvement of the methodology, elements that are crucially necessary to reach a reliable, as much as possible, estimate of hazard (Tables 1–3).

Most of the available SHA studies for Egypt (e.g. Ibrahim and Hattori, 1982; Abdel-Fattah, 2005; Mohamed et al., 2012; EzzElarab et al., 2016)

Table 1
Available regional scale seismic hazard assessment (SHA) studies for Egypt, with the related input data, arranged in chronological order.

Study	SHA method	Input parameters Earthquake Catalog (EC)	Seismotectonic Zones (SZ)	Ground Motion Prediction Eq. (GMPE) (or Structural Model (SM) if specified)
Sobaih et al. (1992)	PSHA	EC till 1984	Ten SZs	Maamoun et al. (1984)
Ahmed et al. (1992)	PSHA	EC from 1900 to 1980s	Five SZs	No available information
Riad et al. (2000)	PSHA	EC from 2800 BCE to 1996	Sixty-two local and regional SZs	Campbell (1981) and Crouse (1991)
Sabry et al. (2001)	PSHA	No information about the data sources used, neither about the earthquake catalog nor the time completeness	Thirteen SZs	Aptikaev and Kopnichev (1980), Hu et al. (1996), McGuire (1978), Bolt and Abrahamson (1982) and Riad and Yousef (1999)
El-Sayed et al. (2001)	NDSHA	EC from 528 till 1997	Ten SZs	Five SMs of Egypt with regional average properties for the bedrock are used.
Abdel-Fattah (2005)	PSHA	EC for the period 1067–2003	Eleven SZs	Deif (1998) and Atkinson and Boore (1995, 1997)
Mohamed et al. (2012)	PSHA	EC with M ≥ 3 updated till 2009	Two SZs models are considered, with weights	Youngs et al. (1997), Zhao et al. (2006), Abrahamson and Silva (1997), Boore et al. (1997), Campbell and Bozorgnia (2003) and Campbell and Bozorgnia (2008)
Mourabit et al. (2014)	NDSHA	EC updated till 2011 for earthquakes with M ≥ 5	Thirteen SZs	Same as El-Sayed et al. (2001)

have reduced the seismic hazard assessment to one or two value(s), i.e. peak ground acceleration (PGA) for the horizontal component (poorly correlated to damage) and response spectrum (RS) at different periods rather than the complete frequency content, effective acceleration, bracketed duration, incremental velocity and damaging potential (e.g. Decanini and Mollaioli, 1998; Bertero and Uang, 1992). Also, they did not pay the due attention, in a sound and physically correct way, to the so called "site effects", that may be not persistent (Molchan et al., 2011), especially in the Nile delta and valleys, can have a large impact on the polarization in the horizontal plane (also defined amplification/de-amplification) of seismic waves and on ground failure or soil liquefaction (e.g. El-Sayed et al., 2004).

In addition, most, if not all of the existing PSHA studies in Egypt supply the horizontal component of the ground motion only, basing on the untested assumption that the amplitude of the vertical component of strong-motion can be defined as a fraction of the horizontal one. The vertical component generally could be less than the horizontal components but this is not necessarily true for high frequency ground motion in the near source condition (e.g. Shrestha, 2009). Actually the directivity, propagation effect and local site condition may combine and produce a dominant vertical component (e.g. Gazli, Uzbeksitan 1976 M6.8; Nahhani, Canada 1985 M6.8; Chi Chi, Taiwan 1999 M7.6) and that is why it is important to reliably estimate the vertical component of the ground motion as well.

Realistic earthquake time histories may be not crucial for the land use and urban planners, but are of a great importance for structural and technical engineers willing to design a new structure and/or evaluate the seismic performance of the existing built environment, and to investigate the non-linear behavior of soil at the site of interest. So, it is important to exploit the existing methodologies for modeling the generation and propagation of seismic waves, as done with NDSHA, which are able to provide a wide database of computed seismograms for Egyptian territories that suffer from the lack of useful strong motion databases.

In fact, the quality of the results obtained by utilizing numerical codes, based on physics modeling, depends on the quality of the input data (Panza et al., 2013a,b). In the existing seismic hazard studies, it seems that one of the major problems is how much the used earthquake

Table 2
Available local scale seismic hazard assessment (SHA) studies for Egypt, with the related input data, arranged in chronological order.

Study	SHA method	Study area	Input parameters EC	SZ	GMPE
El-Hefnawy et al. (2006)	PSHA	Sinai peninsula	EC with M ≥ 3 for the period from 184 BCE and 2003	Twenty-five SZs	Joyner and Boore (1981)
Deif et al. (2009b)	PSHA		EC from 112 BCE to 2006	Twenty-eight SZs	Ambraseys et al. (1996)
Fat-Helbary and Ohta (1996)	PSHA	Aswan area	About 350 events with M ≥ 3.2 recorded between 1981 and 1995	Both Line Source Model (LSM), for the natural sources, and Area Source Model (ASM), for induced seismicity	Fat-Helbary and Ohta (1994b)
Deif et al. (2009a)	DSHA		Single-event scenarios are used	Three seismotectonic models are considered in this study	Ambraseys and Bommer (1991a), Fat-Helbary and Ohta (1994b), Ambraseys et al. (1996) and Deif and Tealeb (2001)
Deif et al. (2011)	PSHA		EC with M ≥ 2.5 for the time interval from 1900 to 2009	Ten SZs	Ambraseys et al. (1996), Abrahamson and Silva (1997), and Boore et al. (1997)
Badawy (1998)	PSHA	Northern Egypt region	EC for the time interval from 1960 to 1995	Three SZs	Intensity-based GMPE is developed and used for the northern Egypt region
Deif (1998)	PSHA		EC extending from 2200 BCE to 1997	Twelve SZs	Deif (1998)
Saleh (2005)	DSHA	Western desert	EC with M_S ≥ 3.5 for the time interval from 1964 to 2003	Eight SZs	Deif and Khalil (2003)
El-Adham and El-Hemamy (2006)	PSHA		EC for the time interval from 184 BCE to 2004	Fifteen SZs	Deif (1998)
Kebeasy et al. (1981)	Intensity-based approach	Alexandria	EC comprises 130 events for the time interval from 2200 BCE till 1978	Two SZs	Gutenberg and Richter (1956)

Table 3
Results of the national and local seismic hazard assessment studies for Egypt, arranged in chronological order. PGA values, in units of g, are rounded to 2 decimal digits, as a rule, to be conservative in the reported results.

Study	SHA method	Gulf of Aqaba	Entrance of Gulf of Suez	Cairo	Nile delta	Aswan	Alexandria	Sinai peninsula
Kebeasy et al. (1981)	Gutenberg and Richter (1956)	[a]	[a]	[a]	[a]	[a]	0.07	[a]
Ibrahim and Hattori (1982)	PSHA	0.03–0.04	0.03–0.04	0.08–0.20	0.08–0.2	0.005–0.01	0.03–0.04	0.03–0.04
Sobaih et al. (1992)	PSHA	0.1–0.13	0.10–0.15	0.04–0.06	0.04–0.06	0.06–0.08	0.06–0.08	0.04–0.15
Ahmed et al. (1992)	PSHA	0.15–0.16	0.18–0.20	0.06–0.07	0.07–0.09	0.10–0.16	0.09–0.10	0.05–0.20
Cairo Earthquake, October 12, 1992 $M = 5.8$ and $I_{MSK} = VIII$.								
Aqaba Earthquake, November 22, 1995 $M = 7.2$ and $I_{MSK} = VIII$.								
El-Sayed (1996)	PSHA	0.40	0.35	0.20	0.20	0.15	[a]	
Fat-Helbary and Ohta (1996)	PSHA	[a]	[a]	[a]	[a]	0.03–0.05	[a]	[a]
Badawy (1998)	Intensity-based PSHA	0.25	0.25	[a]	[a]	[a]	[a]	[a]
Deif (1998)	PSHA	0.18–0.22	0.14–0.2	0.06–0.08	0.02–0.06	[a]	0.04–0.06	0.04–0.22
Riad et al. (2000)	PSHA	0.11–0.22	0.11–0.22	0.11	0.11	[a]	[a]	[a]
Sabry et al. (2001)	PSHA	0.20–0.23	0.17–0.25	0.15–0.17	0.17–0.23	0.10–0.12	0.17–0.20	0.17–0.25
El-Sayed et al. (2001)	NDSHA	0.15–0.33	0.15–0.30	0.08–0.30	0.08–0.30	0.04–0.15	0.02–0.30	[a]
Abdel-Fattah (2005)	PSHA a) Deif (1998)	0.13–0.19	0.17–0.21	0.13–0.15	0.13–0.15	0.13–0.17	0.13–0.15	0.11–0.21
	b) Atkinson and Boore (1995)	0.09–0.15	0.11–0.17	0.09–0.11	0.07–0.11	0.11–0.17	0.07–0.09	0.05–0.15
Saleh (2005)	DSHA	0.04–0.08	0.04–0.12	0.004–0.08	0–0.02	0–0.04	0–0.02	0–0.08
El-Hefnawy et al. (2006)	PSHA	0.21–0.27	0.15–0.21	[a]	[a]	[a]	[a]	0.06–0.27
El-Adham and El-Hemamy (2006)	PSHA	[a]	[a]	[a]	0.004–01	[a]	0.1–0.16	[a]
Deif et al. (2009b)	PSHA	0.1–0.18	0.08–0.1	[a]	[a]	[a]	[a]	0.020–0.18
Deif et al. (2009a)	DSHA	[a]	[a]	[a]	[a]	0.15	[a]	[a]
Deif et al. (2011)	PSHA	[a]	[a]	[a]	[a]	0.03–0.15	[a]	[a]
Mohamed et al. (2012)	PSHA	0.18–0.23	0.10–0.13	0.08–0.10	0.03–0.08	0.10–0.20	0–0.03	0.05–0.23
Mourabit et al. (2014)	NDSHA	0.15–0.6	0.15–0.6	0.08–0.3	0.02–0.08	0.04–0.3	0.08–0.3	[a]

All PGA values from PSHA studies are computed with 10% probability of exceedance in 50 years.
[a] No PGA estimated for the study area.

catalogs are representative of the real seismicity of the study area (e.g. Badawy, 1998; Saleh, 2005). This recalls for the importance to use all available information (e.g. paleoseismology; geodesy) and to plan new comprehensive investigations where crucially necessary in order to better identify and characterize the seismic sources for Egypt. This is a key factor in SHA by whatever approach and may help in reducing the possible uncertainties, since using historical earthquake records alone cannot enhance the performance of the hazard map. Badawy (1998) has mentioned that, before the 1960s the earthquake location accuracy is not adequate for the analysis. The catalog used in this study is too short and insufficient to reliably estimate the seismic hazard, particularly when the assessment is carried out using PSHA methods, which strongly depend on the amount of data available (35 years of seismological observations are useless in the hazard estimation because of the undue extrapolation to large earthquake occurrence rate), see Table 2. Also, most of the existing studies do not clearly communicate the characteristics of the earthquake catalog being used (e.g. Sabry et al., 2001).

The second important factor is the GMPE in the case of PSHA or DSHA and the lithosphere structure in the case of NDSHA. In fact, most of the GMPEs employed in the estimation of earthquake ground motion parameters for Egypt have been developed for other regions that differ, for instance, in tectonic regime, faulting style and crustal structure thus they are "imported GMPEs". Moreover, the adoption of such equations is bound to lead to the disruption of the tensor characteristic in the predicted earthquake ground motion.

The reason behind the adoption of imported GMPEs is the very limited strong motion database, which is not sufficient to construct an empirical relationship for Egypt or to explore and evaluate the suitable GMPE. The limit is due to the small number of recorded strong motion events (about 8 events), small magnitude range (4.0–5.5) and inadequate spatial distribution of the accelerometers (about 12 strong motion stations distributed irregularly over the territory at far distance from the most of active sources), see Fig. 1.

The existing SHA studies for Egypt have incorporated many different GMPEs from regions of tectonic setting somehow similar to the present-day tectonic setting of Egypt, but they did not consider at all the profound effects of the propagation path and the possible change in the rupture process that definitely are quite variable from path to path. There is no consensus on a single or a set of GMPE(s) that should be used. The choice of suitable GMPE(s) always depends on the map-makers' preference, not on a rigorous evaluation by a large group of experts, and most of the studies have used more than one GMPE with different weighting values with the aim of taking into account possible epistemic uncertainties.

Moreover, from the inspection of the seismic hazard studies, there is not a sufficient communication for the characteristics of the GMPEs being used. Abdel-Fattah (2005) for example, gives the priority to the results based upon the "imported" GMPE of Atkinson and Boore (1995, 1997) because, from his point of view, there is a good consistence between the local and regional seismicity and tectonics of the region (i.e. North America), for which the Atkinson and Boore (1995, 1997) GMPE was estimated, and the local and regional seismicity and tectonics of Egypt. No evidences are given to support this choice, but just considerations and opinions (conventional wisdom), not to mention that the scatter between the two sets of estimates, >60%, makes it meaningless the precision given of 0.02 g, which corresponds to about 2% (Tables 1 and 3).

Thus, it is important to resort to a more reliable solution for modeling the generation and propagation of seismic waves (e.g. the structural models and related computation of realistic broadband signals as done with NDSHA). In spite of this, the regional structural models are an important input in SHA computation based on NDSHA and have a profound effect on the resultant ground motion maps. All of the existing models for Egypt are too simple and it is clear the need for the revision of the crustal models, taking into account all the crustal studies available for different regions of the Egyptian territory, and eventually, to plan new comprehensive studies over a regular grid where crucially necessary.

In some of the exiting SHA studies (e.g. Kebeasy et al., 1981; Badawy, 1998, see Table 2), the attenuation relationships which have been developed based upon the decay of macroseismic intensity in Egypt have been used to estimate the annual seismic hazard maps in terms of intensity variations with different level of non-exceedance. In fact, because of the subjective nature of intensity determination, the discrete character

Fig. 1. Spatial distribution of strong motion stations (white triangles) and the recorded events (red stars) during the period from 2008 till 2016.

of the intensity scale and the poor correlation of intensity with specific source characteristics and strong motion data, the intensity-based ground motion estimates are not preferred.

In addition, the ground-motion variability has not been taken into account in most of the existing traditional PSHA studies for Egypt. Incorporating this kind of variability can be done by integrating over the standard deviation reported in GMPEs being used, which significantly affects estimated ground motions, especially at very low probabilities of exceedance. Only few studies have clearly introduced and considered the ground motion variability in the hazard analysis (e.g. Deif et al., 2009a,b). This is could be the reason behind the low PGA values that has been estimated for Egypt. The dropping of sigma (σ) in SHA does not only lead to underestimating the computed ground-motion intensity but it is also inconsistent with the standard probabilistic approach (Bommer and Abrahamson, 2006).

Most of the estimated ground motion maps for Egypt are not validated against the available observation or the macroseismic data. Also, the uncertainties associated with the computation of ground motion parameters are neither sufficiently assessed nor clearly presented to the different potential users.

4. Discussion

We must accept and adopt as reliable, the seismic hazard maps which fit well with what actually recorded (better performance) and that are based upon correct and tested theory, physics, assumptions and methodology, with full understanding of their limitations and of their relation to other steps in engineering and risk analysis; then we have to try to improve them when new data or theoretical developments become available.

In Egypt different authors have carried out many seismic hazard studies for different time and space scales, as reported in Tables 1–3. Most of these studies are based on the traditional probabilistic approach and show that the ground motion acceleration values on the maps are largely exceeded by earthquakes occurred after their publication (e.g. Figs. 2–6). The failure of these maps is evidenced by testing the PGA values converted from observed intensity based on the table given by Medvedev and Sponheuer (1969) against the predicted ground motion before the occurrence of earthquake which cannot be overlooked. The maximum observed intensity (I_{MSK}) is VIII for the 1992 Cairo earthquake corresponding to 0.2 g, VII for the 1981 Aswan earthquake, corresponding to 0.1 g. Moreover the maximum I_{MSK} for the 1969 earthquake (March 31, 1969 M_w 6.9) is XI and equivalent to 0.4 g, while for the 1995 earthquake (November 22, 1995 M_w 7.2) is more than VIII, corresponding to 0.2 g (Fig. 6). Ibrahim and Hattori (1982) have computed the PGA map for Egypt, the high PGA value for Cairo region could be due to the effect of interpolation of PGA map. Thus, it is more useful to analyze the cause(s) of the failure to understand what went wrong and improve the assessment and therefore, the mitigation process.

The input differences between the existing PSHA studies are the earthquake catalogs, geometry of seismotectonic models (Tables 1 and 2) and analyst expertise and preconceptions; as a consequence, a large scatter in the ground motion parameters values for the same region, but from different studies (sometimes in the same year, i.e. with same earthquake catalog) is observed, as reported in Table 3 and shown in Figs. 2–6. Seemingly, one of the main problems of PSHA computation in Egypt is the relatively short time base of seismic observations and absence of useful information about active faults (Tables 1 and 2). Saleh (2005) studied the seismic hazard in Egypt using DSHA and the PGA hazard values estimated by this work are the lowest among many other results from NDSHA and PSHA for the Gulf of Aqaba (Fig. 2), Cairo (Fig. 3), Nile delta (Fig. 4) and Alexandria (Fig. 5) regions. This is due to the shortness of the earthquake catalog that covers the time span from 1964 to 2003 and ignores the pre-instrumental earthquake catalog which represents an important segment of the available seismological information for Egypt.

Considering a set of possible hazard maps for Egypt computed with different input data and adopting different models and assumptions (sensitivity test) can help in adequately defining the errors in the resultant hazard maps (Hassan et al., 2017). Sensitivity check of hazard maps for different input data can be easily done in a straightforward way with NDSHA. Skeptical reviews and testing of published hazard maps and assessments should be regularly done and published to evaluate the state of art of hazard knowledge and to identify possible steps forward and needs.

The PGA values estimated using the NDSHA approach represent the upper boundary for the different seismic hazard maps in the different regions in Egypt (Figs. 2–6); thus, they turn out to be conservative and physically reliable. Also, there is no significant change in PGA values

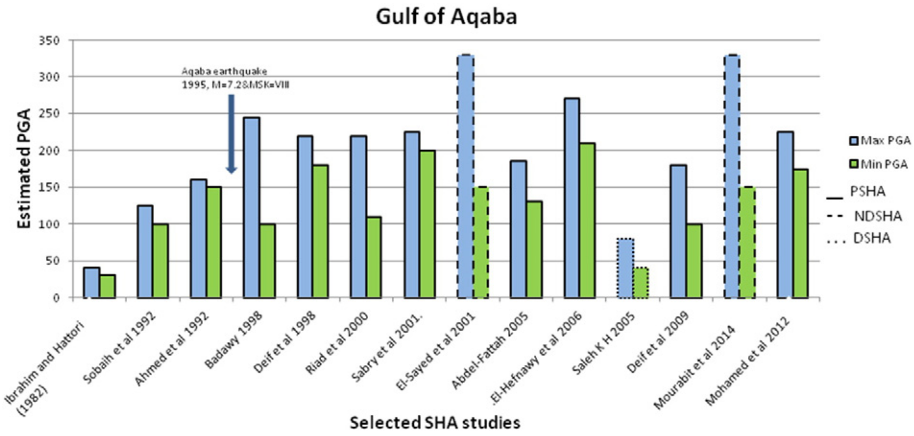

Fig. 2. Comparison between the Max and Min PGA values estimated by the different studies for the Gulf of Aqaba region.

from El-Sayed et al. (2001) and Mourabit et al. (2014), this may be due to the fact that, NDSHA needs only earthquake catalogs with M ≥ 5 (during the period from 2001 to 2014 occurred only few events of moderate magnitude). It is worth to mention that, the computation of NDSHA maps available for Egypt is carried out using the earthquake catalog and no information about the control faults has been used, so far. Although, the fact that the earthquake catalogs for Egypt used in Mourabit et al. (2014), which is a NDSHA based study, and Mohamed et al. (2012) "PSHA studies" are almost the same, the predicted ground motion values obtained from NDSHA are still larger and comparable with the observed intensities.

The comparison among different probabilistic seismic hazard maps (at regional and local scales, Tables 1 and 2) for the same site reveals that the PGA values are not consistent and large differences are found; the local studies can be more detailed, though not necessarily more reliable (e.g. Klügel, 2005). For example, the PGA values for Aswan, reported in Table 3, vary in the range from 0.005–0.2 g (see also Fig. 6), showing a large scatter in the values. This makes it difficult, for the potential users, to decide what value to rely on in the design or retrofitting of the build environment. Furthermore, there are large differences between PGA values determined by the same study at the same site, but using different GMPEs (e.g. Abdel-Fattah, 2005), Tables 1–3.

It is important to mention that the application of weights to each logic tree component (e.g. seismicity parameters, seismotectonic and GMPEs) used in the existing PSHA studies for Egypt can lead to artifacts, since the weights are given according to the author's experience and judgment rather than the stringent physical arguments and the judgment of a group of experts. Moreover, the use of weights without careful judgment may add new source of uncertainty, i.e. the author bias; this fact explains why the PGA values which are obtained by different studies in Egypt at the same site, but with the same PSHA algorithm are significantly different. Actually, with weights used in existing PSHA for Egypt, given any set of numbers, any desired average value can be obtained.

Furthermore, a large number of the reviewed studies (e.g. Ibrahim and Hattori, 1982; Badawy 1998; Abdel-Fattah, 2005) supply the PGA maps as the only significant ground motion parameter. The recently developed studies (e.g. Deif et al., 2009a,b; Mohamed et al., 2012) have provided both PGA and spectral acceleration values at the nodes of regular grid for Egypt. Different earthquake hazard maps can naturally be appropriate for different purposes. A map showing the predicted ground motion variation in terms of PGA or intensity scale may be useless to the designer of critical structures and geotechnical engineer who need detailed, and more realistic, seismic inputs consisting of three components seismogram, but, at the same time, this map may be of some use to the land use planner who needs a handy way to evaluate the earthquake impacts on mankind and property.

The revision of existing seismic hazard studies in Egypt also indicate that, just few of those studies (e.g. El-Sayed et al., 2001) are tested against the available historical and instrumental seismicity. El-Sayed et al. (2001) tested the predicted ground motion parameters against the observed intensity (in terms of maximum MSK) for earthquakes of 1955 (Alexandria offshore), 1969 (entrance of Gulf of Suez), 1981 (Aswan) and 1992 (Cairo), with intensity values of VIII, IX, VII and VIII, respectively, and found a good comparison between the observed and converted ones. However, any earthquake hazard map must be tested

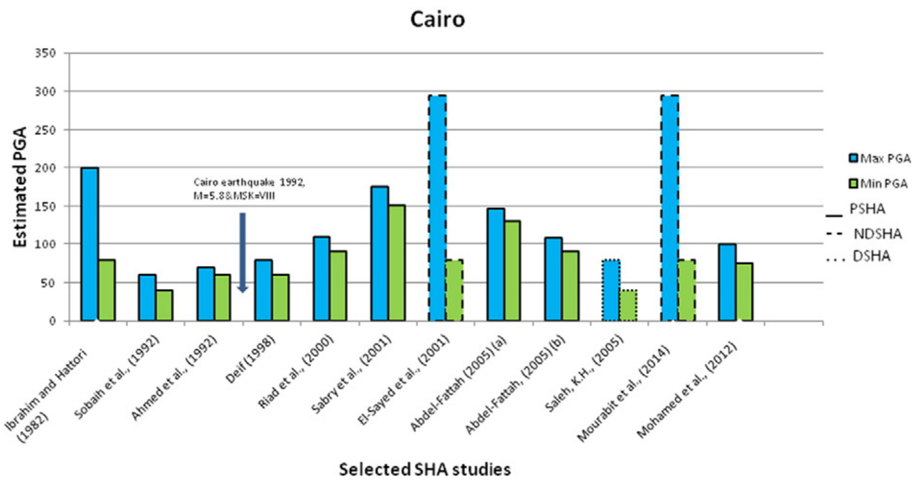

Fig. 3. Comparison between the Min and Max PGA values estimated by the different studies for the Cairo region.

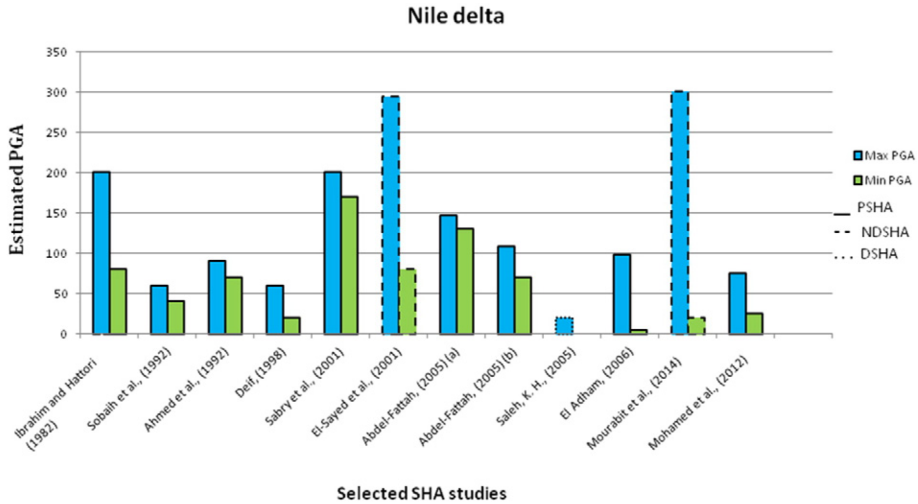

Fig. 4. Comparison between the Max and Min PGA values estimated by the different studies for the Nile delta region.

against real seismic data before any practical estimation of risks can be made. Otherwise, the use of untested seismic hazard maps may and do cause high level of unpredicted fatalities and economic losses (Wyss et al., 2012).

The better evaluation and presentation of hazard maps, and their uncertainties and limitations, the better end users decisions and adopted risk strategies. Conversely, the unclear presentation of the maps, and related uncertainties and limitations, will lead to inadequate decisions and thus wrong perception of real risk for the society.

In spite of the poor performances and basic shortcomings of existing PSHA studies available for Egypt, the seismic design strategy, as well as the building code and its update, rely upon the maps from those studies. In order to overcome the limits of design procedures based upon PSHA seismic input (Fasan et al., 2015; Rugarli, 2014), it is necessary to resort to a new seismic design strategy based upon the NDSHA definition of the seismic input in Egypt. NDSHA aims to supply an envelope value, in other words a value that should not be exceeded, therefore it is immediately falsifiable and verifiable: if in a seismically active region an earthquake occurs with a magnitude larger than that indicated by NDSHA it is necessary to measure the variance. If it turns out to be larger than the multiple of standard deviation used to define maximum controlling earthquake, for instance (Dominique and Andre, 2000) equal to the maximum observed magnitude plus $2\sigma = 0.5$, then maps are immediately falsified; similarly if the peak values recorded at the bedrock at the occurrence of an earthquake after the compilation of NDSHA maps exceed, within error limits, those given in the same maps.

5. Conclusions

In this study for the insight understanding of the development of seismic hazard studies for Egypt, we properly collect and test the existing SHA maps, computed at different scales, against the available observations and physical assumptions, data quality and methodology and, finally, we propose some suggestions that could be considered before new seismic hazard maps can be produced and then adopted, for the real benefit of society.

From the present review of the seismic hazard studies in Egypt, the following conclusions can be drawn and may be considered in the next seismic hazard maps:

1. It is urgently necessary to review the list of seismic sources and controlling earthquakes with the aim to produce realistic and reliable seismic hazard maps for Egypt.
2. After the occurrence of every significant large earthquake in Egypt, there is ensuing change both in seismotectonic sources and in hazard maps (see the chronological order of seismic hazard studies summarized in Tables 1–3); this is an evidence of lack in seismic sources identification and characterization, that results in the

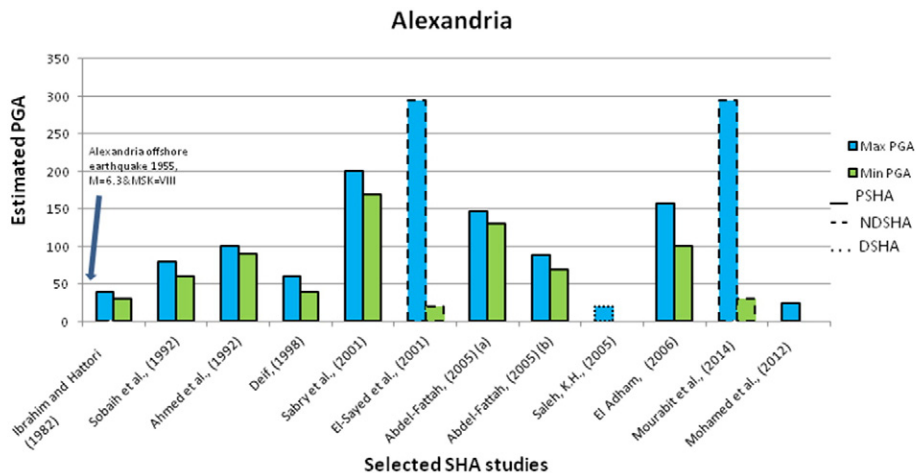

Fig. 5. Comparison between the Min and Max PGA values estimated by the different studies for the Alexandria region.

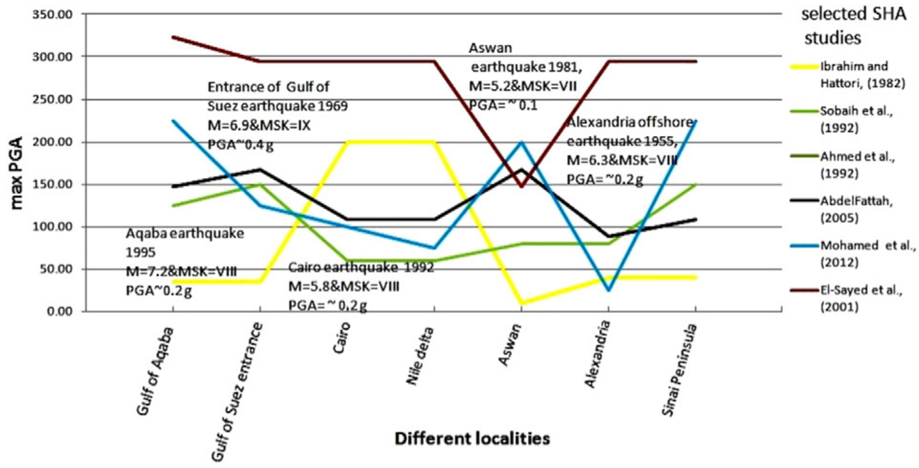

Fig. 6. Max PGA values estimated by the different SHA studies for different regions in Egypt.

underestimation of seismic hazard. Revisions are appropriate, but not each time a strong earthquake occurs.

3. Most of the existing PSHA and DSHA studies in Egypt have reduced the assessment results to the single measure of PGA and RS that, alone, do not express the damaging capability, and ignore other parameters that have profound effect on damage.
4. The dropping of sigma (σ) "the ground motion variability" in SHA does not only lead to underestimating the computed ground-motion intensity but it is also inconsistent with the standard probabilistic approach.
5. The structural anelastic models are an important input in SHA computation using scenario-based approaches and have a profound effect on the resultant ground motion parameters. All of the existing models are too simple, and the need for the revision of the crustal models is obvious, taking into account all the crustal studies available for different region of Egyptian territory and eventually, to plan new studies where crucially necessary.
6. The use of weights in the logic tree components of PSHA can lead to misleading results, adding the author's bias into the gross uncertainty of the seismic hazard assessment process. Thus, this drawback can be reduced but not eliminated, if the adopted weights in a logic tree are determined by a large group of experts rather than by the author's experience and judgment.
7. From the SHA studies in Egypt published so far, it is clear that the instrumental and historical earthquake catalogs are good in the description of known past and present earthquake activity but not for reliably anticipating the expected ground motion parameters.
8. Parametric tests at local scale are an indispensable task (especially after the damage of Onagawa nuclear power plant after the April 2011 aftershock, with M = 7.1 of the March 2011 M ~ 9.0 main Tohoku earthquake) in the seismic hazard analysis for critical structures in Egypt (Panza et al., 2012); this is a possibility naturally offered by NDSHA, practically at no additional cost.
9. Joint use of all available data from seismology, geodesy (e.g. GPS and INSAR) geophysics, paleoseismology, morphostructural analysis and tectonics is crucial in the identification and characterization of seismogenic zones where large, yet unobserved earthquakes may occur. Such information will significantly reduce the possible uncertainties about the seismic sources and thus, enhance the performance of seismic hazard maps in Egypt.
10. It is well recommended for the seismic hazard analysts to understand the needs of the potential users (e.g. public and engineers) to enhance the usefulness of their studies. Also, it's important to clearly explore, evaluate and communicate the uncertainties associated with the estimation of seismic hazard map to different users; this could help in deciding how much credence to place on the estimation itself. Moreover, the computed seismic hazard map must be tested against the available observations and macroseismic data before they can be accepted and then fruitfully adopted.
11. It is of crucial importance to assemble all the available seismic hazard controlling parameters with the seismicity (historical and instrumental earthquakes), faults spatial distribution, intensity levels, soil distribution and land-use maps, into an adequately powerful and efficient database (e.g. a Geographic Information System, GIS), that could allow for the adoption of advanced visualization techniques to facilitate decisions for both engineers and land use planners.

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