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Full length article

Demonstration of pb-PSHA with Ras-Elhekma earthquake, Egypt

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ABSTRACT

The main goal of this work is to: (1) argue for the importance of a physically-based probabilistic seismic hazard analysis (pb-PSHA) methodology and show examples to support the argument from recent events, (2) demonstrate the methodology with the ground motion simulations of May 28, 1998, Mw = 5.5 Ras-Elhekma earthquake, north Egypt. The boundaries for the possible rupture parameters that may have been identified prior to the 1998 Ras-Elhekma earthquake were estimated. A range of simulated ground-motions for the Ras-Elhekma earthquake was "predicted" for frequency 0.5–25 Hz at three sites, where the large earthquake was recorded, with average epicentral distances of 220 km. The best rupture model of the 1998 Ras-Elhekma earthquake was identified by calculated the goodness of fit between observed and synthesized records at sites FYM, HAG, and KOT. We used the best rupture scenario of the 1998 earthquake to synthesize the ground motions at interested sites where the main shock was not recorded. Based on the good fit of simulated and observed seismograms, we concluded that this methodology can provide realistic ground motion of an earthquake and highly recommended for engineering purposes in advance or foregoing large earthquakes at non record sites. We propose that there is a need for this methodology for good-representing the true hazard with reducing uncertainties.

1. Introduction

The goal of this study is to: (1) argue for the importance of a pb-PSHA and show examples to support the argument from recent events, (2) demonstrate the methodology with the ground motion simulation of May 28, 1998, Mw = 5.5 Ras-Elhekma earthquake, north Egypt using empirical Green's functions and compared to site specific calculations utilizing numerical modeling along with site specific response functions. Data for (2) is sparse, and at a significant distance from the 1998 earthquake, so it only serves to show that the computations are working properly, and do not provide a validation of near-source ground motion calculation. The Ras-Elhekma earthquake occurred in the off-shore of north Egypt (Fig. 1) at 250 km northwest of Alexandria City (AL, Fig. 1). The assigned maximum intensity was VII MM at Ras-Elhekma village (RA, Fig. 1), 50 km toward south of the epicenter, and V–VI MM at Alexandria City. ISC (International Seismological Center) reported that the event was felt as far as 450 km in Nicosia, Cyprus with intensity II-MM. It is one of the good recorded events along north offshore area of Egypt.

We applied the physically-based methodology proposed by Hutchings et al. (2007) to "predict" the ground motion for the Ras-Elhekma earthquake and develop a pb-PSHA. The basic elements of the methodology is to develop finite rupture models derived from physics and an understanding of the earthquake process, then synthesize a range of ground motions based upon the range of physical parameters. Ground motions were computed with the Green's function summation solution of the representation relation (Hutchings, 1994). The basic premises of the methodology: constrained the fault rupture characteristics based on a range of physical parameters, the possible fault-rupture scenarios range spans the earthquake process limits and effectively constrains the range of predictions, precise synthesis of ground motions for a particular scenario of fault rupture, uncertainty can be reduced by identify the specific parameters that contribute most to the epistemic variability in the ground-motion predictions,

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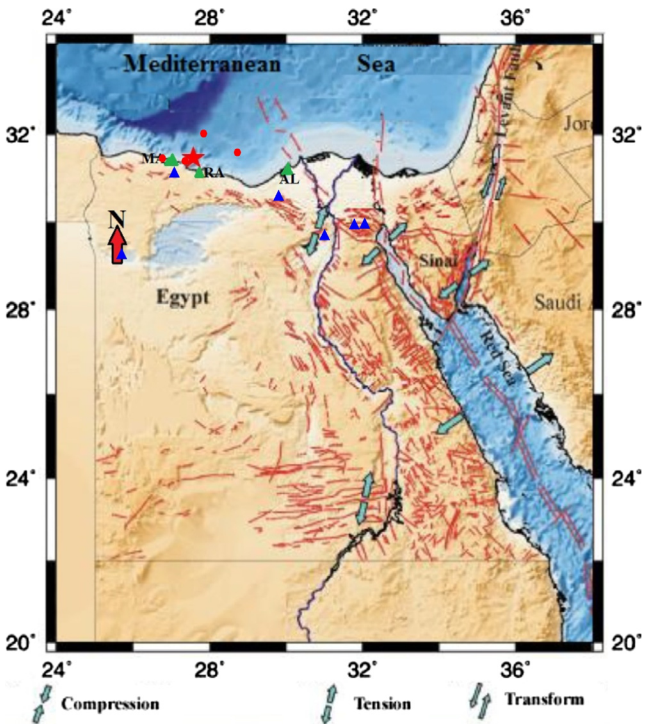

Fig. 1. Tectonic map of Egypt (after Abou Elenean, 2004). Red star is the Ras-Elhekma earthquake, red circles are small earthquakes used as empirical greens function, blue triangles are seismic stations.

and synthesized seismograms that match observed records are generated by rupture scenarios close to what actually occurred. These premises are discussed at length by Hutchings et al. (2007), Scognamiglio and Hutchings (2009). If the premises are valid, then this approach offers a new means to calculate hazard from future earthquakes. It has three basic advantages: (1) it is physically-based so that uncertainty can be reduced by research, (2) it can be applied to specific sites and regions, and (3) it provides full time series so that accurate risk can be assessed. Heuze et al. (1994) incorporate this methodology with nonlinear soils models.

We propose that there is a need for this methodology because current approaches based on simple empirical relations are inadequate due to: (1) too few empirical data, (2) miss-representing the true hazard, (3) lack of a means to reduce uncertainty, and (4) not providing adequate input for risk analysis.

2. Importance of pb-PSHA, problems with PSHA

The first goal of this work is to argue the importance of pb-PSHA in assessment earthquake hazard and risk analysis. Over fifty years past the state-of-the-practice for probabilistic seismic hazard analysis (PSHA) has been based upon estimating annual frequency of exceedance (or its reciprocal, return period) for a ground motion parameter at sites (i.e. a hazard curve, Cornell, 1968). Typically, the parameter is peak acceleration or spectral response. It requires (1) an interpretation of seismic sources that constitute a hazard to a particular site so that the distances of earthquakes from the site can be determined; (2) an interpretation of earthquake recurrence for each source; (3) models of ground-motion prediction in the form of empirical attenuation relationships; and (4) given these input evaluations, the PSHA method integrates over all values of the variables and produces a hazard curve. The hazard curve incorporates the uncertainties in elements (1), (2), and (3) above. This is discussed further in SSHAC (1997) and Papoulia et al. (2015). Risk to structures is then calculated by relating the level of the parameter estimated for annual frequency of exceedance to risk through empirical relations (Wang, 2006; Conte et al., 2003) or to select a time history to calculate the risk (Porter, 2003; Baker and Cornell, 2004). Pb-PSHA (as proposed here) has the same elements of standard PSHA and risk analysis, but replaces element (3) with calculations of physically-based synthetic seismograms, and risk analysis with directly calculating the risk to structures from these seismograms.

Bommer and Abrahamson (2006) and Strasser et al. (2009) shown that the empirical attenuation relations have uncertainty that has not been reduced over the past several years of adding empirical recordings to regression relations. Hutchings et al. (2007) pointed out that several issues with the PSHA approach, including the sparse data within 20 km of past earthquakes, the ergodic assumption, characterizing the scatter of observed ground motion parameters with log-normal distributions, and lack of source and site specific information, can be overcome with the pb-PSHA.

An example of what may contribute to the inability to reduce uncertainty in peak acceleration attenuation relations is born-out by data from the 2006 Mw = 6.0 Park field earthquake. Fig. 2 shows peak acceleration recorded from the earthquake. At distances less than 10 km, the values are random and vary by a factor of 10 (more if you include the one value at 2 g).

Fig. 2b shows why this may occur. The fault length is about 40 km and there is no way to know what location along the fault was the source of a recorded peak value, and it is probably different for each station. So, the idea of plotting a parameter as a function of distance from the fault probably only makes sense when the stations are far enough away from the fault that the area of the fault doesn't contribute much to the distance calculation. These are distances from the fault where strong ground motions are not generally an issue anyway.

An example that suggests that asperities along a fault may be the source of peak acceleration is shown in Fig. 3. The ground motion with the highest peak recorded at the Kashiwazaki-Kariwa Nuclear Power complex (K-KNPP) from the 2007 earthquake arrived 5 s after the initial arriving S-wave energy; possibly ground motion from a late occurring asperity some distance from the initial rupture of the earthquakes.

Another example of the randomness and variability in near source ground motion, and the likely inability of empirical relations to predict the motion, are response spectral values recorded from the 1999 Mw = 7.8 Chichi, Taiwan earthquake. Fig. 4a shows locations near the fault where response spectra were calculated. These are basically the same distance from the fault (shown in red). Fig. 4b shows the distribution of response spectra calculated. This shows a factor of about 4 variations, which is much better than the peak acceleration. This is likely due to using the entire seismogram rather than one value. So, response spectra may offer an approach to reduce uncertainty, but as discussed below, it still is not source or site specific and may be completely different from that of the actual hazard.

Of course, factors such as site conditions and fault type are contributing to the scatter in empirical relations. Fig. 5 shows peak accelerations from the Mw = 7.8 Chichi earthquake plotted as function of distance. At distance of 50–100 km the variability is almost a factor of 100. This is probably primarily due to propagation path and site response differences. This scatter is not significantly different that observed at near source distances for peak acceleration, suggesting that there are also many factors unaccounted for in the regression approach.

These previous examples are for individual earthquakes, referred to as intra-earthquake distributions. When different earthquakes are considered (inter-earthquake), then even greater

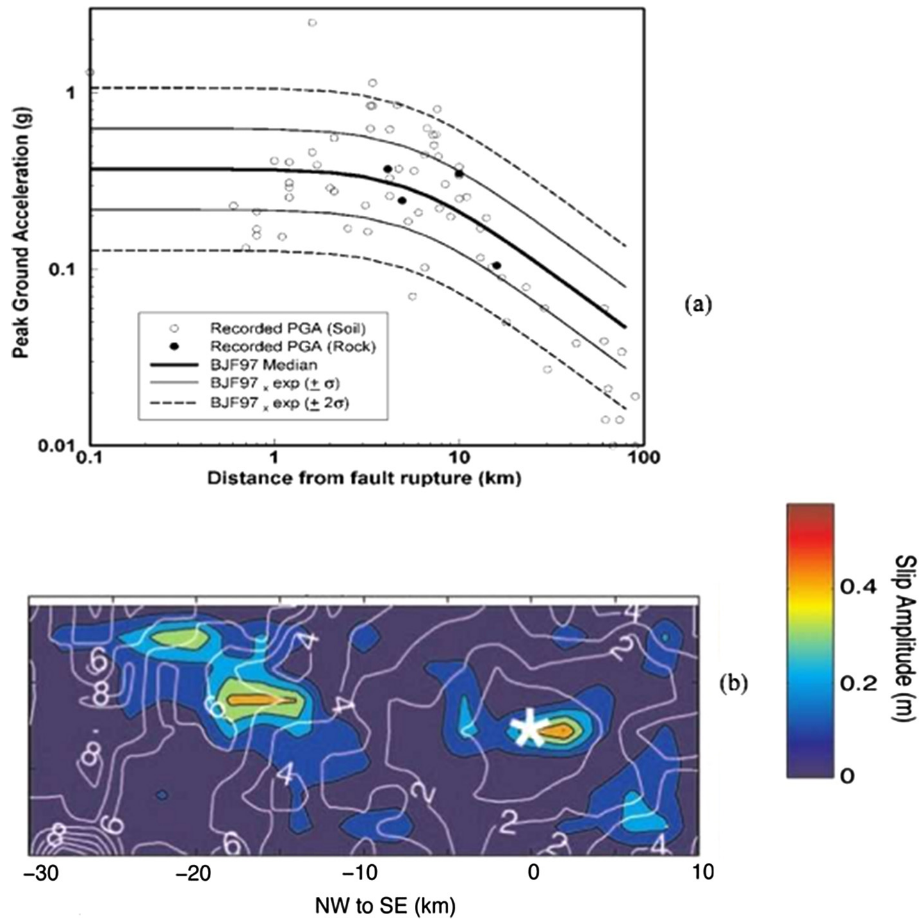

Fig. 2. (A) Plot of peak acceleration versus distance for the Mw = 6.0 earthquake form (Bommer and Abrahamson, 2006). (B) One interpretation of the fault rupture displacement, with hotter colors being higher displacement, and possible asperities (from Liu et al., 2006).

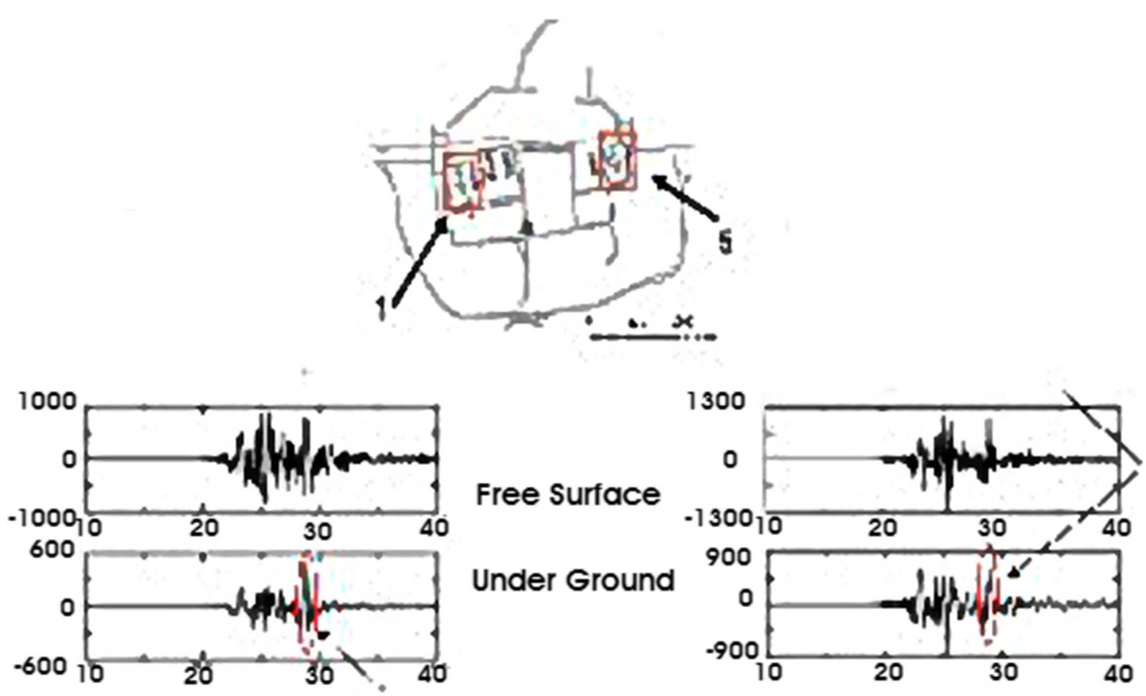

Fig. 3. (a) Ground motion at the K-KNPP complex from the 2007 earthquake (see Fig. 7 for reference).

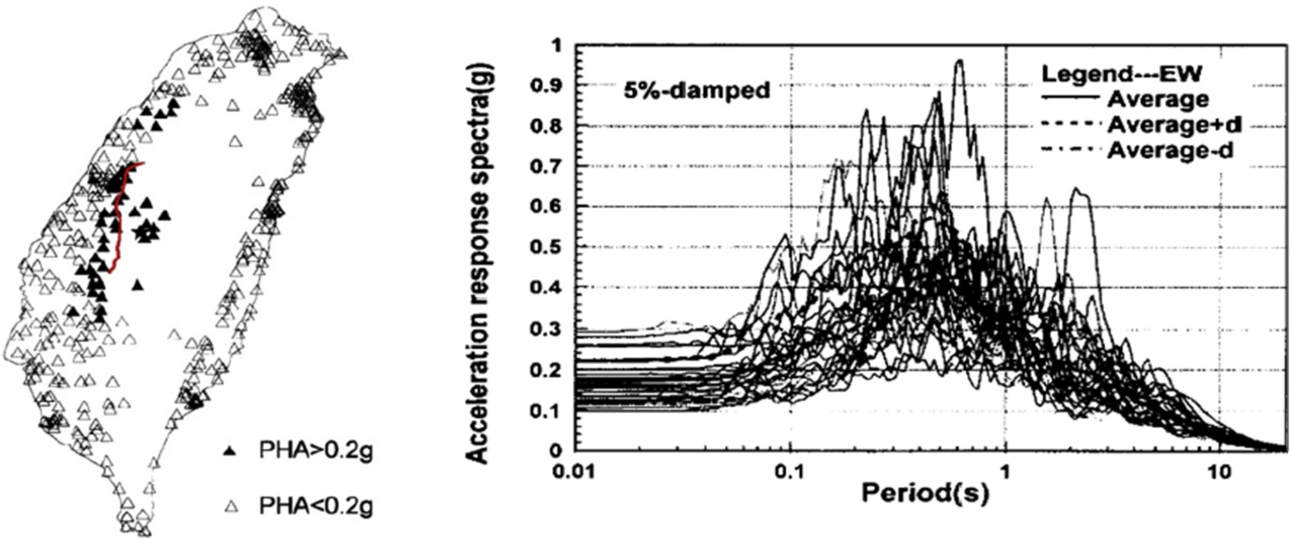

Fig. 4. Observation locations (triangles) near the fault (red line) at the left, where absolute acceleration response was calculated at the right, Guo-Quan et al. (2001).

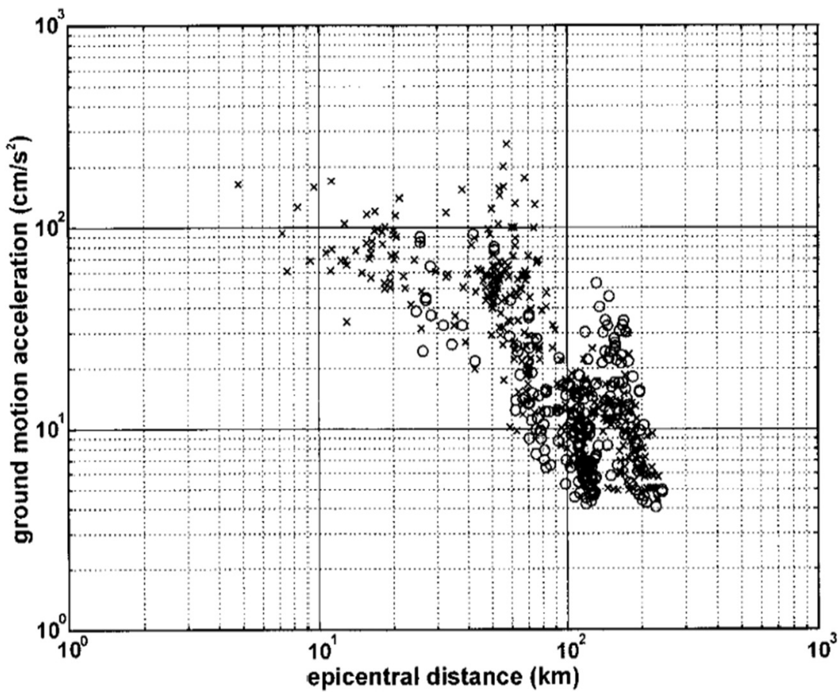

Fig. 5. Plots of peak acceleration versus distance for the Mw = 7.9 Chichi, Taiwan earthquake, Guo-Quan et al. (2001).

variability can be expected. To characterize ground motion using these results for an entirely different location (ergodic assumption) raises concerns about the validity of the hazard calculations. Strasser et al. (2009) summarize recent findings on inter- and intra-event, and inter- and intra-station variability, as well as the effect on soil non-linearity, in peak acceleration and response spectra. Generally, there is still not sufficient data to make definitive conclusions on the relative values of these parameters.

Another major concern in characterizing these random data for hazard calculation is to force it to be described as a log-normal distribution with mean zero and standard deviation. Hutchings et al. (2007) points out that such characterization have tails and, as such, have no limit to values being predicted from these relations. This is shown in Fig. 6. There have been recent attempts to truncate these distributions and this will help. However, the shape of the distributions is still unknown and this will cause errors in calculating the hazard. For example, examining peak acceleration from Fig. 2, it is quite apparent that these data in between 1 and 10 km is not represented by a log-normal distribution, but rather, possibly a bi-modal boxcar distribution.

To fully capture the uncertainties in hazard and risk analyses all elements within the overall framework have to account for uncertain and incomplete data, inexact models of the phenomena, and intrinsic variability in the physical system being modeled. Uncertainty can be aleatory, which is due to inherent randomness of the process that cannot be modeled; or epistemic, which is due to uncertainty in knowledge about the processes. Epistemic uncertainty can be reduced by research; aleatory uncertainty is inherent in the system or process and thus cannot be reduced. These epistemic uncertainties and aleatory variability are always present,

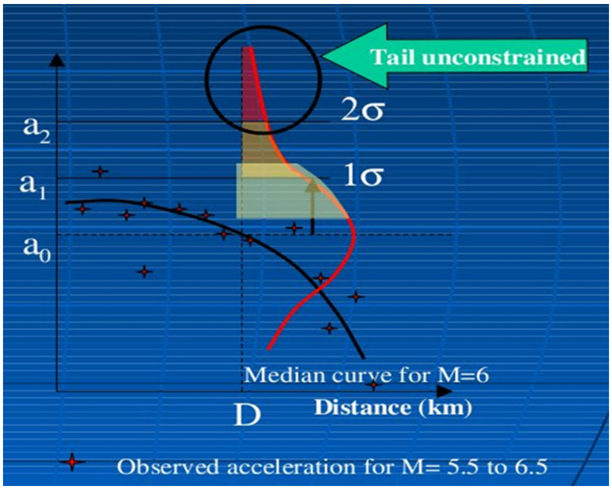

Fig. 6. A cartoon showing a normal distribution fit to data. The shape of the distribution is largely unconstrained by data primarily near the mean, and the tails have no limit to predicted values of the parameter.

and capturing them fully is one of the major challenges in hazard and risk analysis. Our premise is that a physically-based approach offers a means to reduce uncertainty because it is primarily based upon epistemic uncertainty, whereas the regression approach is primarily based upon aleatory uncertainty. In this study we attempt to: (1) properly account for uncertainty in a pb-PSHA, and (2) narrow the range of rupture parameters and, thus, the uncertainty in the prediction.

For risk assessment, the reverse of developing attenuation relationships is typically used. That is a peak acceleration (or response spectra) is identified, along with the controlling magnitude, distance, and geology, then the empirical strong motion data base is searched to find records that the desired parameters. These records may have very little in common with the actual ground motion that will occur at the site. And, the risk may be completely miss-calculated. Fig. 7 shows two records with the same peak acceleration used to calculate the dynamic response of a nine story building (McCallen and Astaneh-Asl, 2015). Also shown are the lateral forces for each floor for linear and non-linear response.

Both the linear and non-linear response is considerably different. The Landers earthquake caused catastrophic failure, whereas the non-linear response of the Turkey earthquake was not significantly different than the linear response.

One might consider the question as to why total uncertainty (aleatory and epistimic) has not be reduced in attenuation relations over the past 50 years (Strasser et al. (2009). Firstly, if you define epistimic uncertainty of the source as a lack of knowledge of the variables that effect the earthquake ground motion (source process, path effect and site effect), and aleatory variability as the range of unknown parameters that represent the complexity in the ground motion, then the answer for the above question is that the PSHA method depends on too simple of formulation.

An attenuation relation represented only by few parameters (magnitude, distance and Vs30 and sometimes faulting type) is not sufficient to account for the complicated processes which controlled by many parameters. For example representing the rise time, rupture velocity, roughens, asperities, source dimension, fault geometry and stress drop of an earthquake by one parameter (magnitude) is not sufficient to describe the process. Although any variation source parameters can cause a significant effect on the peak values, frequency content, and spectral shape. Similarly, the path and site effects are very complicated due to the high heterogeneity in the earth crust and surface geology, and cannot be modeled only by two parameters; R and Vs30. Since these factors are different for each location where earthquakes occur, and source process can be different for repeating earthquakes at the same location, it is not likely that there will be enough data to capture to processes sufficiently to predict the future. Hence, each new earthquake brings new data form different conditions and the uncertainties are not reduced. To reduce the aleatory uncertainties we should increase the number of known parameters that contribute to epistimic uncertainties and can be reduced with more knowledge.

2.1. Performance based design

One application of pb-PSHA is in performance based design (Porter, 2003). Determining cost-effective, accurate designs is hampered by inadequate understanding of earthquake ground motions, the complexity of soil structure interaction, and the difficulty of calculating fully realistic dynamic structural response. "Per formance-based-design" (PBD) attempts to meet these goals without extra "margins" to compensate for uncertainties. That is, the safety and integrity of structures are assured by calculating structural response to the predicted ground motion and designing to calculated hazard.

An example of the need for PBD is the effect at the Kashiwazaki-Kariwa Nuclear Power complex in Japan from 2007 with M = 6.8 at epicenter distance 23 km from the facility. The Chuetsu-oki earthquake generated ground motion exceeds the Nuclear design ground motion by up to a factor of 2–4 (Fig. 8). Tokyo Electric Power Company (2009) attributed partially the cause of the unexpectedly high ground motion to local geology, a higher stress drop earthquake than expected, and site conditions where PSHA did not

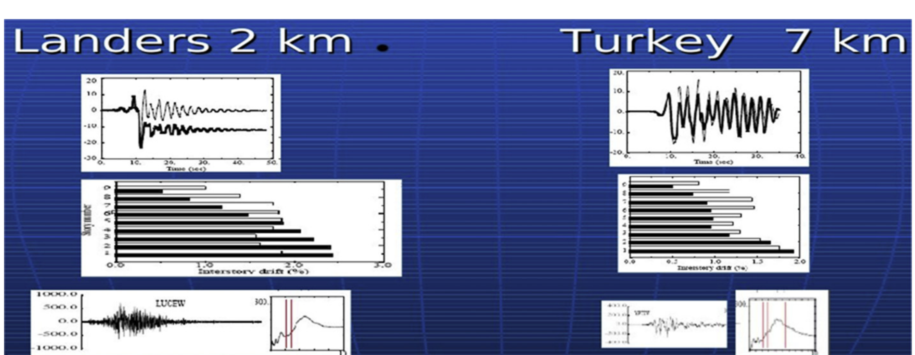

Fig. 7. Two earthquakes with similar magnitude distance and peak acceleration, but considerable different effect on the building. From McCallen and Astaneh-Asl (personal communication).

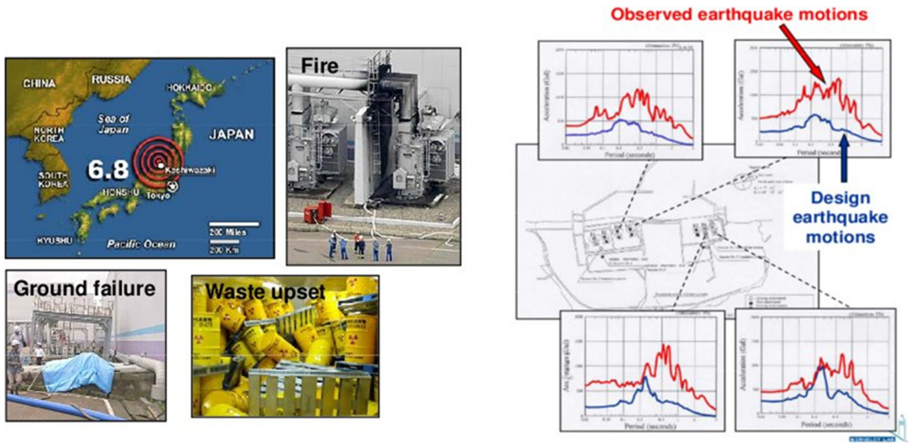

Fig. 8. (a) location of the earthquake and sit of the Kashiwazaki-Kariwa Nuclear Power complex, (B) absolute acceleration response curves for the design ground motion (blue) and observed ground motion (red), and (c) ground failure and damage to ancillary facilities.

account for any of these factors. However the pb-PSHA (with site specific Green's functions) accounted for all those factors. And the reactor would design for real expected ground motions.

2.2. Incorporating uncertainty into pb-PSHA

Both the PSHA and pb-PSHA generate a catalog of ground motions from all earthquakes that could occur over a period of time that is long enough to allow re-occurrence at all locations along all faults and source zones. These seismograms (pb-PSHA) or single parameter values (PSHA) are intended to include the full epistemic and aleatory uncertainty of the problem. In the case of pb-PSHA, this includes all rupture processes for all magnitudes, and for PSHA this includes all magnitudes and regression parameters such as distance, directivity, faulting type. The library of seismograms from pb-PSHA can be used to obtain single parameter values to develop hazard curves in the form of the annual probability of exceedance as for traditional PSHA or be directly applied in calculating building response for physically-based risk analysis (pb-RA).

For the Ras-Elhekma earthquake we synthesized a range of ground-motions for Mw = 5.5 earthquake along the fault that generated the 1998 earthquake. We calculated 50 scenario earthquakes to encompass all possible rupture processes that might have been anticipated prior to the occurrence of the earthquake, and along all portions of the fault that may have had a Mw = 5.5 earthquake. This captures the epistemic uncertainty of the problem. We also include aleatory uncertainty as outlined in Hutchings et al. (2007). This encompasses a "prediction" of ground motion for this fault and this magnitude earthquake. The premises stated above should apply to this prediction, and provide a validation test. We synthesized ground motions for the frequency range 0.5–25 Hz. The simulated records were compared with the observed records at three sites that recorded the earthquake. The best-fitting rupture models occur in the vicinity of 31.40°N, 27.69°W with a center of rupture near a 22.78 km depth and have nearly bilateral rupture, which is consistent with independent investigations.

3. Demonstration of pb-PSHA methodology with Ras-Elhekma earthquake

The second goal of this study is demonstrating the pb-PSHA methodology with the May 28, 1998, Mw = 5.5 Ras-Elhekma, North Egypt, earthquake using empirical Green's functions and compared to site specific calculations utilizing numerical modeling along with site specific response functions. The 1998 earthquake occurred at the north west of offshore of north Egypt at latitude 31.45°N and longitude 27.65°E along the African margin to the northwest of Alexandria City. Hassoup and Tealeb (2000) presented a description of the intensity distribution recognized by the Ras-Elhekma earthquake based on 280 MMI questionnaires and field observations. It caused a strong shaking in Cairo and most of the Nile Delta area. Cracks on buildings were observed in several places of Mersa-Matruh Province at the north south coast of Egypt.

3.1. Main shock data

Seven records of Ras-Elhekma earthquake were obtained around Cairo province, but no records were obtained from the north of Egypt. Three of these records were recorded by 3-component stations FYM, HAG and KOT (Table 1). Abou Elenean and Hussein (2007) describe the parameters of the main shock record in detail. Table 2 lists source parameters of the 1998 Ras-Elhekma earthquake reported by several institutions. Focal mechanism solutions show a high-angle reverse fault mechanism generally trending NNW–SSE.

3.2. Green's functions

In our methodology we apply the Green's function summation approach to calculating seismograms (Heaton, 1982; Hutchings, 1994). We utilize the compute code EMPSYN (Hutchings, 1994) in the calculation. It utilizes synthetic or empirical Green's functions. We use empirical Green's functions when available as they

Table 1
Station data available for this study.

Station	Location	Instrument	Dist. (km)	No. EGF	Main
BRG	30.57 29.84	3-comp, SP	227	0	No
FYM	29.692 31.043	3-comp, SP	381.84	5	Yes
HAG	29.95 32.093	3-comp, SP	459.54	4	Yes
KOT	29.93 31.829	3-comp, SP	437.34	4	Yes
MAT	31.094 27.096	3-comp, SP	63.27	4	No
SWA1	29.26 25.71	3-comp, broadband	680	2	No

Table 2
Source parameters for May 28, 1998 earthquake published by different institutions.

Author	Lat. (°)	Long. (°)	Fault plane			Mw	Mo × 1017 (N m)	H (km)
			Strike (°)	Dip (°)	Rake (°)			
A & H*	31.45	27.64	333	43	87	5.42	1.68	25
NEIC	31.40	27.66	320	51	65	5.51	2.1	34
HRVD	31.39	27.36	335	46	91	5.50	2.0	39
CSEM	31.40	27.67	328	43	70	5.60	2.9	28

* A & H: Abou Elenean and Hussein (2007).

incorporate the specific path and site effects for each station (Hutchings and Wu, 1990). Employing numerical Green's functions is recommended for modeling the low frequencies (<0.5–1.0 Hz), and can be merged with EGFs to obtain broadband Green's functions (Jarpe and Kasameyer, 1996). Here we also utilize synthetic Green's functions for high frequencies where EGFs are not available. We also use numerical modeling along with site specific response functions.

There are two main advantages of EGF approach. EGFs provide the exact elastodynamic Green's function for the real earth and the exact rigidity at the source. Limitations are that insufficient EGFs to cover all portions of a fault and with the same focal mechanism as the main event are necessary for exact waveform modeling. Hutchings and Wu (1990) and Hutchings (1991) address interpolation and errors in using insufficient EGFs.

All seismic stations of Egyptian National Seismic Network were in operation in 2003; four small earthquakes have been recorded from the same source area of the Ras-Elhekma earthquake (Table 1). Three of them were recorded at the same stations that recorded the main shock. We synthesize records at the stations shown in Table 1.

3.3. Source parameters of EGFs

For effectively impulsive point sources we used ***EGFs*** events with moments greater than the threshold identified by Hutchings and Wu (1990). To minimize significant finite source effects and keep the basic assumption of an impulsive point source EGF, we use the output of a source parameter study to deconvolve out the finite Brune source from the recordings (Hutchings et al., 2007). We used NetMoment of Simultaneous Inversion to estimate critical source parameters of Moment, Source Corner Frequency, and Site Specific attenuation (t^*) for the four small records that provided EGFs (Hutchings, 2002; Gok et al., 2009). Table 3 lists the calculated source parameters for the four small records.

3.4. Constrain the fault rupture model of 1998 earthquake

The boundaries of the possible rupture parameters that may have been identified prior to the 1998 Ras-Elhekma earthquake were identified based on the possible source volume of the earthquake. Rupture parameters are randomly varied by program HAZARD (Hutchings et al., 2007) to create scenario earthquakes as shown in Table 4.

3.5. Strong ground-motion prediction results

In this section we predict the range of ground motion that may occur from Ras-Elhekma earthquake 1998 along its fault or within the source zone. The program HazStats was used to predict the range of ground motions that might have been identified prior to the 1998 earthquake. We run 500 scenarios within the possible

Table 3
Source parameters of EGF's records.

Date	Time	Lat.	Long.	Dep.	Mw	Mo	Fo	t^*					
								FYM	HAG	KOT	SWA	BRG	MAT
1998 10/01	08:42:59.78	32	27.87	20	3.0	0.339E+21	10	0.0662	0.0211	0.0275	X	X	X
1999 09/04	23:23:00.48	31.57	28.75	5	3.1	0.495E+21	10.9	0.0574	0.0192	0.0191	X	X	X
2002 10/10	04:47:00.00	31.44	26.78	10	2.8	0.203E+21	5	X	X	X	0.0246	Noise	0.0058
2005 11/05	00:17:00.00	31.38	27.38	27.7	2.7	0.119E+21	4.3	Noise	Noise	X	0.0153	Noise	00.23

X is a symbol for missing record at this station.
Noise means the ratio of noise to signal is high.

Table 4
Fault rupture parameters of 1998 earthquake.

Parameter	Values range
Moment	$1.68 \cdot 10^{24}$–$2.9 \cdot 10^{24}$ dyne cm
Fault geometry	Fault shapes elliptical with fault area 21.99–69.11 km^2
Hypocenter	Scenario earthquake rupture areas fall between 0 and 25.0 km
Strike	The strike limit of possible rupture is being between 320° and 335°
Slip vector	An average of 0.63 for the S-wave as a correction factor
Dip	The dip was limited to range from 43.0° to 51.0°
Asperities num.	Are circular in shape and there number is randomly chosen to be between 0 and 7
Rise time	Varies at each point on the fault and is a dependent variable.
Rupture roughness	It is the percentage of elements at the rupture surface randomly selected to be 0%, 10%, 20%, 33%, or 50%
Rupture velocity	Vary from between 0.75 and 1.0 times the shear-wave velocity
Healing velocity	Randomly varied to be between 0.8 and 1.0 times the rupture
Slip distribution	Slip amplitude values are allowed to vary between 10 and 100 cm
Stress drop	Average 23.4 bars
Source volume	Between 31.10° and 31.70°N, 27.50° and 27.90°E, and 18 to 30.0 km depth

source volume of the 1998 earthquake. Properly fifty models were selected from the larger set of 500 scenarios to test our prediction hypothesis.

To capture the variability of ground motion we examined whether we ran enough scenarios using the mean of the absolute acceleration response at a 0.5-s period as a function of the number of scenarios run. After about 40 scenarios, the mean stabilizes, indicating that our 50 models span the full variability of ground motion possible from this approach.

Then we calculated the median (lognormal mean) plus one-standard-deviation values of linear ground motion at station sites of FYM, HAG, and KOT and compared these to the real recorded values. FYM, HAG, and KOT are the only local stations that recorded the main event and its aftershocks at distinctly different sites. Fig. 9 shows the Fourier amplitude spectra and the absolute acceleration response spectra (AAS) for the 50 scenarios at each site of FYM, HAG, and KOT.

3.6. The 1998 earthquake rupture model

To prove that the methodology is calibrated properly we determine the rupture scenario of Ras-Elhekma earthquake that offers the best fit to the observed seismograms.

The goodness of compatibility between the observed and synthesized records was calculated using Anderson (2003) method to recognize the best rupture models. Anderson suggested calculat-

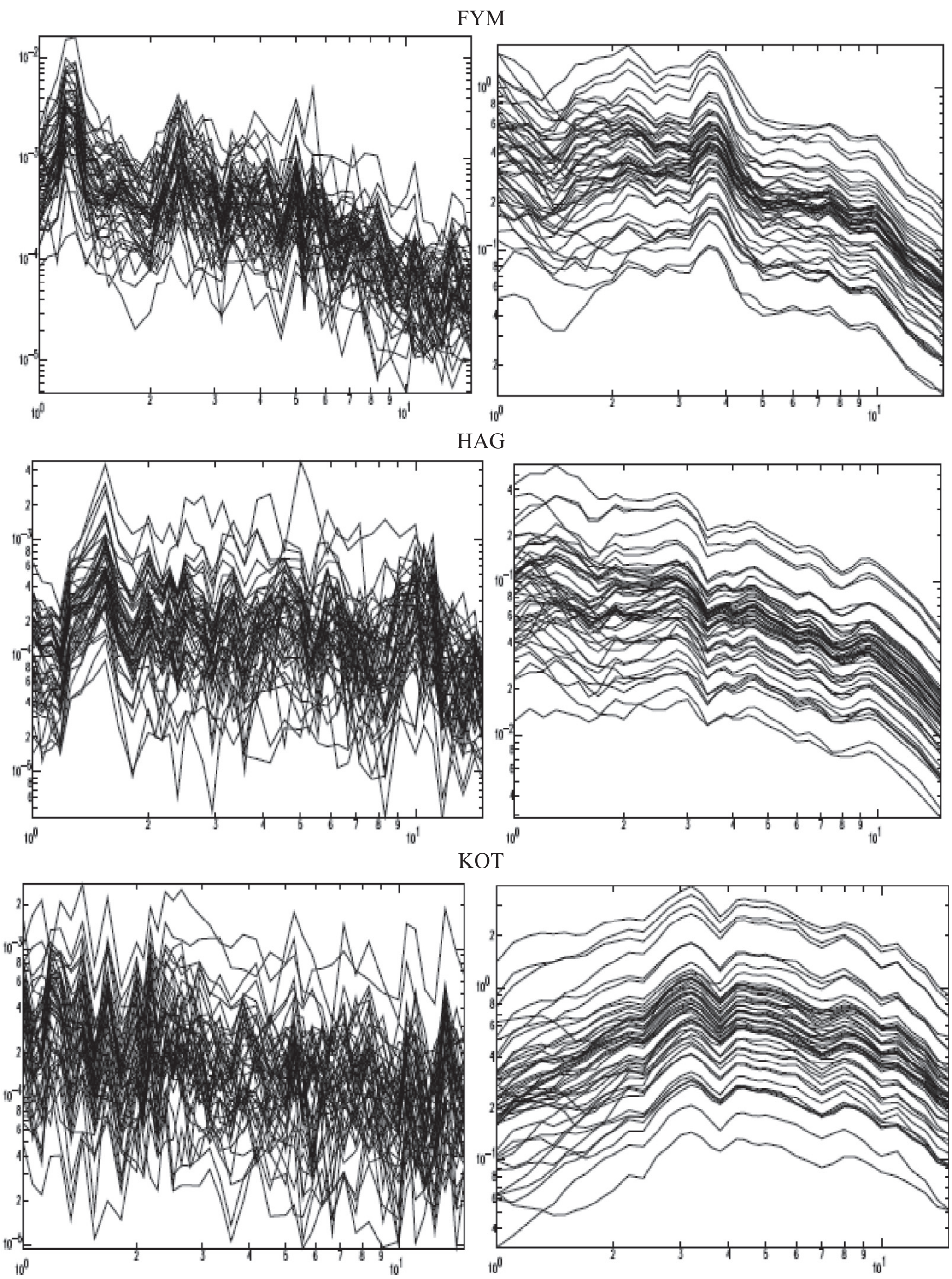

Fig. 9. Right, Fourier amplitude spectra (FFT) and Left, the absolute acceleration response spectra (AAS) for the 50 scenarios at each site of FYM, HAG, and KOT.

ing the fit of ten parameters named as: Arias duration, energy duration, Arias intensity, energy integral, peak acceleration, peak velocity, peak displacement, absolute acceleration response, Fourier spectra, and cross-correlation. Each estimate parameter is given a value of 0–10, so that the final score is between 0 and 100, with the latter being a perfect fit. Anderson finds that the scores of 40–60 represent a fair fit, 60–80 a good fit, and 80–100 an excellent fit. We averaged all estimates for goodness of fit over their values at frequency bands 1–2 Hz, 2–5 Hz, 5–10 Hz, 10–20 Hz, and 1–20 Hz as suggested by Anderson (personal communication, September 2005), except Fourier and absolute acceleration response, which are calculated for each at frequency band 1–20 Hz only and averaged. Program COMPARE was used for this calculation. We averaged the values obtained from three components of selected stations and further averaged the values obtained at all three sites, which gave us a final score that represents how well a rupture model generates the observed accelerograms. Values score for the 50 models ranged from 20 to 53.

One model had the best rating (model M164, with ratings of 53) of fits to observed seismograms. Fig. 10 shows, in general, the shape of the spectra and character of the time series match well at each station, there is some misfit over short frequency intervals. However, the choice of a "match" is based upon the "score" from the Anderson comparison method of ten parameters over five frequency bands. Also, notice that the spectral shapes and character of the seismograms are considerably different at each site. The site-specific character of these factors is controlled by the EGFs and the geometric relationship to the source rupture.

The parameters of the best rupture model of the 1998 earthquake were estimated as follow: it occurred in 31.40°N, 27.69°W, center of rupture ~22.78 km depth and nearly bilateral rupture, Strike N326.7°E, dips ~43.7°, rupture velocity Vr 0.85Vs, and healing velocity 0.86Vr. The fit to seismograms indicates that this methodology can provide realistic ground motion in advance of an earthquake for engineering purposes.

To synthesized ground motion time series of the main earthquake in areas where it was not recorded; the rupture scenario M164 was used and modeled accelerograms at stations BRG, MAT and SWA1 stations. Fig. 11 shows the synthesized seismograms at those 3 seismic stations. In general, station MAT had accelerations up to the 60 gal; stations BRG and SWA had small accelerations 25 and 17 gal respectively.

4. Discussion and conclusions

In this study, we argued the importance of pb-PSHA methodology (Hutchings et al., 1997) using examples from recent events to support the argument. The main goal of the method is using the physical parameters that can be bounded by research to predict a range of ground-motion hazard for a specific earthquake magnitude within a specific source volume or along a specific fault to reduce the uncertainty of the calculated hazard. However the current methods for hazard calculations based on empirically derived parameters that are characterized by probability distributions. Bommer and Abrahamson (2006) shown that the uncertainty in the empirical attenuation relations has not been reduced over long time of adding empirical recordings to regression relations. Hutchings et al. (2007), Papoulia et al. (2015) and previous section of this study pointed out several issues with the PSHA approach that can be overcome with the pb-PSHA. These issues are including the sparse data within 20 km of past earthquakes, the ergodic hypothesis, typifying the scatter of observed ground motion parameters with log-normal distributions, and lack of source and site specific information. An example of what may contribute to the inability to reduce uncertainty in peak acceleration attenuation relations is born-out by data from the 2006 Mw = 6.0 Park field earthquake. At distances less than 10 km, the peak acceleration values are random and vary by a factor of 10 (more if you include the one value at 2 g). The fault length is about 40 km and there is no way to know what location along the fault was the source of a recorded peak value, and it is probably different for each station. So, the idea of plotting a parameter as a function of distance from the fault probably only makes sense when the stations are far enough away from the fault that the area of the fault doesn't contribute much to the distance calculation. These are distances from the fault where strong ground motions are not generally an issue anyway. Another example of the randomness and variability in near source ground motion, and the likely inability of empirical relations to predict the motion, are response spectral values recorded from the 1999 Mw = 7.8 Chichi, Taiwan earthquake. Of

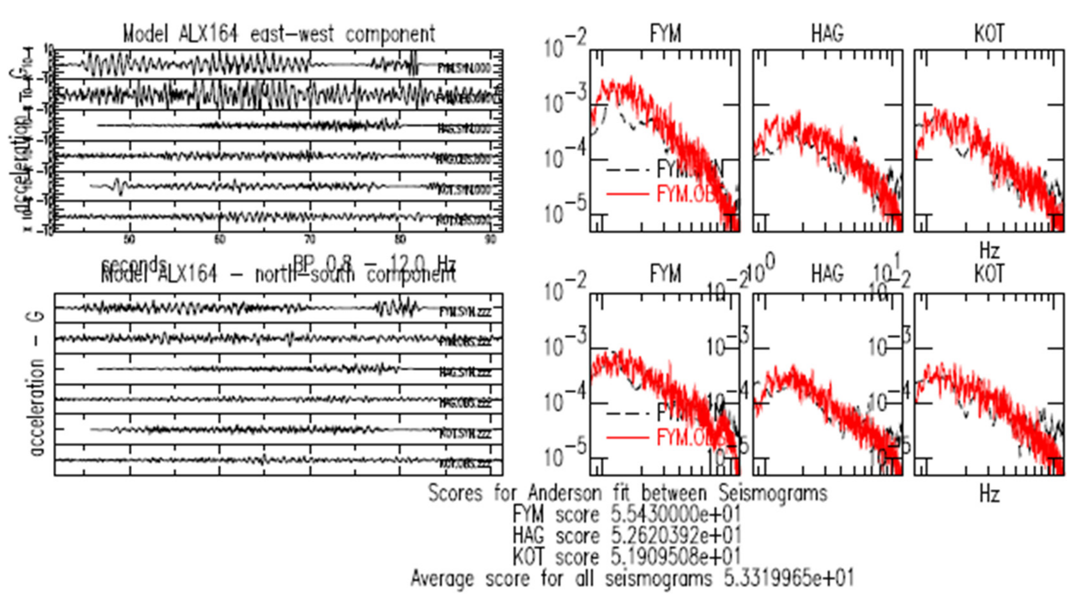

Fig. 10. Right, comparison of the synthetic and observed Acceleration time series for E and N components of each FYM, HAG and KOT respectively. Left, comparison synthetic (black broken line) and observed (red line) spectra of E-component (up) and N-component (down) for FYM, HAG and KOT stations. Lower, the score fit for each station.

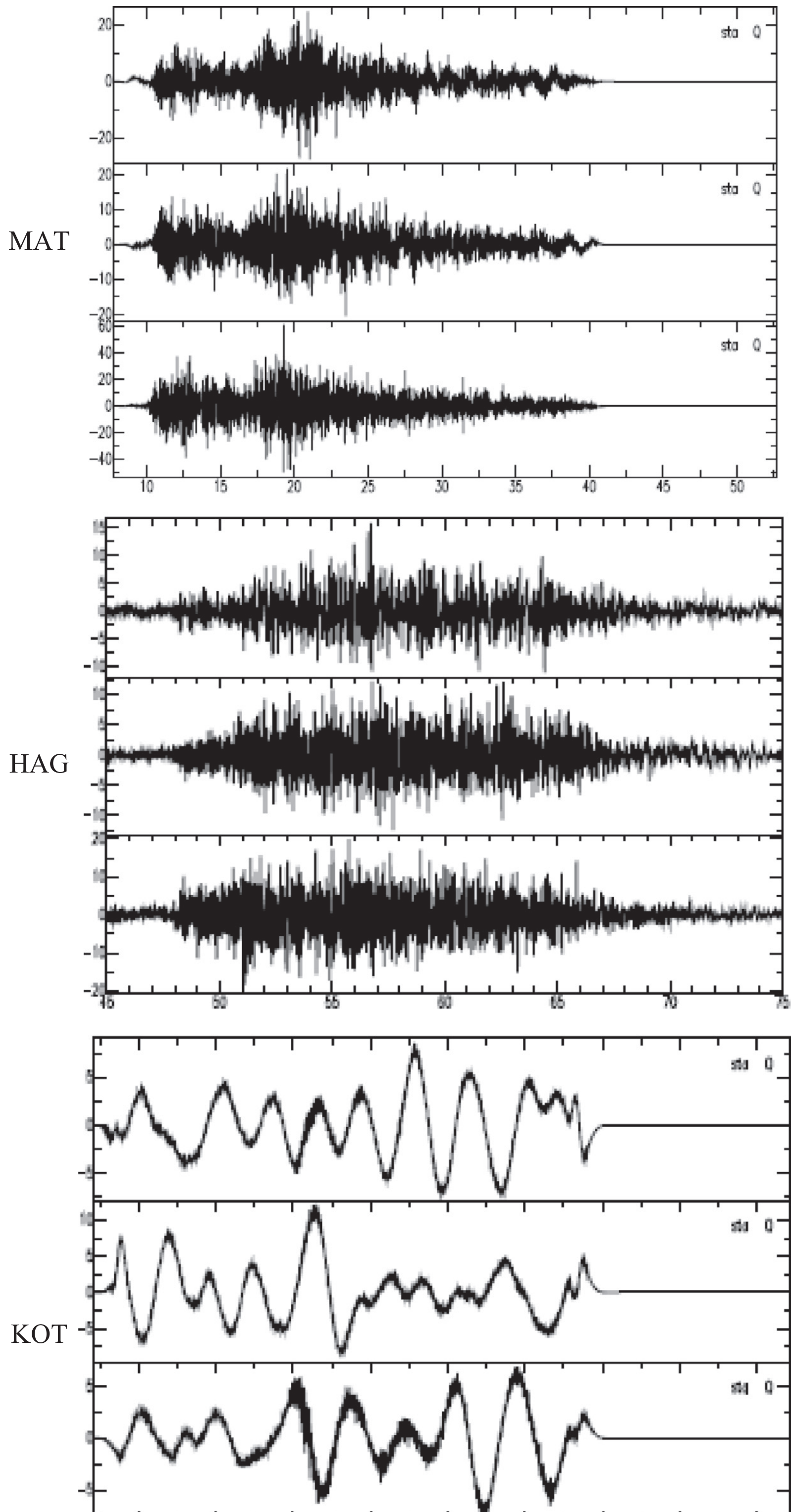

Fig. 11. Synthesized 3-components seismograms at MAT, BRG and SWA1 stations.

course, factors such as site conditions and fault type are contributing to the scatter in empirical relations.

Another major concern in characterizing these random data for hazard calculation is to force it to be described as a log-normal distribution with mean zero and standard deviation. Hutchings et al. (2007) points out those characterizations have tails and, as such, have no limit to values being predicted from these relations. However, the shape of the distributions is still unknown and this will cause errors in calculating the hazard.

To fully capture the uncertainties in hazard and risk analyses all elements within the overall framework have to account for uncertain and incomplete data, inexact models of the phenomena, and intrinsic variability in the physical system being modeled. Uncertainty can be aleatory, which is due to inherent randomness of the process that cannot be modeled; or epistemic, which is due to uncertainty in knowledge about the processes. Epistemic uncertainty can be reduced by research however aleatory uncertainty is inherent in the system or process and thus cannot be reduced. These epistemic uncertainties and aleatory variabilities are always present, and capturing them fully is one of the main challenges in the earthquake hazard and risk analysis.

Both the PSHA and pb-PSHA generate a ground motion catalog of all earthquakes could occur over a long enough period of time to allow re-occurrence at all locations along all faults and source zones. These seismograms (pb-PSHA) or single parameter values (PSHA) are intended to include the full epistemic and aleatory uncertainty of the problem. Using more knowledge about fault process, the physically-based approach offers a means to reduce uncertainty because it is primarily based upon epistemic uncertainty, whereas the regression approach is primarily based upon aleatory uncertainty.

We demonstrate the pb-PSHA methodology with the ground motion simulation of May 28, 1998, Mw = 5.5 Ras-Elhekma earthquake, north Egypt. The boundaries for the possible rupture parameters that may have been identified prior to the 1998 Ras-Elhekma earthquake were estimated. Rupture parameters are randomly varied by program HAZARD (Hutchings et al., 2007) to create 500 scenarios. Fifty models (Fig. 9) from the larger set of 500 scenarios were used to test our prediction hypothesis within the possible source volume for the 1998 event.

We identify the best rupture models based on the goodness of fit between recorded and simulated seismograms at sites FYM, HAG, and KOT (Fig. 10) using Anderson (2003) method. The best model occurred in the vicinity of 31.40°N, 27.69°W, with the center of rupture 22.78 km depth and nearly bilateral rupture. Strike N326.7°E, dips ranged 43.7°, rupture velocity 0.85Vs, and healing velocity 0.86Vr. We used the best rupture scenario of the 1998 earthquake to synthesize the ground motions at interested sites where the main shock was not recorded, and modeled accelerograms at stations BRG, MAT and SWA1 stations (Fig. 11). The site-specific character is taken in consideration by the Empirical Green's Function and the geometric relationship to the source rupture. The EGFs were provided by deconvolved out the finite source effects of the aftershocks (M_w < 4.0) that are larger than the criteria for having impulsive point sources to generate impulsive point source EGFs.

Based on the good fit of simulated and observed seismograms, we concluded that this methodology can provide realistic ground motion of an earthquake and highly recommended for engineering purposes in advance or foregoing large earthquakes. We propose that there is a need for this methodology for good-representing the true hazard with reducing uncertainties.

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