28 May 2010, 2:00 pm - 3:30 pm

An alternative Method for Probabilistic Seismic-Hazard Assessment: A Case Study of Three Cities

Hing-Ho Tsang
University of Hong Kong, Hong Kong

Saman Yaghmaei-Sabegh
University of Tabriz, Iran

P. Anbazhagan
Indian Institute of Science, India

M. Neaz Sheikh
University of Wollongong, Australia

T. G. Sitharam
Indian Institute of Science, India

See next page for additional authors

Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

AN ALTERNATIVE METHOD FOR PROBABILISTIC SEISMIC-HAZARD ASSESSMENT: A CASE STUDY OF THREE CITIES

Hing-Ho Tsang[1],
[1] University of Hong Kong, Hong Kong

Saman Yaghmaei-Sabegh[2], P. Anbazhagan[3], M. Neaz Sheikh[4], T. G. Sitharam[3], J. S. Vinod[4]
[2] University of Tabriz, Tabriz, Iran
[3] Indian Institute of Science, Bangalore, India
[4] University of Wollongong, Wollongong, Australia

ABSTRACT

The conventional source-based method of probabilistic seismic-hazard assessment is considered difficult to conduct for regions lacking adequate information on the source characteristics, or with a paucity of recorded strong ground motion data. Meanwhile, the historic method is unreliable in estimating the hazard at low probability. This paper proposes a midway approach, derived from the source-based method, yet does not require the characterization of seismic sources. While the method possesses the simplicity of the historic method, it is extended to account for large events that have not been observed historically, in order to improve the reliability of hazard calculation at low probability. Moreover, any site-specific and event-specific characteristics that influence ground motions, such as site effects, and directivity can be incorporated in the early stage of the numerical procedure, which is considered beneficial for microzonation study. This paper demonstrates the application of this method for three cities in China, Iran, and India respectively, in comparison with previous results computed by source-based method.

REVIEW OF EXISTING PSHA METHODS

Cornell (1968)

The most commonly employed approach for probabilistic seismic-hazard assessment (*PSHA*) is that developed originally by Cornell (1968). This approach incorporates the influence of all potential sources of earthquakes and their corresponding activity rates. The concept of a potential source of earthquakes plays a very important role in this methodology. A potential source of earthquakes, which can be in the form of a point, a fault, or area, is a location where future earthquakes may occur. To describe a potential source of earthquakes, one must decide its form, size, boundary, and the activity rates of earthquakes of different magnitudes. Hence, this method is fundamentally a *source-based* approach. As this approach is considered difficult to conduct for regions lacking adequate information on the source characteristics, or with a paucity of recorded strong motion data, various alternative procedures have been developed.

McGuire (1993)

McGuire (1993) has proposed a so-called *historic* method, which is based on historical earthquake events and does not involve characterization of sources. The major assumption of this method is that future seismicity at a particular site can be statistically represented by its seismic history. For each historical earthquake, the probability distribution of ground motion is estimated. By summing up the distribution functions of all historical earthquakes, followed by dividing the whole function by the number of years of the historical catalog, the annual rates at which different levels of ground motion are exceeded can be obtained. However, the major disadvantage of the historical method is its unreliability at low probability, especially for low-seismicity regions.

Frankel (1995)

Frankel (1995) has developed a method for the United States national seismic-hazard mapping program that eliminated the need to characterize seismic sources as well. For regions far from identified active faults, the probabilistic amplitude calculation was based on smoothed historical seismicity. The uncertainties associated with the historical catalog, such as the location error, could be reduced by smoothing the historical seismicity spatially to different length scales. However, the choice of the correlation distance *c* assumed for the Gaussian function in the smoothing process is highly subjective, and yet to be justified. The spatially-smoothed historical seismicity could be spread out if the assumed correlation distance *c* is too large, which could undoubtedly affect the precision of the hazard calculation, especially at site-specific level.

Tsang and Chandler (2006)

This paper presents a midway approach, namely, *direct amplitude-based* (DAB) approach (Tsang and Chandler, 2006), derived from the source-based method, yet does not require the characterization of seismic sources. While the method possesses the simplicity of the historic method, it is extended to account for large events that have not been observed historically, in order to improve the reliability of hazard calculation at low probability. Moreover, any site-specific and event-specific characteristics that influence ground motions, such as non-linear site effects, and directivity can be incorporated in the early stage of the numerical procedure, which is considered beneficial for microzonation study. A generic analytical (closed-form) solution has been derived to avoid a lengthy integration process. Detailed description of DAB approach has been given in the following section. Using the proposed DAB approach, seismic-hazard assessment for three cities in China, Iran, and India, respectively, has been carried out (Sections 3-5).

DIRECT AMPLITUDE-BASED (DAB) APPROACH

Analytical Framework

The source-based approach can be analytically represented by Equation (1) (Cornell, 1968; Reiter, 1990). The effects of all earthquakes of different sizes, occurring at different locations within different earthquake sources and having various probabilities of occurrence are integrated into a single seismic-hazard curve that shows the probabilities of exceeding different levels of ground shaking at the site during a specified period of time, as follows:

$$P[Z>z]=\sum_{i=1}^{N_s}\upsilon_i\int_{M=M_0}^{M=M_u}\int_{R=0}^{R=\infty} P[Z>z\,|\,M,R]\,f_i(M)\,f_i(R)\,dRdM \qquad (1)$$

where $P[Z>z]$ is the probability of ground shaking level Z exceeding z; υ_i is the mean rate of occurrence of earthquakes between threshold and maximum magnitudes (M_0 and M_u) being considered in the i-th source; $P[Z>z\,|\,M,R]$ is the probability that the ground shaking level Z of a given earthquake with magnitude M and source-site (or epicentral) distance R will exceed z; $f_i(M)$ is the probability density function (*PDF*) of magnitude within the i-th source; $f_i(R)$ is the *PDF* of source-site (or epicentral) distance, describing the spatial distribution between the various locations within the i-th source; and N_s is the number of sources being considered.

The alternative method, *direct amplitude-based* (DAB) approach, was developed based on the analytical framework of the source-based approach, using the idea of considering an infinite number of sources, *i.e.* $N_s\to\infty$ in Equation (1). In effect, every finite point can be considered as a "source," assuming that there is no repetition of earthquake occurrence at any individual point. The DAB approach can be analytically represented by Equation (2) and details of the derivation process can be found in Tsang and Chandler (2006).

$$P[Z>z]=N(\Delta_{\min})\int_{\Delta_{\min}}^{\Delta_{\max}}P[Z>z\,|\,\Delta]\,f(\Delta)\,d\Delta \qquad (2)$$

where $f(\Delta)$ is the *PDF* of the ground motion or spectral response amplitude, which can be obtained by differentiating the cumulative distribution function (*CDF*), derived from the amplitude-recurrence relationship. Details of the amplitude-recurrence relationship are given in the following section. $\Delta_{\min}$ and $\Delta_{\max}$ are minimum and maximum median ground motion or spectral response amplitudes, respectively, and $N(\Delta_{\min})$ is the mean rate of the amplitude (Δ) exceeding the minimum value ($\Delta_{\min}$). The rationale of maximum median amplitude $\Delta_{\max}$ will be discussed in the following section as well.

The steps involved in this approach are shown in Fig. 1. It can be seen that there is no need to characterize seismic sources, because all events that significantly affect the site are included in the analysis, without considering the spatial distribution of seismicity.

Amplitude-Recurrence Relationship

In the source-based approach, developing a magnitude-recurrence relationship, also known as the Gutenberg-Richter relationship, is the pre-requisite, as its derivative is the *PDF* of magnitude $f_i(M)$ in Equation (1). In the DAB approach, a similar recurrence relationship has been proposed by using the ground-motion or spectral response amplitude Δ_j as the subject parameter. Such recurrence relationship is similar to the amplitude-recurrence method developed by Milne and Davenport (1969), which was based on counting the annual number of exceedances of a specified acceleration at a site.

However, it is likely that the earthquake catalogs used are complete for different periods at different magnitude or intensity levels, which is an important issue that has not been explicitly considered in the historic method. Hence, ground-motion amplitudes of all historical earthquakes in each catalog (of certain magnitude range and period of time) can be computed (refer Step 2 in Fig. 1), followed by normalizing the amplitude recurrence rates of each catalog to the same period of time (e.g., one year). Then, a single amplitude-recurrence relationship could be obtained by summing up the normalized recurrence rates from all catalogs (refer Step 3 in Fig. 1).

It has been proposed that a doubly truncated exponential recurrence relationship for the logarithm of the median amplitude ($\log_{10}\Delta$) should be employed, with the consideration of maximum (Δ_{max}) and minimum values (Δ_{min}). The maximum value (Δ_{max}) can be used to account for a large event that has not been observed historically. Determining this maximum median amplitude (Δ_{max}) would be similar to performing deterministic seismic-hazard assessment. This is also similar to the definition of the maximum magnitude for each source in the source-based approach and the concept of characteristic earthquake in Frankel's smoothed seismicity approach. Hence, the full range of possible earthquakes that could generate strong ground shaking at the site can be captured. This can then improve the reliability of the historical method at low probability. Nevertheless, any suitable form of recurrence relationship can be chosen, depending on the data collected, while no restriction has been imposed herein.

For the doubly truncated exponential recurrence relationship for the logarithm of the ground motion or spectral response amplitude, the number of events leading to the amplitude Δ exceeding certain value is

$$N(\Delta)=N(\Delta_{\min})\left(\frac{\Delta^{-b}-\Delta_{\max}^{-b}}{\Delta_{\min}^{-b}-\Delta_{\max}^{-b}}\right) \tag{3}$$

from which the *CDF* of the ground motion or spectral response amplitude can be expressed as

$$F(\Delta)=\frac{\Delta_{\min}^{-b}-\Delta^{-b}}{\Delta_{\min}^{-b}-\Delta_{\max}^{-b}} \tag{4}$$

Further, the *PDF* can be obtained by differentiating the *CDF* with respect to Δ.

$$f(\Delta)=\frac{b\Delta^{-(b+1)}}{\Delta_{\min}^{-b}-\Delta_{\max}^{-b}} \tag{5}$$

For the *b*–parameter, maximum likelihood estimation has been adopted. The *b*–parameter for each amplitude-recurrence relationship may be obtained from

$$b=\frac{\bar{\Delta}}{\bar{\Delta}-\Delta_{\min}} \tag{6}$$

where $\bar{\Delta}$ is the mean or the expected value of Δ.

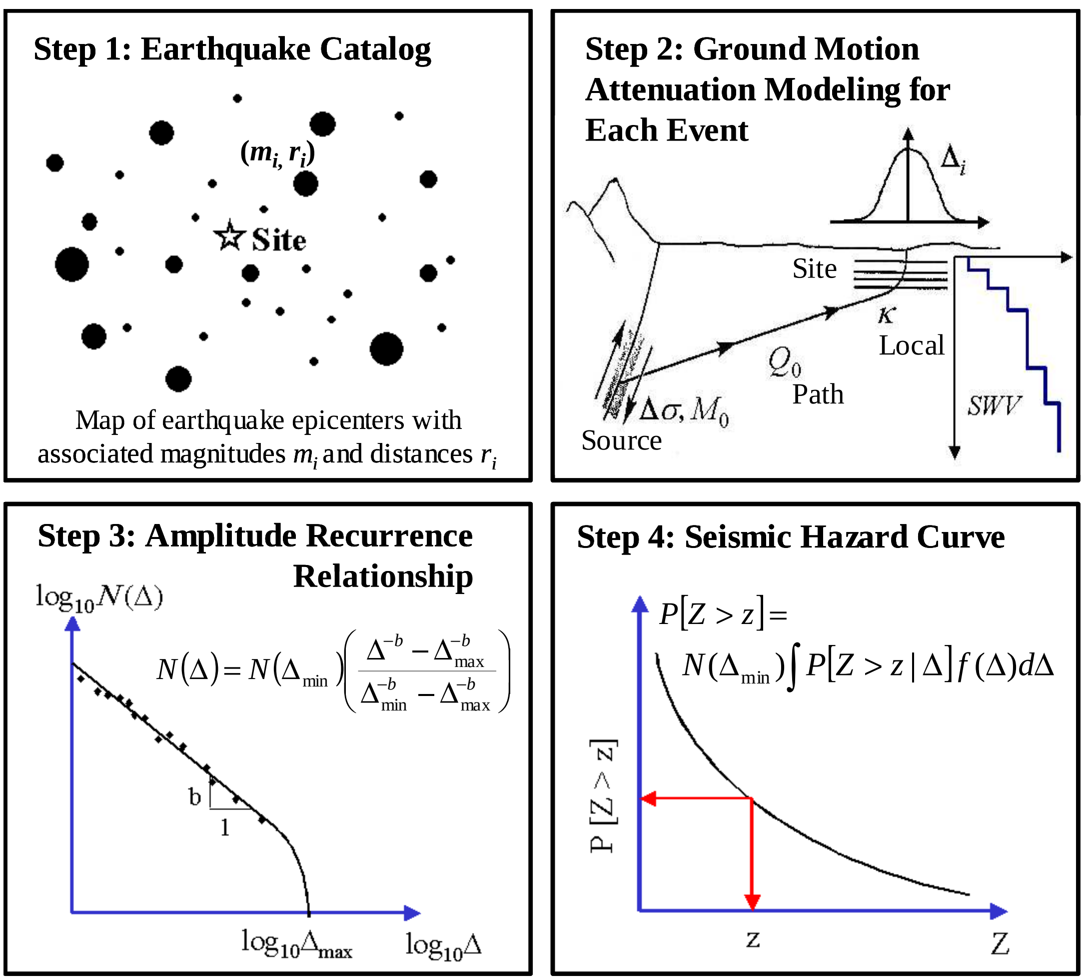

Fig. 1. Steps involved in the direct amplitude-based (DAB) approach of PSHA (Tsang and Chandler, 2006).

Analytical (Closed-Form) Solution

The source-based approach, as shown in Equation (1), is basically an integration process, with respect to two main variables, namely magnitude and distance, which normally requires lengthy computation and is carried out by means of computer programs. However, limitations on the uses of the attenuation relationships and the choices of geographic source types may exist in the available computer programs, which may not be able to cover some complex cases. Ordaz (2004) has provided closed-form solutions to avoid lengthy computations. Owing to the same limitations, closed-form solutions can only be provided for some simple cases that have mainly been used to check the accuracy of the computer programs.

In this section, a generic analytical solution has been derived for the DAB approach. As there is no specification of seismic sources, and also, the ground motion amplitudes are computed before performing the integration, the integration process would be free from the aforementioned limitations, which can give the closed-form solution its generic nature.

Moreover, for the source-based method to consider non-linear site effects (e.g. Tsai, 2000; Cramer, 2003), the integration has to be performed with respect to one additional variable, the bedrock ground motion, which would further increase the number of integration steps, and hence computation effort. However, in the proposed DAB approach, any event-specific and site-specific effect, including non-linear site response, can be incorporated at an earlier stage of the numerical procedures. Hence, the generic analytical solution proposed herein can still be applied, without any modification. This forms a significant additional advantage of the DAB approach, with its generic closed-form solution as shown as follows.

$$P[Z > z] = \frac{\eta}{z^b}\left\{\exp\left(\frac{m^2}{2}\right)\left[D(u+m)-\frac{1}{2}\right] - \exp(-mu)D(u)\right\}_{\Delta_{\min}}^{\Delta_{\max}} \qquad (7)$$

where $D(u)$ is the *CDF*,

$$u = \frac{1}{\sigma}\log\frac{\Delta}{z} \quad , \quad m = \frac{b\sigma}{\log e} \quad \text{and} \quad \eta = \frac{N(\Delta_{\min})}{{\Delta_{\min}}^{-b} - {\Delta_{\max}}^{-b}}$$

The credibility of the DAB approach has already been demonstrated in Tsang and Chandler (2006), in which peak ground velocity (PGV) has been adopted as the “amplitude”.

CASE STUDY: HONG KONG, CHINA

Hong Kong is situated in southeast China near the south-eastern margin of the Eurasian Continental Plate in a stable continental intraplate region about 700 km from the nearest plate boundary, which underlies Taiwan and trends south to the Philippines and northeast to Japan. Although Hong Kong is located in a region of low-to-moderate seismicity, the possibility of a major earthquake in or near the territory cannot be ruled out. The area of Dangan Islands, 30 km southeast of Hong Kong, was identified by the China Earthquake Administration as a potential source of earthquakes of up to moment magnitude of 7.5 (Chau *et al.*, 2004). However, seismic design has yet to be specifically required in the current building design codes in Hong Kong.

Stochastic simulations of the seismological model, with the consideration of site-specific and event-specific characteristics, were performed for each historical event surrounding Hong Kong. The limit of maximum source-site distance of the earthquake database was decided by considering the seismicity pattern of the region surrounding Hong Kong. Seismic activity rates are significantly higher at distances exceeding 600 km from Hong Kong, where large magnitude earthquake events ($M > 7$) have occurred more frequently. As the ground motion of an event with $M = 7.5$ and $R = 1000$ km is comparable to that of an event with $M = 6$ and $R = 350$ km, the limit for the maximum source-site distance of earthquake events collected has been set as 1500 km in this study. Also, the minimum magnitudes are taken as $M = 3.5$ and $M = 6$, for $R < 500$ km and $R > 500$ km, respectively. The regional average crustal conditions have been employed, with details of the input parameters contained in Chandler *et al.* (2005a; 2005b; 2006a; 2006b). On the other hand, to capture the range of possible large earthquakes, three independent studies have been employed (Chandler and Lam, 2002; OAP/BD, 2004; Chau *et al.*, 2004) in defining the maximum median (PGV) amplitude. The results based on the three scenarios have been equally weighted by a logic-tree approach to capture the epistemic uncertainty.

After obtaining the PGV-recurrence relation by Equation (3), the analytical solution (Equation (7)) has been employed to compute the probabilities of exceeding different levels of PGV, and hence form a seismic-hazard curve. The standard deviation $\sigma_{\log(\text{PGV})}$ employed in this study is 0.3, which is on a higher side of the typical range of values collected globally by Douglas (2003). Also, this value is consistent with the combined aleatory and epistemic standard deviation derived in Campbell (2003) for the hybrid empirical attenuation relations in eastern North America, which has also employed a seismological modeling approach.

Figure 2 shows the seismic-hazard curves computed separately for the three proposals of maximum median amplitudes. The return period is plotted against PGV, where the former has been computed by taking the reciprocal of the annual probability of exceedance. The results for the return period up to 2475 years are very similar, and significant deviation can only be observed at rather low probabilities, with about 10% difference in the hazard predictions at a return period of 10,000 years. In addition, the PSHA results from Pappin *et al.* (2008), using the source-based approach, have been superimposed in Fig. 2. The credibility of the DAB approach has been shown by the consistency of the results. The full potential of the proposed approach could be realized by applying it to soil sites for which the site-to-site variability is more significant.

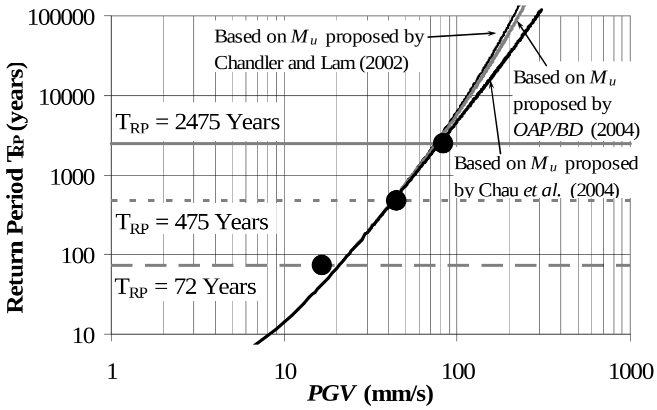

Fig. 2. Seismic-hazard curves showing the return period (reciprocal of the annual probability of exceedance) against PGV for Hong Kong, China (Tsang and Chandler, 2006). The three cited studies made alternative proposals for estimating maximum median PGV. The three solid circles are the PSHA results from Pappin et al. (2008), using the source-based approach.

In this study, peak ground acceleration (PGA) has been selected as the "amplitude" for comparison between different cities. Figure 3 shows the doubly truncated PGA-recurrence relationship using Equation (3). The same three independent studies have been employed for defining the maximum median PGA. The seismic-hazard curves computed separately for the three proposals of maximum median amplitudes have been shown in Fig. 4. The three solid circles are the PSHA results from Pappin *et al.* (2008), using the source-based approach.

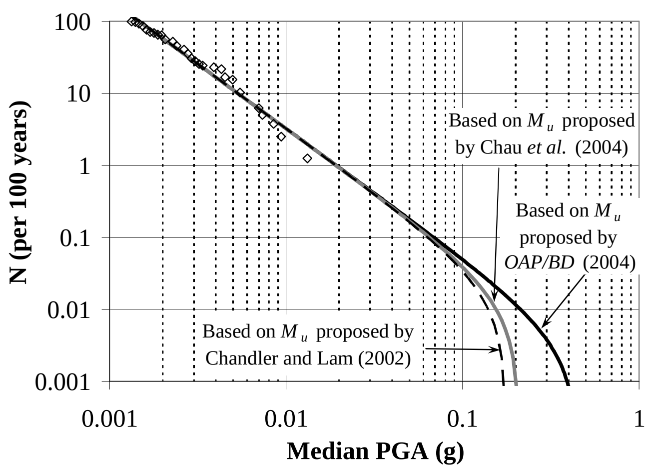

Fig. 3. PGA-recurrence relationship for Hong Kong, China. Three proposals have been made for estimating maximum median PGA.

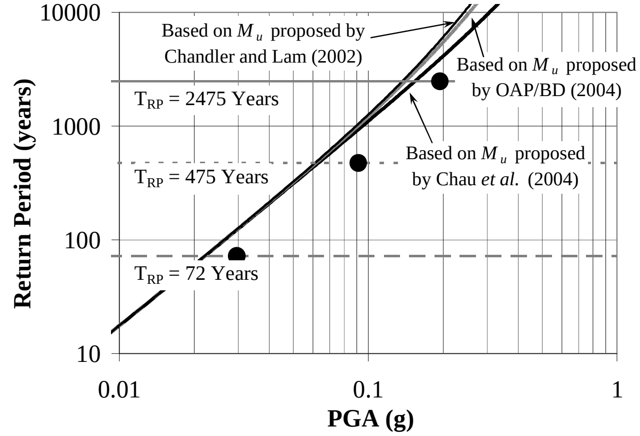

Fig. 4. Seismic-hazard curves showing the return period against PGA for Hong Kong, China. The three solid circles are the PSHA results from Pappin et al. (2008), using the source-based approach.

CASE STUDY: TEHRAN, IRAN

The capital of Iran, Tehran city, has been selected for the case study. Iran is situated at the Himalayan-Alpied seismic belt and is one of the high seismic zones in the world. Many destructive earthquakes occurred in Iran in the past few centuries. Tehran is a densely populated metropolitan city with more than 10 million habitants. It is also the political and economical center of Iran. Tehran has been destroyed by catastrophic earthquakes for at least six times in the recorded history.

Ghodrati Amiri *et al.* (2003) have conducted a PSHA for Tehran using the source-based approach, with PGA on rock sites as the ground motion parameter. An earthquake catalog that contains both historical (before 1900) and instrumental events up to year 2002 has been adopted. Earthquakes occurred within a radius of 200 km from Tehran were collected and processed. The calculations were performed based on the logic tree method using three ground motion prediction equations (GMPEs) for rock sites proposed by Ramazi (1999), Ambraseys and Bommer (1991), and Sarma and Srbulov (1996), with weightings 0.4, 0.35, and 0.25, respectively. As the standard deviation $\sigma_{\log(\mathrm{PGA})}$ of all three GMPEs is close to 0.3, a single value of 0.3 has been adopted for all three GMPEs, which is the same as that in the Hong Kong case study.

In order to make direct comparison with the results in Ghodrati Amiri *et al.* (2003), the same earthquake catalog and GMPEs have been adopted in this case study using DAB approach. For the maximum median PGA amplitude, two proposals have been adopted. The first one was based on the maximum magnitude of 7.9 adopted in Tavakoli (1996) and supported by Ghodrati Amiri *et al.* (2003), in which the estimate was 7.8 +/– 0.2 based on the statistical method proposed by Kijko (2000). Another proposal was based on the earthquake generation capacity of the closest fault – North Tehran fault. Maximum magnitude of 7.0 was estimated based on the fault length, using the empirical formula derived by Nowroozi (1985). The source-site distance adopted for both proposals is 7.0 km based on the closest surface distance between the city center of Tehran and the North Tehran fault. The three GMPEs were also employed for computing maximum median PGA.

Figure 5 shows the doubly truncated PGA-recurrence relationship using Equation (3). The seismic-hazard curves computed separately for the two proposals of maximum median PGA have been shown in Fig. 6. The hazard values for return period 475 and 975 years calculated by Ghodrati Amiri *et al.* (2003) have also been superimposed onto Fig. 6.

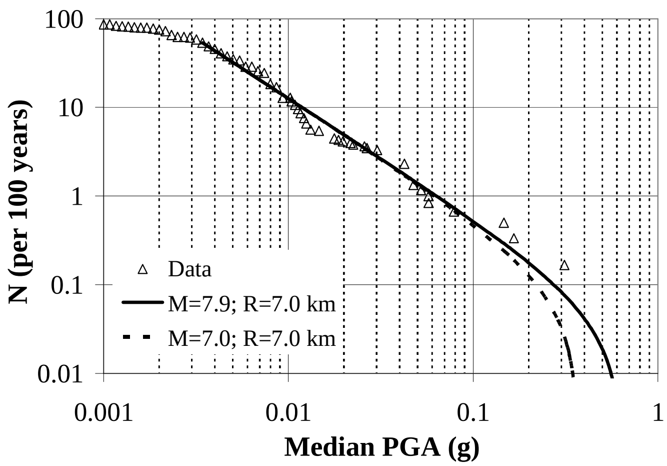

Fig. 5. PGA-recurrence relationship for Tehran, Iran. Two proposals have been made for estimating maximum median PGA.

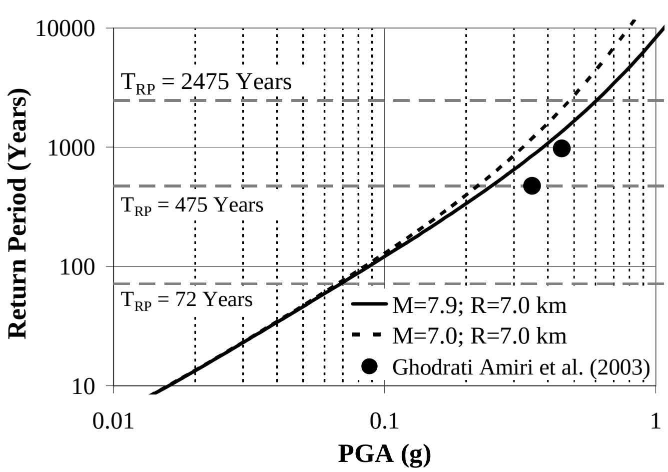

Fig. 6. Seismic-hazard curves showing the return period against PGA for Tehran, Iran. The two solid circles are the PSHA results from Ghodrati Amiri et al. (2003), using the source-based approach.

As observed in the Hong Kong case study (Fig. 4), it is seen from Fig. 6 that the hazard values calculated using DAB approach is lower than those calculated by the source-based method. This finding is consistent with that in Barani *et al.* (2007) (refer Fig. 8 in Barani *et al.*, (2007)), in which hazard estimates, in terms of PGA values, computed by the source-based method are higher than those computed by the spatially smoothed seismicity method (Frankel, 1995) that does not require source characterization either. A larger discrepancy can be seen at shorter return period (475 year), as the hazard values at longer return periods are expected to be controlled by the maximum magnitude (in source-based method) or maximum median (PGA) amplitude (in DAB approach), the more consistent results towards longer return period seem to be reasonable.

For the large discrepancy at 475 years return period, a possible reason is that in Ghodrati Amiri *et al.* (2003), uniform seismicity (i.e. $f(R)$ is a constant) was considered when seismic source zones were characterized. Hence, unrealistic scenarios might have been considered in the hazard calculation. This includes large magnitude earthquake (say, $M > 7.5$) at very short distance (say, $R < 5$ km) where no fault has been identified. It would undoubtedly overestimate the hazard of the study region. It is also a hidden problem with the use of source-based method if adequate attention has not been paid when characterizing seismic sources. It is recommended that a joint *PDF* of magnitude and distance, $f(M, R)$, should be adopted for source-based method.

CASE STUDY: BANGALORE, INDIA

Seismic activity in India is clearly evident from a number of recent earthquakes, which were concentrated along the boundaries of Indo-Australian Plate and Eurasian Plate, as well as within Indo-Australian Plate. In this case study, Bangalore, a city in southern India has been selected. South India has been predominantly considered as a stable continental region, however, numerous earthquakes of magnitude of 6.0 occurred since the eighteenth century and some of which were disastrous.

Anbazhagan *et al.* (2009) have conducted a PSHA for Bangalore using the source-based approach, with PGA and spectral acceleration on rock sites as the subject parameters. Uniform hazard response spectrum has also been derived. An earthquake catalog that contains earthquake events for the period of 1807–2006 has been used. Analyses have been carried out for the region covering a radius of 350 km with Bangalore as the center. GMPE for rock site in the Peninsular India developed by Raghukanth (2005) has been used. The standard deviation $\sigma_{\log(PGA)}$ of GMPE is 0.14.

In order to make direct comparison with the results presented in Anbazhagan *et al.* (2009), the same earthquake catalog and GMPE have been adopted in this case study using DAB approach. For the maximum median PGA amplitude, two proposals have been adopted. The first one was based on the maximum observed magnitude of around 6.0 in the study region, while the second one was the "upper bound" value of 6.5 (6.0 +/– 0.5), which was estimated using the maximum likelihood approach proposed by Kijko and Sellevoll (1989). The source-site distance adopted for both proposals is 16.0 km based on the closest hypocentral distance between the city center of Bangalore and the closest fault – Mandya-Channapatna-Bangalore fault (epicentral distance of 5.2 km; focal depth of 15 km).

Figure 7 shows the doubly truncated PGA-recurrence relationship using Equation (3). The seismic-hazard curves computed separately for the two proposals of maximum median PGA have been shown in Fig. 8. The PSHA result from Anbazhagan *et al.* (2009), using the source-based approach, has also been superimposed onto Fig. 8 as shown by the solid rectangle.

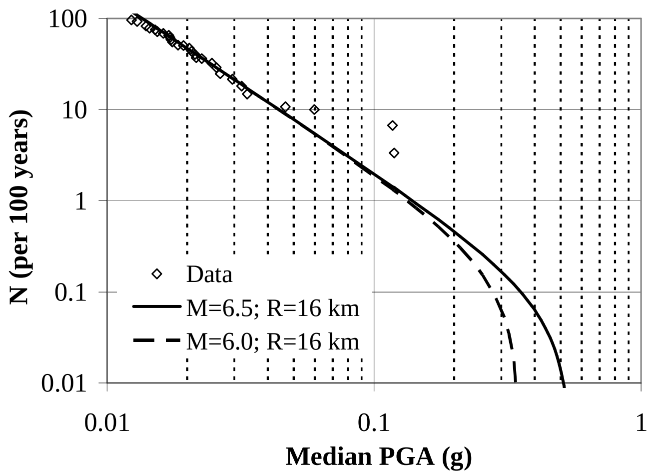

Fig. 7. PGA-recurrence relationship for Bangalore, India. Two proposals have been made for estimating maximum median PGA.

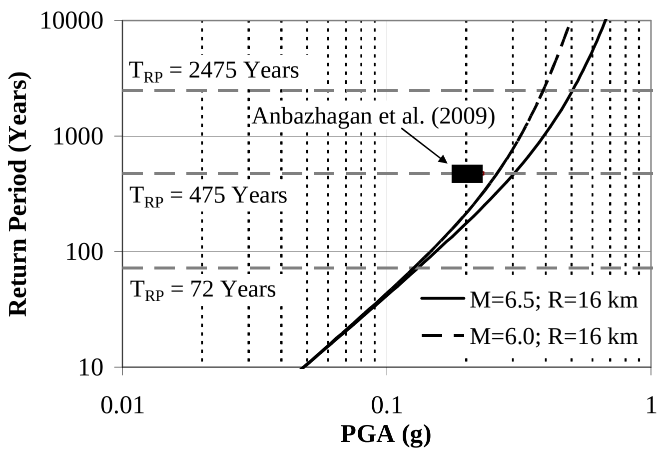

Fig. 8. Seismic-hazard curves showing the return period against PGA for Bangalore, India. The solid rectangle is the PSHA result from Anbazhagan et al. (2009), using the source-based approach.

The apparent discrepancy between the hazard values calculated using source-based method and DAB approach can be attributed to the following reason:

After careful investigations on the earthquake catalog, it is found that there are abnormally few data in the period 1901–1966, which is unusual for such a large region. Hence, it is likely that the catalogue is incomplete in this period of time. Also, in the period 1997–2006, instrumental records for small magnitude earthquakes are lacking. Such incompleteness of catalogue would lead to an underestimation of the seismicity rate, if appropriate treatment has not been applied in conducting PSHA. It is important to note that in this case study using DAB approach, all events in the above-mentioned two periods have been removed and have not been included in the hazard calculation. The completeness criteria adopted in this study are as follows: $M > 5$ for periods 1800–1900 plus 1967–2006 (a total of 140 years) and $5 > M > 3$ for period 1967–1996 (30 years).

COMPARISON BETWEEN HONG KONG, TEHRAN, AND BANGALORE

Figure 9 shows the doubly truncated PGA-recurrence relationships of the three cities considered in this case study. The corresponding seismic-hazard curves have also been shown in Fig. 10. In this section for comparison between the three cities, Bangalore curves are based on the maximum median PGA of the earthquake scenario with $M = 6.0$ and $R = 16.0$ km, Hong Kong curves are based on the combined results from the three proposals of maximum median PGA assigned with equal weightings, and the Tehran curves are based on the maximum median PGA of the earthquake scenario with $M = 7.9$ and $R = 7.0$ km.

It is clear that the seismicity and seismic hazard of Hong Kong is the lowest among the three cities, as both the PGA-recurrence relationship and the hazard curve consistently show lower values of PGA for the whole range of annual activity rate and all return periods.

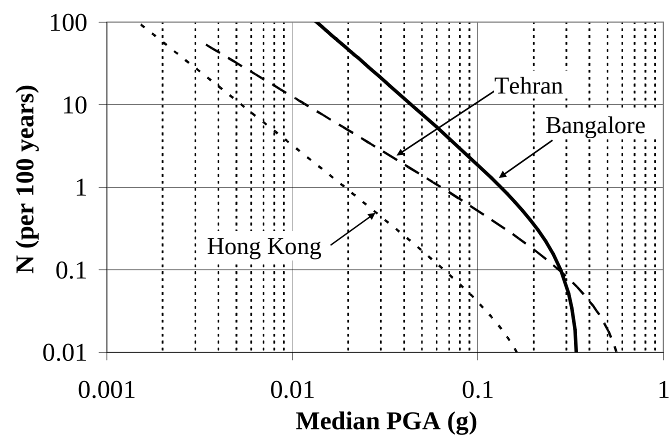

Fig. 9. PGA-recurrence relationships for Hong Kong, Tehran, and Bangalore.

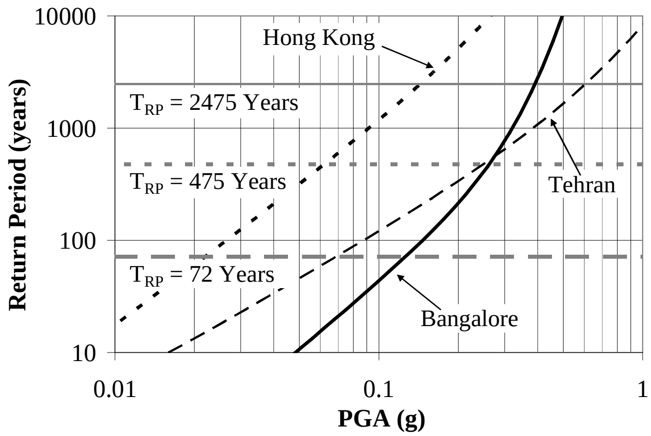

Fig. 10. Seismic-hazard curves showing the return period against PGA for Hong Kong, Tehran, and Bangalore.

Interesting results can be observed between Bangalore and Tehran. From the PGA-recurrence relationships as shown in Fig. 9, a much higher seismic activity rate can be observed in Bangalore at low shaking levels. The number of events around Tehran that produced a PGA between 0.01g and 0.1g is much smaller than that around Bangalore. This may be explained by the extents of the area from which earthquake records have been complied in the catalogs used for this study. The largest source-site distance of earthquake events in the Tehran catalog is only 200 km, while that of Bangalore and Hong Kong are respectively 350 km and over 500 km. The ratio of area considered in Tehran study to Bangalore study would be 1:3. Although the seismicity of Tehran is expected to be higher, such large ratio would undoubtedly lower the seismic activity rate, especially for low-to-moderate shaking levels, which could be generated by distant earthquakes (with source-site distance greater than 200 km). However, a more in-depth study is needed to verify this argument.

On the other hand, the GMPEs adopted for the three cities have been plotted in Fig. 11, and superimposed with Atkinson and Boore (2006) model for hard rock site condition in eastern North America. It is observed that Tehran (weighted) model lies somewhere in between Bangalore and Hong Kong models for M = 5. However, it is seen that the rate of increase with magnitude of Tehran model is lower than those of the other three GMPEs, of which the rates of increase are fairly similar. In other words, Tehran model predicts a lower PGA for larger magnitude. As the seismicity of Tehran, as well as its maximum median amplitude estimates, relies very much on large magnitude events, the predicted low levels of shaking for large magnitude events reflected by the GMPE of Tehran may result in a lower hazard.

Nevertheless, a cross-over point can be seen at PGA of around 0.3g. The higher activity rate in Tehran at high shaking level is considered reasonable, as earthquakes with large magnitude (M > 7.0) can occur at a short distance (say, within 15 km), which would in turn result in a larger maximum median amplitude that controls the "tail" (truncated part at high shaking level) of the recurrence relationship. On the contrary, earthquakes occur around Bangalore are considered to be of moderate magnitude (M < 6.0) and with distance greater than 15 km.

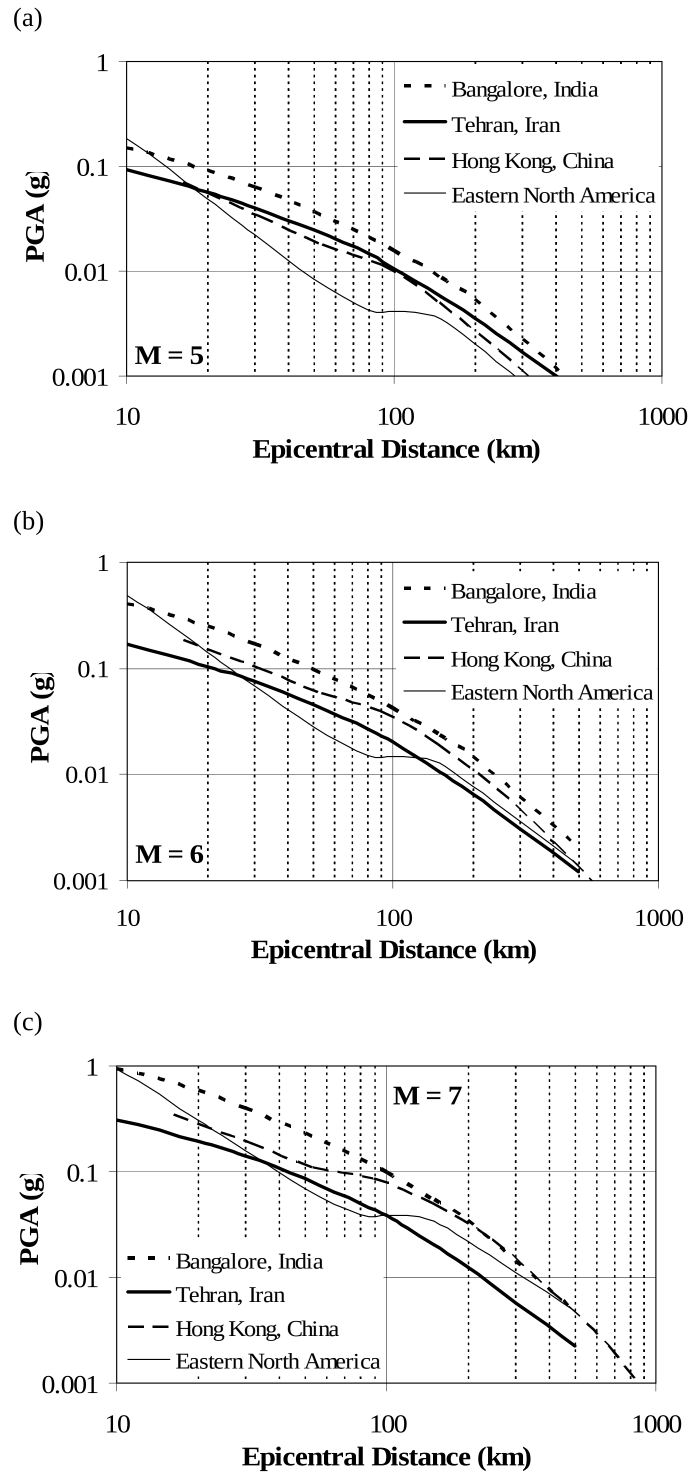

Fig. 11. Ground-motion prediction equations (GMPEs) adopted for the three cities, superimposed with Atkinson and Boore (2006) model for hard rock site condition in eastern North America.

A closer look at the "tails" (high shaking level) in both Figs. 9 and 10 reveal that the Bangalore and Tehran hazard curves tend to have a wider separation beyond the cross-over point, than that in the corresponding recurrence relationships. It can be explained by the much lower standard deviation $\sigma_{\log(PGA)}$ of Bangalore GMPE which has a value of 0.14, while that of Tehran GMPE is equal to 0.3. If the same value of 0.3 was adopted as the standard deviation of Bangalore GMPE, its hazard predictions, in terms of PGA values, would be increased by around 40% at return period of 72 years, 60% at 475 years and 80% at 2475 years. Hence, the significant influence of the standard deviation on hazard calculation is evidenced, especially at long return period.

SUMMARY AND CONCLUSIONS

1. The commonly-used methods of probabilistic seismic-hazard assessment (PSHA) have been briefly reviewed. A simpler and more direct method, namely, direct amplitude-based (DAB) approach for conducting PSHA has been introduced.

2. The advantages of the proposed approach include: (i) it does not require the characterization of seismic sources; (ii) while the method possesses the simplicity of the historic method, it is extended to account for large events that have not been observed historically, in order to improve the reliability of hazard calculation at low probability; (iii) any site-specific and event-specific characteristics that influence ground motions can be incorporated in the early stage of the numerical procedure; (iv) it does not require lengthy integration process as a generic analytical (closed-form) solution has been derived.

3. Applications of the new method have been demonstrated for three cities, namely, Hong Kong, China; Tehran, Iran, and Bangalore, India. The results computed by the new method have been compared with previous results computed by source-based method.

4. From the Tehran case study, it is revealed that the assumption of uniform seismicity (i.e. $f(R)$ is a constant) when characterizing seismic sources using source-based method may lead to an overestimation of the hazard. This is because some unrealistic scenarios, for instance, large magnitude earthquake (say, M > 7.5) at very short distance (say, R < 5 km) where no fault has been identified, might have been considered in the hazard calculation.

5. The completeness of the earthquake catalog has to be carefully examined. If the catalog is incomplete in certain period of time and an appropriate treatment has not been applied when conducting PSHA, the seismicity would be underestimated. This might be a reason for the discrepancy in the hazard calculation for Bangalore.

6. The extents of the area from which earthquake records have been complied in the catalogs may significantly affect the accuracy of the hazard results. Although the seismicity of Tehran is expected to be higher than that of Bangalore, the much smaller area of the catalog would undoubtedly lower the seismic activity rate, especially for low-to-moderate shaking levels, which could be generated by distant earthquakes.

7. Reliable prediction for ground motion or spectral response by the ground-motion prediction equations (GMPEs) is essential for a credible PSHA. The standard deviation $\sigma_{\log(PGA)}$ of the GMPE would also significantly influence the hazard results, especially at long return period.

8. Source-based method for PSHA is considered less transparent particularly in the characterization of seismic sources. It requires detailed information about the seismotectonic settings and the geological conditions of the study region, while subjective judgments are usually required in the process. The DAB approach proposed in this paper provides an alternative method for conducting PSHA. It may also serve as a useful tool for checking the credibility of the results obtained from other currently-used methods.

REFERENCE

Ambraseys, N.N. and J.J. Bommer [1991]. "The Attenuation of Ground Accelerations in Europe", *Earthquake Engrg. Struct. Dyn.*, Vol. 20, No. 12, pp. 1179-1202.

Anbazhagan, P., J.S. Vinod and T.G. Sitharam [2009]. "Probabilistic Seismic Hazard Analysis for Bangalore", *Natural Hazards*, Vol. 48, pp. 145-166.

Atkinson, G.M. and D.M. Boore [2006]. "Earthquake Ground-Motion Prediction Equations for Eastern North America", *Bull. Seism. Soc. Am.*, Vol. 96, No. 6, pp. 2181-2205.

Barani, S., D. Spallarossa, P. Bazzurro and C. Eva. [2007]. "Sensitivity Analysis of Seismic Hazard for Western Liguria (North Western Italy): A First Attempt Towards the Understanding and Quantification of Hazard Uncertainty", *Tectonophysics*, Vol. 435, pp. 13-35.

Campbell, K.W. [2003]. "Prediction of Strong Ground Motion Using the Hybrid Empirical Method and its Use in the Development of Ground-motion (Attenuation) Relations in Eastern North America", *Bull. Seism. Soc. Am.*, Vol. 93, pp. 1012-1033.

Chandler, A.M. and N.T.K. Lam [2002]. "Scenario Predictions for Potential Near-field and Far-field Earthquakes Affecting Hong Kong", *Soil Dyn. Earthquake Engrg.*, Vol. 22, pp. 29-46.

Chandler, A.M., N.T.K. Lam and H.H. Tsang [2005a]. "Shear Wave Velocity Modelling in Crustal Rock for Seismic Hazard Analysis", *Soil Dyn. Earthquake Engrg.*, Vol. 25, No. 2, pp. 167-185.

Chandler, A.M., N.T.K. Lam, H.H. Tsang, M.N. Sheikh [2005b]. "Estimation of Near-Surface Attenuation in Bedrock for Analysis of Intraplate Seismic Hazard", *J. Seism. and Earthquake Engrg*., Vol. 7, No.3, pp. 159-173.

Chandler, A.M., N.T.K. Lam and H.H. Tsang [2006a]. "Regional and Local Factors in Attenuation Modelling: Hong Kong Case Study", *J. Asian Earth Sci.*, Vol. 27, No.6, pp. 892-906.

Chandler, A.M., N.T.K. Lam and H.H. Tsang [2006b]. "Near-surface Attenuation Modelling based on Rock Shear-Wave Velocity Profile", *Soil Dyn. Earthquake Engrg.*, Vol. 26, No.11, pp. 1004-1014.

Chau, K.T., K.W. Lai, Y.L. Wong, R.H.C. Wong, L.X. Wang, Y.W. Chan, W.T. Wong, Y.S.H. Guo and W. Zhu [2004]. "Three-dimensional Surface Cracking and Faulting in Dangan Islands Area, South of Hong Kong", *Proc. Third Intern. Conf. on Continental Earthquakes*, Beijing, China, 12–14 July 2004.

Cramer, C.H. [2003]. Site-specific Seismic-hazard Analysis that is Completely Probabilistic, *Bull. Seism. Soc. Am.*, Vol. 93, pp. 1841-1846.

Cornell, C.A. [1968]. "Engineering Seismic Risk Analysis", *Bull. Seism. Soc. Am.*, Vol. 58, pp. 1583-1606.

Douglas, J. [2003]. "Earthquake Ground Motion Estimation Using Strong-motion Records: A Review of Equations for the Estimation of Peak Ground Acceleration and Response Spectral Ordinates", *Earth-Sci. Rev.*, Vol. 61, pp. 43-104.

Frankel, A. [1995]. "Mapping Seismic Hazard in the Central and Eastern United States", *Seism. Res. Lett.*, Vol. 66, No. 4, pp. 8-21.

Ghodrati Amiri, G., R. Motamed and H. Rabet Es-Haghi [2003]. "Seismic Hazard Assessment of Metropolitan Tehran, Iran", *J. Earthquake Engrg.*, Vol. 7, No. 3, pp. 347-372

Kijko, A., M.A. Sellevoll [1989]. "Estimation of Earthquake Hazard Parameters from Incomplete Data Files. Part I: Utilization of Extreme and Complete Catalogs with Different Threshold Magnitudes", *Bull. Seism. Soc. Am.*, Vol. 79, pp. 645-654

Kijko, A. [2000]. "Statistical Estimation of Maximum Regional Earthquake Magnitude $m_{\max}$", Workshop of Seismicity Modeling in Seismic Hazard Mapping, Poljce, Slovenia, May 22-24.

McGuire, R.K. [1993]. "Computations of Seismic Hazard", *Ann. Geofis.*, Vol. 36, pp. 181-200.

Milne, W.G. and A.G. Davenport [1969]. "Distribution of Earthquake Risk in Canada", *Bull. Seism. Soc. Am.*, Vol. 59, pp. 729-754.

Nowroozi, A. [1985]. "Empirical Relations between Magnitude and Fault Parameters for Earthquakes in Iran", *Bull. Seism. Soc. Am.*, Vol. 75, No.5, pp. 1327-1338.

OAP/BD [2004]. "*The Seismic Effects on Buildings in Hong Kong*", Buildings Department, Government of the HKSAR, Consultancy Agreement No. CAO K49, conducted by Ove Arup and Partners (HK) Ltd.

Ordaz, M. [2004]. "Some Integrals Useful for Probabilistic Seismic Hazard Analysis", *Bull. Seism. Soc. Am.*, Vol. 94, pp. 1510-1516.

Pappin, J.W., R.C.H. Koo, M.W. Free and H.H. Tsang [2008]. "Seismic Hazard of Hong Kong", *Electronic J. Struct. Engrg.*, Vol. 8, pp. 42-56.

RaghuKanth, S.T.G. [2005]. *"Engineering Models for Earthquake Sources"*, Ph.D. Thesis, Indian Institute of Science, Bangalore, India

Ramazi, H.R. [1999]. "Attenuation Laws of Iranian Earthquakes", *Proc. Third Intern. Conf. on Seism. and Earthquake Engrg.*, Tehran, Iran, pp. 337-344.

Reiter, L. [1990]. *"Earthquake Hazard Analysis: Issues and Insights"*, Columbia University Press, New York.

Sarma, S.K. and M. Srbulov [1996]. "A Simplified Method for Prediction of Kinematic Soil-foundation Interaction Effects on Peak Horizontal Acceleration of a Rigid Foundation", *Earthquake Engrg. Struct. Dyn.*, Vol. 25, No.8, pp. 815-836.

Tavakoli, B. [1996]. *Major Seismotectonic Provinces of Iran*, International Institute of Earthquake Engineering and Seismology, Internal Document (in Persian).

Tsai, C.C.P. [2000]. "Probabilistic Seismic Hazard Analysis Considering Nonlinear Site Effect", *Bull. Seism. Soc. Am.*, Vol. 90, pp. 66-72.

Tsang, H.H. and A.M. Chandler [2006]. "Site-Specific Probabilistic Seismic-Hazard Assessment: Direct Amplitude-Based Approach", *Bull. Seism. Soc. Am.*, Vol. 96, No.2, pp. 392-403.