DEVELOPMENT OF LOCALLY REPRESENTATIVE SEISMIC HAZARD MODELS

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Abstract:. Seismic hazard studies in regions of low and moderate seismic activities often resort to the use of attenuation relationships developed elsewhere but there are always doubts as to whether these imported relationships are representative of local conditions. Numerous well established stochastic attenuation models have also been developed for applications in Central and Eastern North America. However, such intraplate models could not be generalised across the globe to other regions of low and moderate seismic activities. Modelling the spatial and temporal distribution of seismic activities can also be thwarted with difficulties because of the paucity of data. This paper presents the experiences of the authors in overcoming these challenges when undertaking seismic hazard studies in different countries. Topics covered in the paper include attenuation modelling and the evaluation of seismic hazards for the determination of the earthquake loading model for engineering design.

Keywords: Moderate seismicity, seismic hazard, attenuation

1. Introduction

Seismic-hazard assessment (SHA) provides an estimate of ground motion at the site of interest, taking into account instrumental and historical earthquake records, information on tectonics, geology and attenuation characteristics of seismic waves. Seismic-hazard assessment is also used for seismic microzonation study, which is important for decision making on land use, evaluation of the level of earthquake preparedness, economical consideration of earthquake-resistant design, retrofit strategy, economic loss estimation in an event of future earthquake, and also for the design of ordinary structures where site-specific studies are not warranted.

Techniques for modelling the spatial and temporal distribution of seismicity for areas of low and moderate activities are described in section 2. The development of ground motion prediction equations (GMPEs), also known as attenuation relationships, is reviewed in section 3. This is a key component in the probabilistic seismic hazard assessment (PSHA) procedure. In regions of high seismicity such as California where strong motion records are abundant, GMPEs are usually developed by regression of recorded ground motion parameters (e.g. Sadigh et al. 1997). In regions lacking recorded strong motion data, GMPEs may alternatively be developed from stochastic simulations of the seismological model, which characterises ground motion properties by their frequency content. The integration of the seismic activity model with the relevant selected GMPEs provides predictions of the recurrence relationship of ground motion parameters and the associated seismic hazard maps. An innovative integration procedure which is known as the *Direct Amplitude - Based* (DAB) Method (Tsang and Chandler 2006; Tsang and Lam 2010) which can be used to circumvent difficulties encountered by the conventional Cornell's iteration method (Cornell 1968) is illustrated in section 4 by case studies.

2. Seismic Activity Modelling

2.1 Historical developments

The level of earthquake activity at an identified seismic source location is normally modelled by the Gutenberg-Richter (G-R) magnitude recurrence relationship. The earthquake activity model of a region comprises the spatial distribution of the potential seismic sources along with the recurrence relationship of each individual seismic source expressed in the G-R form. It is important that the records are complete. Historical records can be very useful supplement to instrumental records, particularly in areas lacking instrumental records and/or areas with a long history of civilised settlement. Meanwhile, geological data on fault activity often provides useful support to the seismological data in identifying and delineating potential seismic sources (Yeats et al. 1997).

2.2 Modelling in areas of low and moderate seismic activity

In areas of low and moderate seismicity, the low level of earthquake activity rate often results in a lack of seismic activity data. Consequently, it is difficult to identify and delineate potential seismic sources and to define the activity level of each individual seismic source. For this reason, regional fault sources have often been grouped into "areal source zones" in which seismic activity is considered to be diffused over the entire zone and not concentrated at a few faults. An example is the work of Pun and Ambraseys (1992) is relation to the South China region. This lumping of fault sources into a diffused areal source has the advantage of aggregating a larger number of seismic records to define the recurrence behaviour of the source. Further, the diffused model overcomes the problems of not accounting for unidentified fault sources such as a buried blind thrust fault.

Seismicity in such regions has therefore been modelled using very large areal source zones defined, rather arbitrarily, in accordance with broad geographical features (such as coastlines and mountain ranges) together with the mapping of significant historical earthquake events (Scott et al. 1994 for Hong Kong; Jacob 1997 for New York City). These are also known as "Broad Source Zones" (BSZ) (Chandler and Lam 2002). In modelling a BSZ, the actual spatial distribution of seismicity within the zone is ignored and assumed to be uniform. The advantage is that only a single G-R relationship needs to be defined using the entire seismic record. This type of areal source is also known as "seismo-tectonic province". The theoretical basis of the BSZ or seismo-tectonic province is controversial, and hence it is important to be aware of the potential implications when adopting a suitable strategy for a given region.

2.3 Large magnitude distant earthquakes

Large magnitude earthquakes can transmit destructive long period ground shaking over very long distances, particularly in a crustal environment of good wave transmission quality such as the mid-continental regions of CENA (Algermissen 1997) or Central and Western Australia. Thus, the overall chance of a facility, or a centre of population, being affected by a large magnitude earthquake is contributed to by a large number of potential seismic sources (including unknown sources) covering a very large area (within a radius of 400-500 km from the site). Consequently, large magnitude earthquakes warrant serious engineering consideration, despite the fact that they are generated very "infrequently" by any particular seismic source. However, making assessment of earthquake performance due to such potential hazards is generally very difficult in intraplate regions, since earthquakes of sufficiently large magnitude occur so infrequently that their activities are often difficult to study simply by mapping historical events or by instrumental monitoring. Studies based on geomorphology, imaging of sub-surface geological structures and carbon dating of soil samples taken from fault scarps (Yeats 1997) have been carried out to study the recurrence interval of pre-historical earthquake activities. Overall, large magnitude long distance earthquakes form a significant hazard and hence are an important issue in the seismic hazard modelling for low and moderate seismicity regions within continents (Lam et al. 2002).

3. Ground Motion Prediction Modelling

The prediction of earthquake ground motions in accordance with recorded observations from past events is the core business of engineering seismology. A GMPE presents values of parameters characterising the intensities and properties of ground motions estimated of projected earthquake scenarios (which are expressed in terms of magnitude and distance). Empirical attenuation models are developed from regression analysis of recorded strong motion accelerograms. In situations where strong motion data are scarce the database of records has to cover a very large area which may be an entire continent or a large part of a continent in order that the size of the database has statistical significance (Toro et al. 1997 for Central and Eastern North America; Ambrasey 1995 for Europe). Thus, attenuation modelling based on regression analysis of instrumental data is problematic when applied to regions of low and moderate seismicity. This is because of insufficient representative data that has been collected and made available for model development purposes.

An alternative approach to attenuation modelling is the use of theoretical models. Unlike an empirical model, a theoretical model only makes use of recorded data to help ascertain values of parameters in the model rather than to determine trends from scratch by regression of data. Thus, much less ground motion data is required for the modelling. Data that is available could be used to verify the accuracies of estimates made by the theoretical model. The heuristic source model of Brune (1970) which defines the frequency content of seismic waves radiated from a point source is developed for such purpose. The model has only three parameters: seismic moment, distance and the stress parameter. Combining this point source model with a number of filter functions which represent modification effects of the wave travel path and the site provides estimates for the *Fourier* amplitude spectrum of the motion generated by the earthquake on the ground surface. The source model (of Brune) in combination with the various filter functions are collectively known as the seismological model (Boore 1983). Subsequent research by Atkinson and others provides support for the proposition that simulations from a well calibrated point source model are reasonably consistent with those from the more realistic finite fault models.

The *Fourier* spectrum as defined by the seismological model only provides description of the frequency properties of the ground motions and not the phase angles of the individual frequency components of the waveforms. Thus, details of the wave arrival times which are required for providing a complete description of the ground shaking remain uncertain as they have not been defined by the seismological model. With stochastic modelling, the pre-defined frequency content is combined with random phase angles that are generated by the *Monte Carlo* process. Thus, acceleration time-histories based on randomised wave arrival details are simulated. The simulations can be repeated many times (for the same earthquake scenario and source-path-site conditions) in order that response spectra calculated from every simulated time-histories can be averaged to obtain a smooth, ensemble averaged, response spectrum.

The seismological model has undergone continuous development since its inception. For example, the original Brune source model has been replaced by the empirical source model of Atkinson (1993) which was developed from seismogram data recorded in *Central and Eastern North America* to represent conditions of intraplate earthquakes. A similar model was subsequently developed by Atkinson and Silva (2000) which was developed from data recorded in *Western North America* to represent conditions of interplate earthquakes. A model to account for the complex spread of energy in space taking into account the wave-guide phenomenon and the dissipation of energy along the wave travel path has also been developed (Atkinson and Boore 1995). The amplification and attenuation of upward propagating waves taking into account the effects of the shear wave velocity gradient of the earth crust have also been modelled by Boore and Joyner (1997). A comprehensive review can be found in Lam et al. (2000).

4. Seismic Hazard Modelling and Case Studies

The effects of all potential earthquake events expected to occur within a specific exposed period are integrated in PSHA with due considerations given to uncertainties and randomness. PSHA is thus able to provide an estimate of ground motion parameters with an annual probability of exceedance (or any other time period), which is a key input for risk analysis and performance-based design.

As introduced earlier, PSHA has been de-coupled into seismic source modelling, ground motion modelling and the integration as the final step in the procedure. One of the well recognized shortcomings of this well established procedure is with difficulties over constraining the source model based on historical data. Consequently, predictions are highly model dependent given that the manner in which certain modelling parameters are decided upon can be fairly subjective. Thus, the procedure is still filled with ambiguities although being widely used. The DAB Method has been developed as a simple and efficient method as an alternative for PSHA.

In this section, the implementation of the DAB approach for three cities in China, Iran, and India, respectively, has been briefly described. Meanwhile, several insights regarding the procedure of conducting PSHA have also been obtained, which could be useful for future seismic hazard studies.

4.1 Direct amplitude-based (DAB) approach

The DAB approach was derived analytically from Cornell's source-based method, yet does not require detailed characterization of seismic sources. Whilst the method possesses the simplicity of the historic method, it could be extended to account for characteristic earthquakes and potential large events that have not been observed historically, in order to improve the reliability of hazard calculation at low probability. Hence, it can also be regarded as a "parametric-historic" method. On the other hand, any site-specific and event-specific characteristics that influence ground motions, such as non-linear site effects, rupture mechanism and directivity, can be incorporated in the early stage of the numerical procedure, which is considered beneficial for microzonation study. The DAB approach can be analytically represented by Equation (1) and details of the derivation process can be found in Tsang and Chandler (2006) and Tsang and Lam (2010).

$$P[Z > z] = N(\Delta_{\min}) \int_{\Delta_{\min}}^{\Delta_{\max}} P[Z > z \mid \Delta] f(\Delta) d\Delta \qquad (1)$$

where Δ is the median ground motion or spectral response amplitude, obtained from GMPEs for each earthquake scenario (discarding the standard deviation); $f(\Delta)$ is the probability density function (*PDF*) of the median amplitude (Δ), which can be obtained by differentiating the cumulative distribution function (*CDF*), derived from the amplitude-recurrence relationship. $\Delta_{\min}$ and $\Delta_{\max}$ are minimum and maximum median ground motion or spectral response amplitudes, respectively, and $N(\Delta_{\min})$ is the mean annual rate of the median amplitude (Δ) exceeding the minimum value ($\Delta_{\min}$).

4.2 Case studies

Implementation of the DAB method is illustrated herein using the case studies of Hong Kong, China; Tehran, Iran; and Bangalore, India. The seismic hazard curves computed by the new method are plotted in Figure 1. Comparison with previous results computed by Cornell's source-based approach has been presented in Tsang et al. (2010). Some insights regarding the procedure of conducting PSHA have also been summarised in the followings.

The case study for Tehran revealed that the assumption of uniform seismicity when characterizing seismic sources in the source-based approach might result in an overestimation of the seismic hazard. Whilst the concept of uniform seismicity as introduced in section 2 seems to be rational, there are difficulties with accurately ascertaining the level of seismic activity for an area in which the disposition of activity is assumed to be uniform. In the case of Tehran, large magnitude near field earthquake scenarios that have been predicted for certain areas are clearly unrealistic as the predictions are contrary to geological evidences. For instance, M7.5 – M8 earthquakes at very short epicentral distances ($R < 5$ km) have been predicted in locations where no major faults have been identified. Such anomalies were purely resulted from the very assumption of uniform seismicity in a somewhat arbitrarily defined source zone. A joint *PDF* incorporating both magnitudes and distances, $f(M, R)$, should be used in the calculation of seismic hazard.

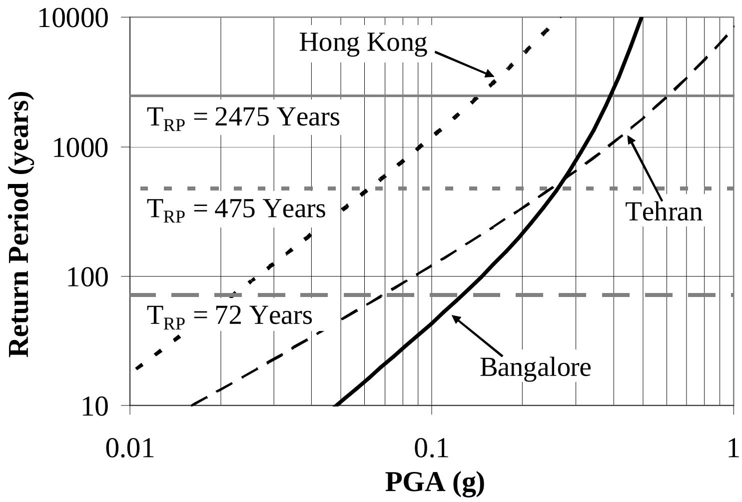

Figure 1: Seismic-hazard curves showing the return period against PGA for Hong Kong, Tehran, and Bangalore

In the Bangalore case study, there is an apparent discrepancy between the hazard values calculated using the source-based method and the DAB method. A careful review of the earthquake catalogue revealed that there were abnormally few data in the period 1901–1966 (refer Table 1, Figures 3, 4 and 6 in Anbazhagan et al. 2009), which is unusual for such a large region in Southern India. 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 result in an underestimation of the rate of seismic activity, if appropriate treatment has not been applied in conducting PSHA. It is noted that in this case study when the DAB method was employed, all events in the above-mentioned (two) periods have been removed and have not been included in the calculation of seismic hazard. 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) (supported by Anbazhagan et al. 2009).

PGA-recurrence relationships as obtained from the DAB method for Bangalore and Tehran revealed some interesting findings. A much higher recurrence rate has been identified with Bangalore at low levels of ground shaking. In other words, the number of earthquake events surrounding Tehran, of PGA in the range 0.01g and 0.1g, is much smaller than that surrounding Bangalore. This is in spite of Tehran apparently possessing a much higher level of seismic hazard as reflected in its level of design PGA. The revealed anomalies might be related to the very different area of coverage by historical events that have been incorporated into the earthquake catalogue of the respective city. The largest source-site distance of earthquake events in the Tehran catalogue was only 200 km, whilst that of Bangalore and Hong Kong were respectively 350 km and 500 km. The area of coverage for Tehran and Bangalore differed by a factor of 3. Such disparity offers a plausible explanation for the much lower recurrence rate of low-to-moderate levels of ground shaking generated by distant earthquakes (with source-site distance greater than 200 km).

Another note to make is that reliable modelling of the ground motion (or spectral response) parameters by the ground motion prediction equations (GMPEs) is essential for a credible outcome of the PSHA. The standard deviation $\sigma_{log(PGA)}$ of the GMPE would also significantly influence estimates of the seismic hazard level, especially at long return periods. With Bangalore, the very low rate of increase in the seismic hazard level with increasing return period (as shown in Figure 1), compared to those of Hong Kong and Tehran, could be explained by the much lower standard deviation with the GMPEs developed for the city.

5. Conclusions

This paper reveals various problems associated with constraining factors that would influence the prediction of seismic hazard for regions lacking representative historical seismic data. Innovative improvements to the current modelling methodologies have been illustrated using case studies undertaken in different countries by the authors.

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