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Seismic hazard estimation based on the distributed seismicity in northern China*

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Abstract

In this paper, we have proposed an alternative seismic hazard modeling by using distributed seismicites. The distributed seismicity model does not need delineation of seismic source zones, and simplify the methodology of probabilistic seismic hazard analysis. Based on the devastating earthquake catalogue, we established three seismicity model, derived the distribution of a-value in northern China by using Gaussian smoothing function, and calculated peak ground acceleration distributions for this area with 2%, 5% and 10% probability of exceedance in a 50-year period by using three attenuation models, respectively. In general, the peak ground motion distribution patterns are consistent with current seismic hazard map of China, but in some specific seismic zones which include Shanxi Province and Shijiazhuang areas, our results indicated a little bit higher peak ground motions and zonation characters which are in agreement with seismicity distribution patterns in these areas. The hazard curves have been developed for Beijing, Tianjin, Taiyuan, Tangshan, and Ji'nan, the metropolitan cities in the northern China. The results showed that Tangshan, Taiyuan, Beijing has a higher seismic hazard than that of other cities mentioned above.

Key words: **distributed seismicity**; **Gaussian smoothed function**; **seismic hazard estimation**; **northern China**; **peak ground acceleration**

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Introduction

Seismic hazard analysis can give possibility of earthquake threat at a site for a period of time using a variety of existing methods and is the foundation of reducing seismic disasters. Seismic hazard analysis contains deterministic method (DSHA) and probabilistic method (PSHA). At present two probabilistic methods are applied to the calculation of seismic hazard that are deductive method and historical method. The deductive method proposed by Cornell (1968) requires distribution of seismic source region deduced by using data of seismicity and seismogeological investigation, however, the seismic hazard maps developed on the basis of delineation of seismic source zones are uncertainty and subjective due to lack of exact and sufficient geological and seismotectonic data. With the establishment of modern seismic network, seismic data are more and more

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plentiful and researches have found earthquake distribution is consistent with regional tectonic distribution and contains much fault information. In current PSHA, models applied comprehensively include fault model, seismicity model and moment release rate model based on GPS and geodetic data (Ward, 2007; Pancha *et al*, 2007).Combined with these three models, we can better reduce and control the uncertainty of PSHA.This mothed is also the key to syncretizing many kinds of technologies. It's mature for this methed that seismicity model is applied in PSHA (The National Seismic Hazard Mapping Project, 2007), but is not employed with calculating background earthquake. As an attempt to avoid the uncertainties related to the source geometry, Veneziano *et al* (1984) proposed historical method, which requires only a catalogue of earthquakes and appropriate attenuation relation in the studied region. Frankel (1995) put forward an improved method for probabilistic seismic hazard analysis based on spatially smoothed seismicity and mapped seismic hazard in the central and eastern United States using the method. XU and JIN (1998) modeled seismicity by the method in moderate-to-large seismic region in China. This method proposed by Frankel (1995) subsequently underwent various modifications, and extensively applied in calculating PSHA in Europe (Pelaez and Lopez, 2002; Pelaez *et al*, 2003; Lapajne *et al*, 1997, 2003; Foteva *et al*, 2006; Al-Tarazi and Sandvol, 2007).

For PSHA, an instrumental record history is short, reliable source is mostly historical seismic data. In this study,taking the northern China as example, we selected the seismic data for the period from A.D.1484 to A.D.2006 (the historical and modern seismic data in this region are comparatively completed), analyzed the completion of these data and then constructed distributed seismicity model of the area using the method proposed by Frankel (1995), which makes it possible to research potential hazard of future earthquake in this region using historical method. In the article, we will introduce in detail the method and principle of seismicity model and how to apply it in seismic hazard analysis. Taking northern China as example, we acquire the distribution of peak ground acceleration in northern China and developed hazard curves for several metropolis. Comparison with current seismic zonation map of China (HU *et al*, 2001) show it is simple and convenient to calculate seismic hazard by this model and with high precision. Especially for those regions without sufficient seismogeological data, this method can be an alternative means applied widely.

1 Research region and seismological data

The research areas cover the range of 110°E~122°E, 32°N~42°N. Seismic data for study include both historical events and instrumental records with M_s4~6.9 from A.D.1484 to A.D.2006 (Figure 1), of which the magnitudes of historical earthquakes(not including instrumental records) are obtained through transformation of magnitude-intensity. Earthquakes with magnitude below 4 are not included because of its incompleteness and weakly damage to structure. For each selected earthquake, foreshocks and aftershocks are firstly removed with the main shock magnitude deletion method. Furthermore, earthquakes of magnitude $M_S \geq 7.0$ are not taken into account in the model, which belong to characteristic earthquake with large fault scale and long reoccurrence period. Therefore, in PSHA, events with $M_S \geq 7.0$ have little effect on hazard curves with 63%, 10% and 5% probabilities of exceedance in 50 years; however, in calculation of low probabilities of exceedance (with recurrence period $T \geq 2\,500$ a), influence of characteristic fault has to be considered.

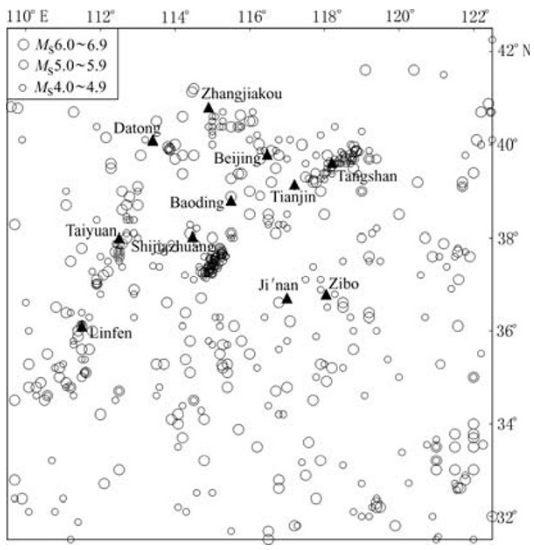

Figure 1 Distribution of earthquakes with $M_S \geq 4.0$ in northern China

2 Seismicity model

2.1 Basic assumption

To construct an appropriate seismicity model, we assume ① events that cause damages to structures will occur near historical main shock occurred with $M_S \geq 4.0$; ② point source represents events that occurred along fault. We think that models based on the above-mentioned assumption can describe the recurrence process of historical seismicity.

2.2 Gutenberg-Richter law

Gutenberg-Richter law applied in current seismic hazard analysis is expressed as the relation between magnitude and annual number of earthquakes with magnitude ranging from lower bound magnitude M_0 to upper bound magnitude M_u (McGuire and Arabasz, 1990; HU, 1988).

$$\begin{cases} N_c(M) = \nu \dfrac{10^{-b(M-M_0)} - 10^{-b(M_u-M_0)}}{1-10^{-b(M_u-M_0)}} & M_0 \leq M \leq M_u \\ \nu = 10^{a-bM_0} \end{cases} \tag{1}$$

In this study, we take separately M_o and M_u as 4.0 and 6.9, respectively. Referring to HUANG *et al* (1990), b-value is equal to 0.679. a-value spatially differs, that is, spatial distribution characteristics are non-uniform, and directly related to local seismicity.

2.3 Spatially smoothed seismic activity rate

The method of spatially smoothed regional seimicity distribution was first proposed by Frankel (1995). This method is very suitable for region where seismologic and geologic data are inaccurate and insufficient and where delineation of seismic source zone exists large subjectivity and uncertainty. And geometrical delineation of seismic source zones is not strict mathematical procedure, generally depends on subjective decisions. The mathematical features of the Gaussian smoothed method automatically avoid the subjective delineation of seismic source zones. Circularly and elliptically Gaussian smoothed function has been used to deal with regional seismicity. Based on seismicity distribution in China, elliptically Gaussian smoothed function should be more corresponding to pattern of seismic distribution. However, qualitative seismtectonic model has not yet been built, so we just consider circularly Gaussian smoothed function, and will bring in elliptically Gaussian smoothed function as soon as possible.

The procedure of circular smoothing is as follows. Firstly, we divide the whole observational region (32°N~42°N, 110°E~122°E) into a grid with spacing of 0.05° in latitude and 0.05° in longitude, so the length of each grid is about 5.5 km×5.5 km. Then we count the number of earthquakes n_i with magnitude greater than M_0, that is, n_i is seismic activity rate in cell i. For there exist error of earthquake location, especially historical earthquake, in this study we employ Gaussian smoothing method and select appropriate radius for effectively controlling the error of epicenter location. For each cell i, the smoothed value $\widetilde{n}_i$ is obtained from

$$\widetilde{n}_i = \frac{\sum_j n_j \exp(-\Delta_{ij}^2 / c^2)}{\sum_j \exp(-\Delta_{ij}^2 / c^2)} \tag{2}$$

In this equation, $\widetilde{n}_i$ is normalized to preserve the total number of events. Δ_{ij} is the distance between the i-th and j-th cells. Correlation distance c is equal to 50 km.

2.4 Establishment of seismicity model

For accurately reflecting the pattern of seismic activity in this region and accounting for the influence of incompletion of seismic data, in this study, we used three different models for the hazard calculation. Model 1 (M_1) covers earthquake catalog of period from A.D.1484 to A.D. 2006 to acquire a-value; Model 2 (M_2) is based on spatially smoothed a-values derived from the earthquakes of magnitude larger than or equal to 4.0 since 1900. Because chaos caused by war led to lack of data, we mainly consider the incompleteness of data in model 2. Model 3 (M_3) used spatially smoothed a-values based on the earthquakes of magnitude larger than or equal to 4.0 since 1970. We primarily consider the incompleteness of data during last century in model 3.

In the calculation, we find the distributions of a-value in model 2 and model 3 concentrate on the vicinity of Tangshan, Shijiazhuang and Xingtai, and is consistent with modern seismicity, but is not evident in the region of Taiyuan, Linfen, Xinzhou, Baotou and Zhangjiakou *etc.* So it's limited just nsing model 2 and model 3 to describe seismicity at large time scale. According to different exposure time in each model, we reasonably assign weights to models 1, 2 and 3. Finally, we derive total model

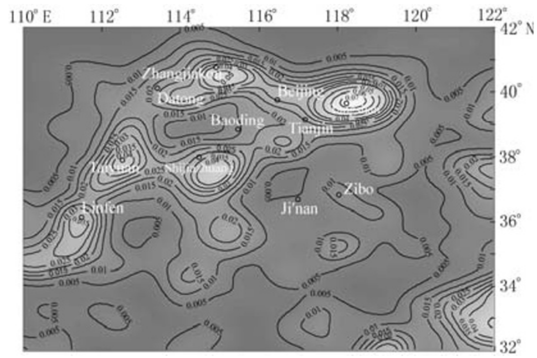

Figure 2 Distribution of a-value Gaussian-smoothed in northern China

$$M_{\mathrm{T}} = 0.85M_1 + 0.1M_2 + 0.05M_3 \tag{3}$$

The coefficients of equation (4) at right side are assigned weights of 0.85, 0.1 and 0.05 to models 1, 2 and 3 respectively, but the selection of these coefficients still exists subjectivity and needs futher improvements in future work (Pelaez and Lopez, 2002). Figure 2 shows distribution of a-value of $M_S \geq 4.0$ event in northern China.

3 Seismic hazard calculation

3.1 Attenuation relationship

YU (2002) has proposed the attenuation relation currently used in North China. According to the previous researchers' experience, employment of single attenuation relation could produce artificial prejudice. In the article, for comparative purposes, we introduce an attenuation relation

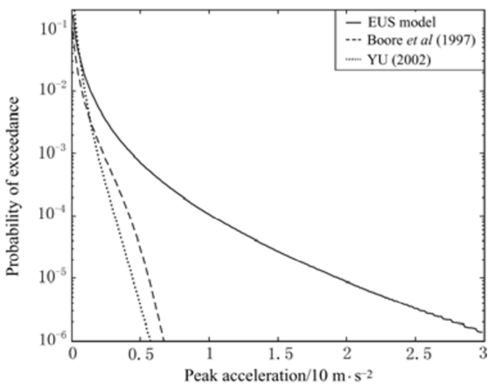

Figure 3 Hazard curves for Tangshan area calculated from Boore attenuation relation for western United States, the relation used in eastern and central United States and the relation currently used in eastern China

developed by Boore *et al* (1997) for the West United States and the attenuation relation (Frankel *et al*, 1996; Atkison and Boore, 1995; Toro *et al*, 1997; Campbell, 2003) used in the Eastern and Central United States. The results indicate that peak ground acceleration (PGA) derived from the attenuation relation used in the Eastern and Central United States is remotely greater than that from YU's and Boore *et al*'s (Figure 3). Therefore, the attenuation relation used in the Eastern and Central United States is not suit for the northern China. Figure 4 shows the median value derived from YU's and Boore *et al*'s attenuation relation with magnitude 5, 6 and 7 respectively. And comparative results indicate that PGA derived from YU's attenuation relation far greater than Boore *et al*'s in near-field. The main reason for the notable difference is that the influence of different styles of earthquake in different earth crust structure to ground motion is different. Conditional probability derived from attenuation relation is expressed as

$$\Phi(y \geq X \mid Y(M, R, \sigma) = \int_X^{+\infty} \frac{1}{\sqrt{2\pi\sigma}} \exp\left\{-\frac{[\lg y - \lg Y(M, R)]^2}{2\sigma^2}\right\} \mathrm{d}\lg y \tag{4}$$

3.2 Calculating method

In seismic hazard analysis, two kinds of methods for estimating gound motion parameters have been created in the past, which are deterministic method (DSHA) and probabilistic method (PSHA). The former is mainly applied to structures for which failure could have catastrophic consequences, such as large dams, nuclear power plants and significant lifeline engineering. The difference between two methods is whether the life times of different structures are considered. The major goals of PSHA are to give the influence of earthquakes occurred in a given site and calculate ground motion parameters with a given probability of exceedance. For a site, we estimate seismic hazard for multiple sources with the following equation (Cornell, 1968)

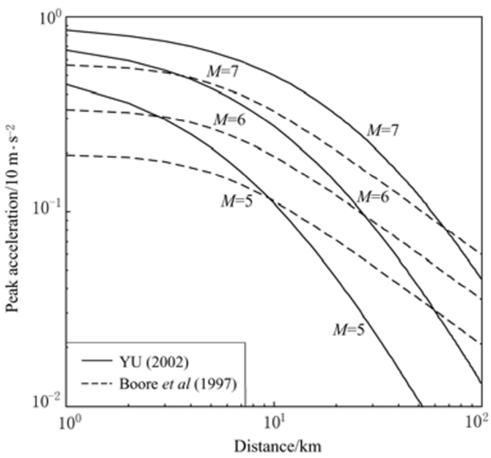

Figure 4 Ground acceleration attenuation relationship

$$\lambda(y) = \sum_{i=1}^{N} \iiint v_i f_M^i(M) f_R^i(r) f_\varepsilon^i(\varepsilon) H[y - Y(M, r, \varepsilon)] \mathrm{d}M \mathrm{d}r \mathrm{d}\varepsilon \tag{5}$$

where $\lambda(y)$ is the annual probability of exceedance when ground motion parameter y exceeds particular value $Y(M, r, \varepsilon)$; ν_i is annual activity rate of earthquake of magnitude equal to and above M_0 for i-th source area; the probability density functions of m, r, ε are $f_M^i(M), f_R^i(r), f_\varepsilon^i(\varepsilon)$ respectively, where m is magnitude, r is the minimal distance between source i and site, ε is defined as the number of logarithmic standard deviations by which the logarithmic ground motion deviates from the median; H is the Heaviside step function; $Y(m, r, \varepsilon)$ is attenuation relationship. For distributed seismicity model, equation (5) can be revised as

$$\lambda(y) = \sum_k \sum_l \tilde{n}_k q(M_l, \Delta M) \Phi[y \geq X \mid Y(M_l, r_k, \sigma)] \tag{6}$$

Where $\tilde{n}_k$ is seismic activity rate normalized by Gaussian smoothing procedure in source k. In equation (6), attenuation relation $Y(m_l, r_k, \sigma)$ presents mean value of ground motion parameters at site with distance to source of r_k under the earthquake with magnitude of m_l. σ is uncertainty in this relationship expressed by the standard deviation. Error function $\Phi(y \geq X \mid Y(M_l, r_k, \sigma))$ is conditional probability that a ground motion parameter y ($R=r_k$, $M=m_l$) exceeds a particular value X. Annual probability exceedance is equal to annual seismic rate for $M=m_l$ multiplied by conditional probability above. Attenuation laws for different magnitude are diverse, and it's also different for conditional probability of ground motion parameter $y \geq X$ for different magnitude earthquake. That is to say, integral of error function is different. From hazard curves, in this case that probability exceedance is the same, ground motion parameter $y \geq X$ for different magnitude earthquake is different. The function q is the fraction of earthquakes in the interval of magnitude $[M_l-\Delta M/2, M_l+\Delta M/2]$ which we can derive from

$$q(M, \Delta M) = \frac{10^{-b(M-M_0)}}{1-10^{-b(M_u-M_0)}}\left(10^{\frac{b\Delta M}{2}} - 10^{-\frac{b\Delta M}{2}}\right) \tag{7}$$

Gutenberg-Richter law in the above-mentioned equation is accumulative magnitude-frequency relation, and this equation can be transferred to incremental relation (Herrman, 1977), that is to say, the annual number of earthquake $N_I(M)$ with a particular magnitude M. Incremental magnitude-frequency relation still conforms to Gutenberg-Richter law, described as $N_I(M)=10^{A-BM}$. The transformational relation between the two relations is expressed as equation (8)

$$\begin{cases} N_I(M) = \int_{M-\Delta M}^{M+\Delta M}\left(-\dfrac{\mathrm{d}N_c}{\mathrm{d}M}\mathrm{d}M\right) = \left(-\dfrac{\mathrm{d}N_c}{\mathrm{d}M}2\Delta M\right) \\ b = B \\ a = A - \lg B - 0.3622 - \lg 2\Delta M \end{cases} \tag{8}$$

So that, after submitting equation (8) to equation (6), we derive

$$\lambda(y) = \sum_k \sum_l N_I(M_l) \Phi[y \geq X \mid Y(M_l, r_k, \sigma)] \tag{9}$$

The seismic hazard curve can easily be combined with the Poisson model to estimate probabilities of exceedance in finite time intervals. So the probability of exceedance of y in a time period T is

$$P(y, T) = 1 - \exp[-\lambda(y)T] \tag{10}$$

By combined with equations (4), (6), (9) and (10), the solved curves $P(y, T)$ is called seismic hazard curves. In current seismic zonation procedure, we usually employ maps of ground motion parameters with a 2%, 5%, and 10% probability exceedance in a 50-year period.

3.3 Result of calculation anddiscussion

Combined with equation above and distribution map of *a*-value (Figure 2), we calculate peak ground motion acceleration with 2%, 5%, and 10% probability of exceedance in a 50-year period in northern China. The results indicate that the peak ground motion distribution patterns are consistent with seismicity distribution patterns in this region. Taking Tangshan as example, we calculate peak ground motion acceleration distributions with several attenuation models including an attenuation relationship developed by Boore for the West United States (1997), the attenuation relationships used in the Eastern and Central United States (Frankel *et al*, 1996; Atkison and Boore, 1995; Toro *et al*, 1997; Campbell, 2003) and the attenuation relationships currently used in eastern China (YU, 2002), illustrated in Figure 3. As shown in Figure 3, while probability exceedance is less than 0.01, PGA derived from the attenuation relationships used in the Eastern and Central United States far exceed that derived from other attenuation relationships. It's controversial whether exceptional PGA derived from the attenuation relationships used in the Eastern and Central United States is reasonable. In the following results, we just propose equal weights results derived from YU's and Boore *et al*'s.

Figure 5 displays peak ground acceleration distributions with 2%, 5%, and 10% probability of exceedance in a 50-year period. At the level of 10% probability of exceedance in a 50-year period, there are several regions where PGA>1 m/s^2, such as Tangshan, Zhangjiakou, Taiyuan, Shijiazhuang and Linfen, *etc,* whereas PGA in the region of Beijing, Tianjin and Ji'nan *etc* is about 1 m/s^2. At the level of 5% probability of exceedance in a 50-year period, PGA in Tangshan area is greater than 2 m/s^2. Except for Ji'nan area, PGA in other regions is within the range of 1.6~1.7 m/s^2. At the level of 2% probability of exceedance in a 50-year period, PGA in major cities area reaches 2 m/s^2, whereas Tangshan has already been greater than 2.6 m/s^2. Comparing with current seismic hazard map of China (Figure 5d), we find that the peak ground motion distribution patterns with a 2% and 5% probability of exceedance in a 50-year period are consistent with current seismic hazard map of China, however in Baotou and Hohhot, our results show a little bit smaller peak ground motion acceleration, which is maybe due to incompleteness of seismicity data, whereas in some other specific seismic zones which include Shijiazhuang and Zhangjiakou areas, our results indicate obviously higher peak ground motions, which is consistent with events distribution displayed in Figure 1. The peak ground motion distribution in Shanxi area present disconnected belt patterns, high PGA corresponding to these areas distributed in the interior basin of Datong, Xinzhou, Taiyuan and Linfen. Compared with the result of current seismic hazard map of China (Figure 5d), we find distribution map derived from seismicity model in this study can better reflect regional tectonic patterns. These reasons are that grid divided in the calculation is denser, and that historical seismological data is more complete. Two thirds of PGA with a 2% probability of exceedance in a 50-year period is equal to new international earthquake-resistance level (Cramer, 2001). If the result obtained is multiplied by 2/3, we find that the peak ground motion distribution patterns in each metropolitan city of the northern China are consistent with current seismic hazard map of China (Figure 5d).

Figure 6 displays a map of 0.5% probability of exceedance in a 50-year period (recurrence time of 10 000 a) in northern China. As illustrated in Figure 6, PGA attained in each metropolitan city of the northern China has already reached 3 m/s^2. In this situation, even if we do not consider

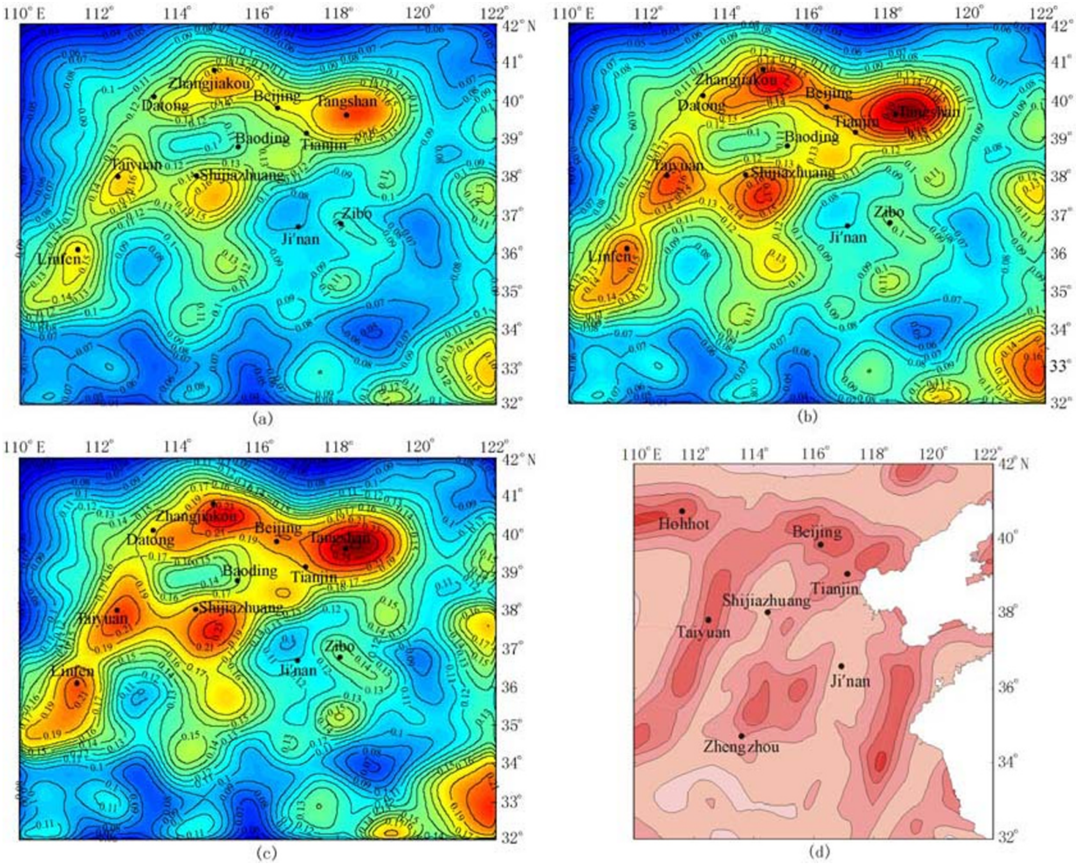

Figure 5 (a) Peak acceleration with 10% probability of exceedance in 50 years; (b) Peak acceleration with 5% probability of exceedance in 50 years; (c) Peak acceleration with 2% probability of exceedance in 50 years; (d) National seismic hazard map of peak ground acceleration distribution in the northern China (HU, 2001). The unit of peak ground acceleration is 10 m/s^2

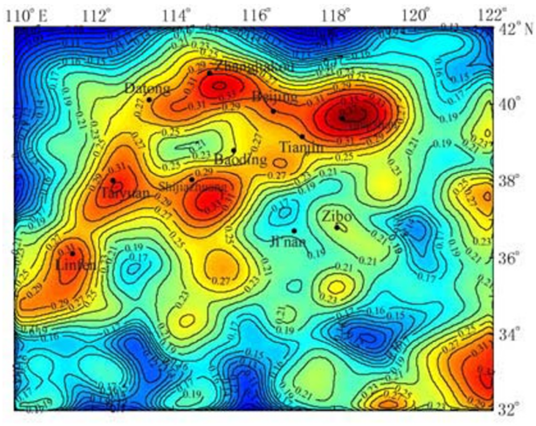

Figure 6 Peak acceleration (with unit in 10 m·s^{-2} with 0.5% probability of exceedance in 50 years

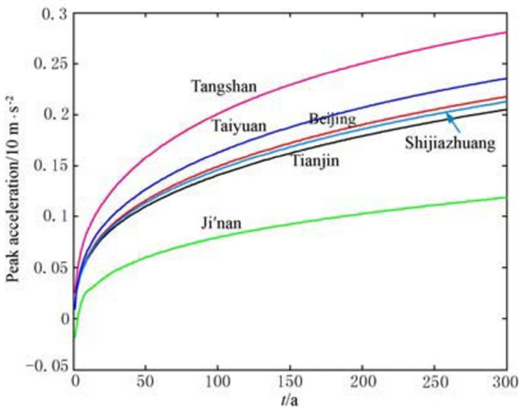

Figure 7 Hazard curve in the northern China with 10% probability of exceedance in 50 years

the effect of characteristic fault (*e.g.* Sanhe-Pinggu fault and Tangshan fault), PGA obtained in many metropolitan cities has exceeded 3 m/s^2. If we account for the influence of characteristic fault and directivity of finite fault, PGA in these areas could be higher. So the calculation of probability of exceedance mainly depends on tail integral of the logarithm of Gassian distributions. To avoid infinitely increase of peak ground motion acceleration for lower probability of exceedance and meet the requirements of engineering design, upper limit of integration is usually truncated by lgY+1σ, lgY+2σ or lgY+3σ. There are different opinions to the method of truncation. And research about this is directly related to defining upper bounds on earthquake ground motions (Bommer *et al*, 2004).

Figure 7 shows hazard curves for different periods with 10% probability of exceedance in a 50-year period in the regions of Beijing and Tangshan *etc.* As shown in Figure 7, peak ground acceleration reached in Tangshan area is highest; there is a lower peak ground acceleration obtained in Taiyuan, Beijing, Shijiazhuang and Tianjin areas; peak ground acceleration reached in Ji'nan area is lowest. Except for Shijiazhuang area, the results obtained above are consistent with current seismic hazard map of China.

We conduct a deaggregation procedure for the four areas of Beijing, Tangshan, Tianjin and Taiyuan with 10% probability of exceedance in a 50-year period. As the distance between source and site changed, we still estimated the influence of potential earthquakes in these areas, illus-

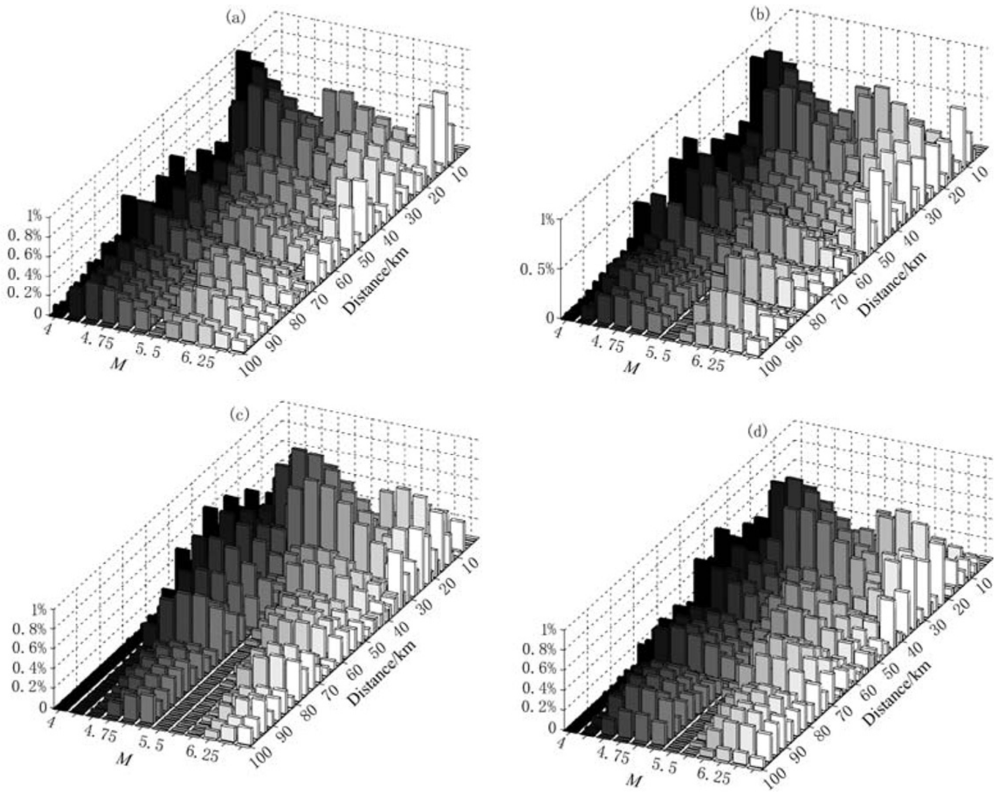

Figure 8 Probabilistic seismic hazard deaggregation in Beijing (a), Tianjin (b), Tangshan (c) and Taiyuan (d) for the 5% probability of exceedance in 50-year

The vertical axis denote contribution rate trated in Figure 8. Under the level of 5% probability of exceedance in a 50-year period, potential earthquakes with magnitude $M≤5.5$ and distance $R≤50$ km lead to significant hazard for Beijing area. Except for moderate and small earthquakes in near field, potential earthquakes with magnitude $M≥5.5$ and distance $R≥50$km significantly influence Tianjin area. In Tangshan area, moderate and small earthquakes within different distances are potential source. And Taiyuan area mainly suffers from moderate and small earthquakes in near distance. PSHA integrates over all possible earthquake occurrences and ground motions to calculate a combined probability of exceedance that incorporates the relative frequencies of occurrence of different earthquakes and ground-motion characteristics. Whereas the process of deaggregation requires that the mean annual rate of exceedance is expressed as a function of magnitude and/or distance. This information (similar magnitude and similar source-site distance) can be used to scenario earthquake and corresponding time histories for seismic design and retrofit (Kramer, 2003).

4 Conclusions

In this article, we do not conduct traditional zonation of potential source, just build three models of seismicty derived from seismic data in northern China, make a Gaussian smoothed procedure in this region, choose several applicable attenuation relations, and then calculate seismic hazard by using a non-zonified probabilistic methods. This method is particularly applicable in the region where seismic and geologic data are inaccurate and insufficient. For the area where there are plentiful seismic data, it's simple and convenient to calculate seismic hazard from applied and theoretical aspect. Moreover, the results derived from non-zonified probabilistic methods are similar to the results from traditional methods. This method is generally limited to calculate PSHA of magnitude $M<7.0$. For earthquake of large magnitude, we should consider the influence of characteristic fault (Frankel *et al*, 1996).

The results indicate that peak ground acceleration reached in Tangshan area at the level of 10%, 5%, 2% probability of exceedance in a 50-year period is highest; Taiyuan area takes second place; PGA in the regions of Beijing and Tianjin reaches the range of 1~1.5 m/s^2. The desegregation of probability of exceedance curves in the four areas of Beijing, Tangshan, Tianjin and Taiyuan indicates potential earthquakes with magnitude (4.0~6.0) and distance (10~50 km) lead to significant hazard for Beijing and Taiyuan areas. Therefore, we can choose strong motion records of earthquakes with similar magnitude and similar source-site distance for seismic design and retrofit. There are some deficiencies for this method. We welcome comments, suggestions and criticisms of the methodology presented here. The next step will optimize smoothing radius and introduce model of characteristic fault and elliptically smoothing model, and strive to make improvements for precise calculation of seismic hazard.

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