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Disaggregation of seismic hazard according to Chinese PSHA method

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ABSTRACT: Probabilistic seismic hazard analysis (PSHA) combines all the possible earthquakes affecting the site, but lost the concept of “real earthquake”. In China, the PSHA is modified to Probabilistic Seismic Hazard Analysis method considering spatially and temporally inhomogeneous seismic activity, but the concept of “real earthquake” is still ignored. To resolve this problem, disaggregation of seismic hazard according to Chinese PSHA method and determination of control earthquake & design earthquake are studied in this article. Finally, the tow principles are established, they are: (1) each design earthquake must have explicit seismogenic structure; and (2) design earthquake spectrum should be equal to the disaggregation target value.

KEYWORDS: CPSHA, design earthquake, seismogenic structure

1. INTRODUCTION

The basic theory of Probabilistic Seismic Hazard Analysis (PSHA) was defined by Cornell (1968) firstly. The method of PSHA was developed and used in practice in past decades of years, and become the most popular method used to analyze the earthquake hazard of a site. PSHA method gain an primary advantage over other methods because it can integrates over all potential earthquake occurrences to estimate ground motion parameters , such as peak ground motion acceleration, velocity, displacement and response spectrum, depends on the attenuation relations.

With the advantage of integration of all the possible earthquakes affecting the site, the lost of the concept of “real earthquake” is come to light. For example, a ground motion acceleration response spectrum with annual exceedence probability 10^{-4} determined by PSHA combines the contributions form many response spectrum from different earthquakes occur on different seismogenic structures, so there is no single event (specified by a magnitude and distance in simplest terms, and more parameters of epicenter and the path of seismic wave may needed) can represent the ground motion response spectrum. If define the earthquakes which contribute a spectrum value at one period, such as 0.1 second, as the set 0.1, it is almost definite that the contents of set 0.1 are different from that of set 1.0. So the probability-consistent response spectra, which are developed by PSHA, are controlled by different earthquakes at different period. It means that structures on the site would resist more than one earthquake which occur on different seismogenic structures with different magnitude and distance from site simultaneously. This is impossible.

At least there tow disadvantages according to probability-consistent response spectra: (1) it can not represent the affects by a specific earthquake, underestimated or overestimated; (2) the parameters, such as the duration or

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nonstationarity of frequency, can not be considered by probability-consistent response spectra. In the spatial correlation analysis of ground motions of lifelines and urban agglomeration and early warnings of strong ground motions, the scenario earthquakes with explicit location and magnitude are needed.

The tow disadvantages of PSHA were recognized by the Aki committee of national research council (1988). Based on the concept of effective magnitude M_e and effective distance R_e which are defined by McGuire and Shedlock (1981) to evaluate the uncertainty of seismic hazard, the Aki committee recommended the dominant earthquake to characterize hazard with more accurately. The dominant earthquake was the mean magnitude and distance of the seismic event that caused a ground-motion at the chosen annual exceedence probability. Without uncertainties in inputs, Japanese researchers Ishikawa and Kameda (1988, 1991, 1993) developed the concept of hazard-consistent magnitude and distance, recommended that $\overline{M}$ and $\overline{R}$ be determined individually for each period of interest and for each seismic zone that contributes to hazard. And Chinese researcher Gao Mengtan (1994) develop the concept of expected magnitude and distance, make the presumptive earthquake in contacted with the explicit seismogenic structures. Base on the research above, the later researchers, such as McGuire (1995), Bazzurro *et al.*(1999), and Takada *et al.*(2004) go further on how to determine the control earthquake (including the concept of dominant earthquake, hazard-consistent earthquake and expected earthquake and so on) base on the PSHA method on vary aspects.

2. BASICS OF CPSHA

The "Probabilistic Seismic Hazard Analysis method considering spatially and temporally inhomogeneous seismic activity" (Pan, 2003) is commonly used to assess seismic hazard in China. This method base on three necessary hypotheses about earthquake activity of potential sources: (1) uniform seismic activity spatially in one potential source; (2) no memory Poisson model of earthquake occurrence in one seismic belt; (3) truncated exponential recurrence relationship (modified G-R relationship) in one seismic belt. The potential source mentioned above is subarea in seismic belt to present the spatial and temporal inhomogeneity of seismic activity in one seismic belt, and it can not describe the spatially and temporally inhomogeneous features of China intraplate seismic activity. In general, the basic work of PSHA method is compartmentalization of seismic potential sources and seismic belts, and the determination of seismic activity parameters of them.

Base on the hypotheses mentioned above and elementary principle of probability theory, the ground motion A on the site is a random variable, probability of A exceeds the given a is

$$P(A \geq a) = 1 - \exp(-\sum_{i=1}^{Ns} \frac{\nu_i}{S_i} \sum_{j=1}^{Nm} f_{i,j} \int \left(\int\int f(m) P(A \geq a|E) dxdy \right) dm) \tag{2.1}$$

the equation (2.1) can write also as

$$P(A \geq a) = 1 - \exp(-\sum_{i=1}^{Ns} \sum_{j=1}^{Nm} \int \int\int P(A \geq a|E) \left(\frac{\nu_i}{S_i} f(m) f_{i,j} dxdydm \right) \tag{2.2}$$

where $\left(\frac{\nu_i}{S_i} f(m) f_{i,j} dxdydm \right)$ is occurrence probability of event E, which occur in the area element $dxdy$

belonging to potential source *i*, and the magnitude of *E* is *m* belonging to magnitude interval *j*; $P(A \geq a|E)$ is a conditional probability of *A* greater than or equal to *a* given the event *E*. This conditional probability presents discreteness of attenuation relation, which is presumed to follow the logarithmic normal distribution, and considering the physical constrain that $\ln A \in (\ln \overline{A} - 3\sigma, \ln \overline{A} + 3\sigma)$, $\overline{A}$ is expectation of random variable *A*, σ is logarithmic standard deviation, so

$$P(A \geq a|E) = \begin{cases} 0 & |\ln(\mathrm{a}) - \ln(\overline{\mathrm{A}})| > 3\sigma \\ 1 - \dfrac{\dfrac{1}{\sqrt{2\pi}\sigma}\displaystyle\int_{\ln(\overline{\mathrm{A}})-3\sigma}^{\ln a} \exp\left(-\dfrac{(t-\ln(\overline{\mathrm{A}}))^2}{2\sigma^2}\right)dt}{\dfrac{1}{\sqrt{2\pi}\sigma}\displaystyle\int_{\ln(\overline{\mathrm{A}})-3\sigma}^{\ln(\overline{\mathrm{A}})+3\sigma} \exp\left(-\dfrac{(t-\ln(\overline{\mathrm{A}}))^2}{2\sigma^2}\right)dt} & |\ln(\mathrm{a}) - \ln(\overline{\mathrm{A}})| \leq 3\sigma \end{cases} \tag{2.3}$$

if define $\varepsilon = \dfrac{\ln a - \ln(\overline{A})}{\sigma}$,then

$$P(A \geq a|E) = f(\varepsilon) = \begin{cases} 0 & |\varepsilon| > 3 \\ 1 - \dfrac{\Phi(\varepsilon) - \Phi(-3)}{\Phi(3) - \Phi(-3)} & |\varepsilon| \leq 3 \end{cases} \tag{2.4}$$

3. VARIABLES FOR DESIGN EARTHQUAKE

According to discussion above, we know that earthquake ground motions on site come from the earthquakes which occur around the site. The expectation of ground motion bins combine location (represented by distance from epicenter to site) and magnitude, marked as (M, D), can be computed by appreciate attenuation relation, namely $\ln \overline{A} = f_{att}(M, D)$, where fatt is average attenuation relation. If want to compute the given ground motion a (calculated by PSHA correlate with given exceedence probability), the discreteness of attenuation relation must be considered, as shown below

$$\ln a = f_{att}(M, D) + \varepsilon\sigma \tag{2.5}$$

So the control earthquake can be described by bin (*M*, *D*). Considering discreteness of attenuation relation, the parameters be used to define control earthquake is shown below

$$\begin{cases} \overline{M} = \sum_{i=1}^{n} m_i \bullet p_i \\ \overline{D} = \sum_{i=1}^{n} d_i \bullet p_i \\ \overline{\mathrm{E}} = \sum_{i=1}^{n} \varepsilon_i \bullet p_i \end{cases} \tag{2.6}$$

where p_i is the exceedence probability of given a by bin (M, D). If occurrence probability of bin (M, D) is p_i^M,

then $p_i = p_i^M \times f(\varepsilon)$, the p_i^M can be calculated by modified G-R relationship.

Most of the attenuation relations commonly used in China are based on ellipse model, and usually the attenuation relations are published as expressions along both major axis and minor axis. But the potential source is surround the site, so parameter θ, the included angle between seismogenic structure line and line linking epicenter on seismogenic structure to the site, must be considered in the definition of control earthquake when estimate the ground motion on the site by control earthquake, as shown below

$$\overline{\Theta} = \sum_{i=1}^{n} \theta_i \bullet p_i \tag{2.7}$$

So the parameters to be used define control earthquakes and estimate ground motion on the site should include the four below: the bin ($\overline{M}$, $\overline{D}$, $\overline{\mathrm{E}}$) described in equation (2.6) and the angle $\overline{\Theta}$ described in equation (2.7). The bin ($\overline{M}$, $\overline{D}$) define the control earthquake in narrow sense by magnitude and distance from epicenter to site, and the parameters bin ($\overline{\mathrm{E}}$, $\overline{\Theta}$) is used to estimate the ground motion by the control earthquake.

4. RESPONSE SPECTRUM BASED ON DESIGN EARTHQUAKE

According to the definition of control earthquake in previous chapter, the control earthquake can be seemed as an equivalent earthquake which ground motion on the site is equal to the given a. The parameters of control earthquake bin ($\overline{M}$, $\overline{D}$), can represent the whole seismotectonic settings of site. But the ground motions, especially the acceleration time history, are not be used in structure dynamics analysis, because the one control earthquake for whole seismotectonic settings can not represent local seismotectonic. For example, a control earthquake with magnitude 6.3 locates in a potential source whose upper-limit magnitude is 6.0. The instances as above are common. Thus the control earthquake becomes an earthquake which can not occur, so the structure dynamics analysis based on this earthquake is not meaning. So the control earthquakes with specific seismogenic structure are needed to be used in relevant analysis.

It is simple under CPSHA method to develop control earthquakes with specific seismogenic structure. In CPSHA method, each seismic potential source has one or more specific seismogenic structures in it. In a potential source an earthquake with magnitude less then the upper-limit magnitude follows spatial uniform distribution, which can occur everywhere in the potential source. So to find a control earthquake with a specific seismogenic structure, it is needed that control earthquake must be attached to one potential source. One or more among all control earthquakes can be as design earthquakes for a site.

In Figure 1 a site (plotted as a green solid triangle shape) and its seismotectonic settings are given. By CPSHA method, the peak ground motion (PGA) with annual exceedence probability 2×10^{-4} (approximative recurrence period 5000yrs) is 0.144g, which is the target value of disaggregation below. If considering only whole seismotectonic settings but the specific seismogenic structure, the control earthquake is $\overline{M}=6.33$ and $\overline{D}=53.5$. Review the distribution of potential sources, we found that there only tow potential sources (No. 14 and 25) in which an M6.33 earthquake can occur within radius 53.5km from site. If this control earthquake serves as the design earthquake, there are tow main problems: (1) it is difficult to determine which is seismogenic structure of the design earthquake, No. 14 or 25? (2) the sum of contribution ratio of the tow potential sources is about 1/3(see the table 1), the 2/3 contribution will be lost and deviate the whole seismotectonic settings of this region.

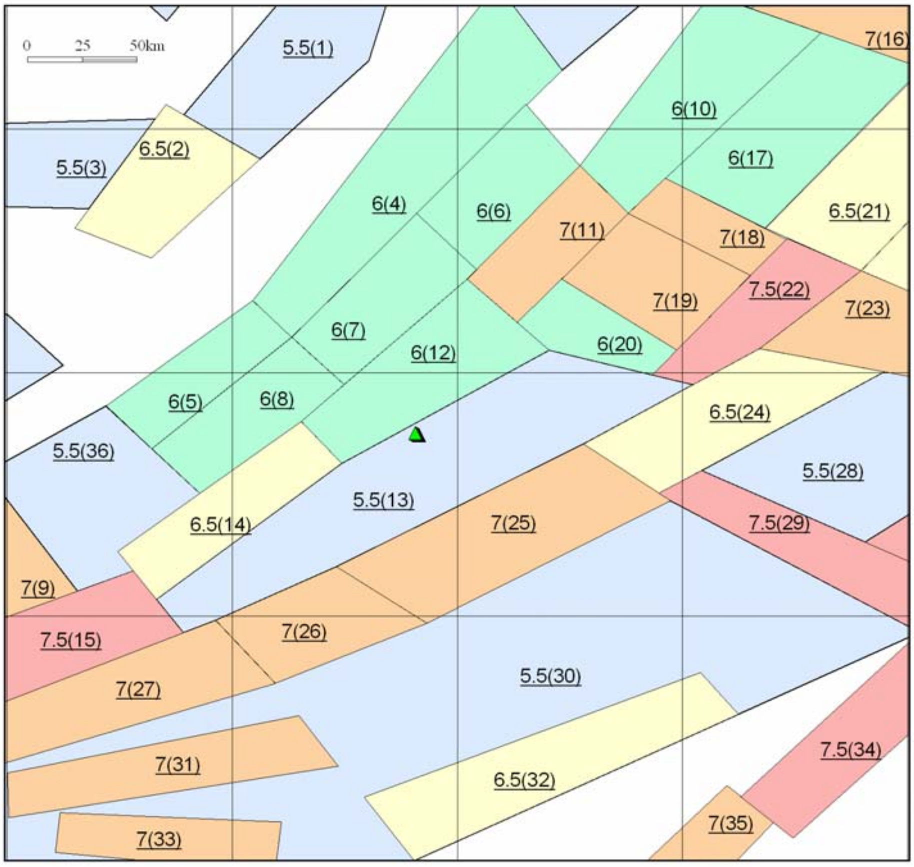

Figure 1 the site and its seismic potential sources compartmentalization
The polygons filled with different color is potential source,
and the number means upper-limit magnitude (serial number) of potential source

Now we review the spatial distribution of ground motion contribution (see figure 2). In the figure 2 the tow horizontal coordinates are longitude and latitude separately, the vertical coordinate is contribution ratio. Each column represents the ground motion contribution ratio on an micro-region (0.1° × 0.1°), and the different segments represent the different magnitude interval. All the columns are drawn according to scale. From the figure 2 and figure 1, we can found that most contribution of ground motion comes from tow magnitude intervals 5.0～5.4 and 5.5～5.9 of potential source 12 and magnitude interval 7.0～7.4 of potential source 25. So it is inconsequence that only one control earthquake is developed for a site. It should be more reasonable that one control earthquake is developed in a potential source, and one or more control earthquakes are chosen to be design earthquakes for structure dynamics analysis on the site.

According to this principle in last paragraph, several main potential sources are listed in table 1. The parameters $\overline{m}_i$, $\overline{d}_i$, $\overline{\theta}_i$ and $\overline{\varepsilon}_i$ describe the control earthquake for potential source i. The expectation of PGA is calculated by average attenuation relation, and the corrected value of PGA calculated according to equation (2.5). When the distance $\overline{d}_i$ small, the corrected value of PGA is larger then target value 0.144g, otherwise it is approximate equal to target value. To maintain consistency of fortification level, the expectation value of control earthquake should be scaled to equal to disaggregation target value. These scaled control earthquakes spectra, which can be called design earthquakes spectra, and the probability consistence spectrum with the annual exceedence probability 2×10^{-4} are drawn in figure 3 together.

Table 1 control earthquakes of every potential source

Number of potential source	Ratio of contribution	$\overline{m}_i$	$\overline{d}_i$ (km)	$\overline{\theta}_i$	$\overline{\varepsilon}_i$	expectation of PGA (gal)	corrected value of PGA (gal)
13	8.31%	5.31	17.3	17.5	1.62	0.073	0.190
12	35.42%	5.76	22.6	26.8	1.19	0.082	0.165
14	5.83%	6.32	51.9	26.9	1.73	0.053	0.147
26	2.40%	6.85	87.7	39.1	2.09	0.042	0.144
25	28.12%	6.79	57.5	59.9	1.44	0.061	0.143
11	9.65%	6.80	85.0	5.4	1.65	0.055	0.146
22	4.55%	7.34	140.5	28.2	2.08	0.042	0.143
29	4.81%	7.32	140.8	7.0	1.89	0.047	0.143

From figure 3 we can found there are relatively great difference among these design earthquakes, and vary widely from low frequency to high frequency. But most design earthquake spectra are less then the probability consistence spectrum. When the design earthquakes are chosen, the characters and contribution ratio of potential source must be considered. So for structure of which fundamental natural period is low, design earthquake 25 should be chosen firstly, and for structure of which fundamental natural period is high, design earthquake12 should be chosen firstly.

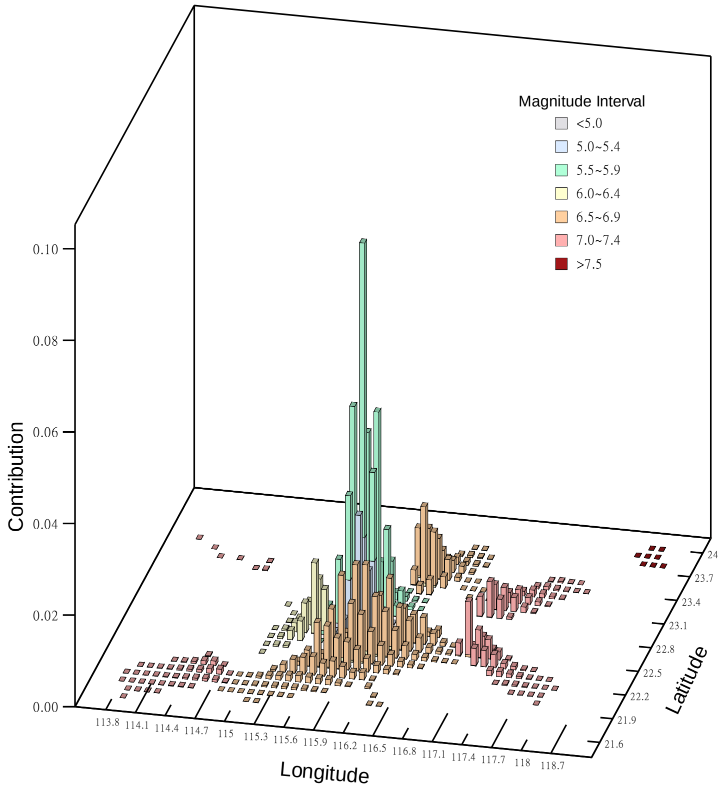

Figure 2 Combine distribution of spatial and magnitude which contribute to PGA on the site

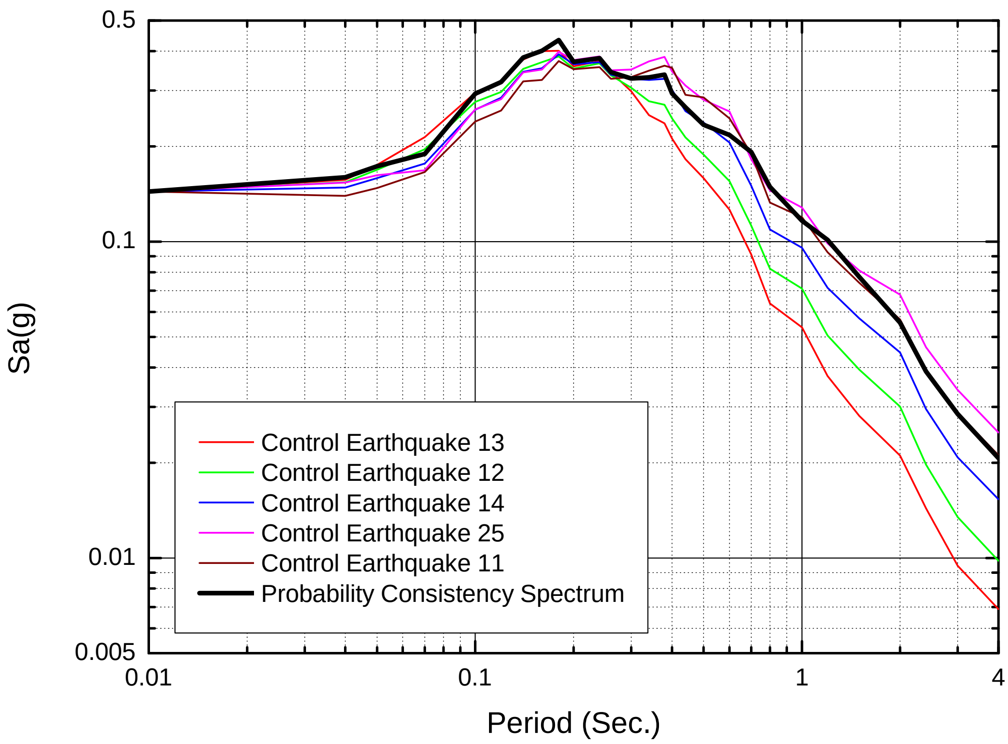

Figure 3 Comparison of main control earthquakes (design earthquake) spectra and probability consistence spectrum

5. CONCLUSION

According to discussion above, when considering the design earthquake for a specific site and a specific engineering structure, influence factors below should be considered:

(1) each design earthquake must have explicit seismogenic structure;

(2) design earthquake spectrum should be equal to the disaggregation target value, this can achieve by simply scaling the expectation of design earthquake spectrum or being corrected by discreteness of attenuation relation. The difference of this tow methods should be researched further.

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