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PROBABILITY-CONSISTENT SCENARIO EARTHQUAKE AND ITS APPLICATION IN ESTIMATION OF GROUND MOTIONS

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SUMMARY

This paper presents a new definition of probability-consistent scenario earthquake (PCSE) and an evaluation method of its magnitude, epicentral distance and orientation. As an example of application, corresponding to 3% probability of exceedance, the magnitude of PCSE near Shanghai area is 6.9, its epicentral distance is about 48 km and the orientation of the epicenter is $N70.4°E$. Observed records of the Lulong earthquake $M_L5.3$ in 1982 are chosen as empirical Green's function to synthesize ground motions of PCSE in the same area. The peak values of synthetic acceleragrams are about 130 Gal, which is consistent with the result analyzed by probability seismic hazard analysis method.

The conventional probability seismic hazard analysis method [Cornell, 1968] is useful to estimation of ground motion intensity for seismic design, but there is no seismic backgrounds, such as magnitude, epicenter and orientation, for the intensity. Another method, which is also often used for seismic design, is that the ground motions are simulated for a given scenario earthquake and a epicentral distance, but this method is deterministic method and the estimated motions are also deterministic rather than probabilistic. Some researchers suggested a concept of probability-consistent scenario earthquake that has the advantages of both methods. For the estimated ground motions by applying this concept, there is exceeded probability, and there are some physically meanings (magnitude and focal distance) too. [Ishikawa *et al,* 1988(a), (b) and Campos-costa *et al,* 1992]. Unfortunately, according to the existing definitions of scenario earthquake, the exceeding probability of a ground motion caused by a scenario earthquake is not strictly consistent with hazard level deduced from the probability seismic hazard analysis method.

The purpose of this paper is to present a new definition of **P**robability-**C**onsistent **S**cenario **E**arthquake (**PCSE**) and an evaluation method of its magnitude, focal distance and orientation. As an example, the methodology is applied in Shanghai area, where there are analysis results with the conventional probability seismic analysis method. At last, Observed records of the Lulong earthquake $M_L5.3$ in 1982 are chosen as empirical Green's function to synthesize ground motions of PCSE in the same area

INTRODUCTION

Definition of PCSE and its evaluation

2.1.1 Definition of PCSE

Using Ishikawa and Kameda approach [Ishikawa and Kameda, 1988 (a), (b)], expected values of magnitude and focal distance of hazard-consistent earthquake can be defined as

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$$\overline{M}_k = \sum_i \sum_j m_i P_k(m_i, r_j | Y \geq y(p_0)) \quad , \qquad (1)$$
$$\overline{R}_k = \sum_i \sum_j r_j P_k(m_i, r_j | Y \geq y(p_0))$$

here, $P_k(m_i, r_j | Y \geq y(p_0))$ is the condition probability of magnitude *m* and focal distance *r*. The condition is the ground motion intensity $Y \geq y(p_0)$, p_0 is probability exceedance obtained from hazard analysis and *k* means kth potential seismic source area. According to this definition, ground motion intensity *Y* caused in scenario earthquake (Magnitude is $\overline{M}_k$, focal distance is $\overline{R}_k$.) will be larger than $y(p_0)$, but the seismic design level in code should be $y(p_0)$. It means that the exceeded probability of intensity *Y* is smaller than p_0 and $\overline{M}_k$ satisfies equation

$$\overline{M}_k \in (M_k(p_0), M_u) , \qquad (2)$$

where $M_k(p_0)$ is the magnitude of potential earthquake in *kth* seismic zone, which can cause ground motion intensity $y(p_0)$ on site, M_u is the maximum magnitude of potential earthquake in *kth* zone.

In this paper the probability-consistent magnitude $\overline{M}_k(p_0)$ and probability-consistent focal distance $\overline{R}_k(p_0)$ are defined as conditional mean values corresponding to a given ground motion intensity $y(p_0)$, considering $\overline{M}_k(p_0)$, $\overline{R}_k(p_0)$ and $y(p_0)$ are restrained by attenuation relationship $y = f(M, R)$, then the definition can be expressed as following:

$$\overline{M}_k(p_0) = \sum_i \sum_j m_i P_k(m_i, r_j | Y = y(p_0)) \qquad (3)$$
$$\overline{R}_k(p_0) = f(M_k(p_0), y(p_0))$$

or

$$\overline{R}_k(p_0) = \sum_i \sum_j r_j P_k(m_i, r_j | Y = y(p_0)) \quad . \qquad (4)$$
$$\overline{M}_k(p_0) = f(R_k(p_0), y(p_0))$$

here, $P_k(m_i, r_j | Y = y(p_0))$ is the condition probability of magnitude *m* and focal distance *r*, the condition is the ground motion intensity $Y = y(p_0)$. If M_0 is the minimum magnitude and M_u is the maximum magnitude of potential earthquakes in potential seismic source area *k*, the PCSE $\overline{M}_k(p_0)$, which causes ground motion intensity $y(p_0)$ on site, satisfies

$$\overline{M}_k(p_0) \in (M_0, M_u) . \qquad (5)$$

Compare equation (2) and (5), it is obvious that there is difference between the two kinds of probability-consistent scenario earthquakes defined by equation (1) and equation (3) or (4), respectively. The exceeded probabilities of the scenario earthquakes defined by using former methods are smaller than p_0. It implies that the scenario earthquake defined by equation (1) is not a probability-consistent scenario earthquake (PCSE) (Luo, 1996).

1.1.1 Evaluation method of PCSE in model I potential seismic zone

In model I potential seismic zone in which the seismic fault is very clear, it is treated as line seismic zone [Kiureghian and Ang, 1977]. As shown in Fig.1, *AB* is a line potential seismic zone, whose length is *L*. The minimum magnitude in this seismic zone is M_0, the maximum magnitude is M_u. Assuming that r_1 is the minimum focal distance from site S to fault *AB* and r_2 is the maximum focal distance, focal distance $\overline{R}_k(p_0)$ of PCSE satisfies

$$\overline{R}_k(p_0) \in (r_1, r_2)\,. \tag{6}$$

In order to calculate focal distance $\overline{R}_k(p_0)$, the minimum focal distance $\overline{R}_{\min}(p_0)$ and maximum focal distance $\overline{R}_{\max}(p_0)$ of PCSE should be calculated. Considering ground motion $y(p_0)$ can be caused by small earthquake in near field and by large earthquake in far field, it is easy to obtain $\overline{R}_{\min}(p_0)$ and $\overline{R}_{\max}(p_0)$ with try-error method and ground motion attenuation relationship. $\overline{R}_k(p_0)$ is between r_1 and r_2, generally, $\overline{R}_{\min}(p_0)$ is equal to r_1. Because earthquake can occurred everywhere in seismic zone *AB*, the distribution of PCSE epicentres is assumed as uniform distribution, in line seismic zone this kind of uniform distribution can be replaced by uniform distribution of focal distance $r(p_0)$, which can be expressed as

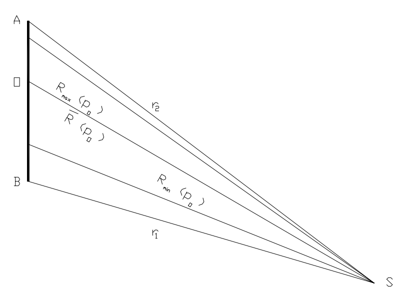

Figure 1. Mode I seismic source zone

$$f(r(p_0)) = \frac{1}{R_{\max}(p_0) - R_{\min}(p_0)}, \tag{7}$$

and the $\overline{R}_k(p_0)$ of PCSE can be calculated from

$$\overline{R}_k(p_0) = \frac{1}{2}(R_{\max}(p_0) + R_{\min}(p_0))\,. \tag{8}$$

By introducing $y(p_0)$ and $\overline{R}_{\min}(p_0)$, $\overline{M}_k(p_0)$ can be deduced from equation (4). The 'o' point in Fig.1 is the seismic centre of PCSE.

1.1.2 Application of PCSE in model II area

In model II potential seismic zone, the seismic fault is not clear, but its fault direction and distribution area are known [Kiureghian and Ang, 1977]. As shown in Fig.2, *ABCD* is a square potential seismic zone, without question the maximum distance r_2 and minimum distance r_1 from site 's' to seismic zone *ABCD* can be obtained easily. Also assuming that the minimum magnitude in this seismic zone is M_0, the maximum magnitude is M_u. As same as above, $\overline{R}_{\min}(p_0)$ and $\overline{R}_{\max}(p_0)$ can be deduced by try-error method. Corresponding to $\overline{R}_{\min}(p_0)$ and $\overline{R}_{\max}(p_0)$, $\phi_{\min}(p_0)$ and $\phi_{\max}(p_0)$ can be obtained. As mentioned above, earthquake may occurred everywhere in zone *ABCD*, the distribution of PCSE epicentres can be assumed as uniform distribution, in square seismic zone this kind of uniform distribution can be replaced by uniform distributions of focal distance $r(p_0)$ and uniform distribution of orientation $\phi(p_0)$. $\overline{R}_k(p_0)$ of PCSE can be calculated from

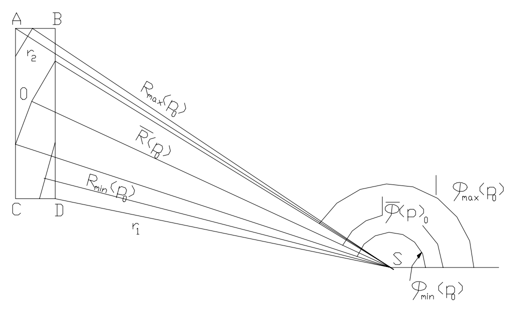

Figure 2. Model II seismic source zone

$$\overline{R}_k(p_0) = \frac{1}{2}(R_{\max}(p_0) + R_{\min}(p_0)), \tag{9}$$

and $\phi(p_0)$ of PCSE can be got from

$$\overline{\phi}_k(p_0) = \frac{1}{2}(\phi_{\max}(p_0) + \phi_{\min}(p_0)). \tag{10}$$

Then $\overline{M}_k(p_0)$ can be deduced from equation (4). Because $\overline{R}_k(p_0)$ and $\phi(p_0)$ are both known, the epicentre of PCSE is decided. 'o' point in Fig.2 is the seismic centre of PCSE.

1.2 Application of PCSE in Shanghai region

There are seventeen potential seismic zones in Shanghai area and Tongji University performed the probability hazard analysis in this area. According to their analysis, the potential source area *A* is one of the most important areas that have large contribution to the probability exceedance value p_0. Fig.3 shows the potential seismic source zone *A* and the site *S*, which is one site in Shanghai city centre, Corresponding to probability exceedance 63.2%, 10% and 3%, the peak accelerations on site *S* are 24Gal, 84 Gal and 130Gal, respectively (Zhang *et al*, 1990).

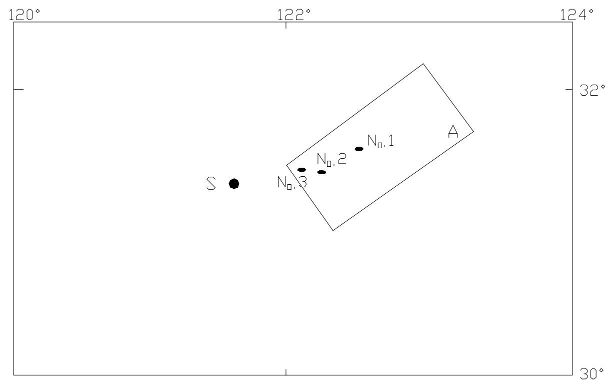

Figure 3. Potential source area *A* and site *S*

The attenuation equation of peak acceleration (Hu, 1988)

$$\log_{10} a = 1.71 + 0.657M - 2.18\log_{10}(R + 30) \tag{11}$$

is chosen to calculate PCSE. As the calculation method of PCSE in Model II seismic source area, three PCSEs were calculated from equation (3) and (11), whose magnitudes $\overline{M}(62.3\%)$, $\overline{M}(10\%)$ and $\overline{M}(3\%)$ are 6.5, 6.7 and 6.9, whose focal distances $\overline{R}(62.3\%)$, $\overline{R}(10\%)$ and $\overline{R}(3\%)$ are 97km, 57km and 48km and whose orientations $\overline{\phi}(62.3\%)$, $\overline{\phi}(10\%)$ and $\overline{\phi}(3\%)$ are *N*72.70°*E*, *N*80.75°*E*, *N*70.79°*E*. The three PCSEs are labeled with *No*.1, *No*.2 and *No*.3 in Fig.3.

2. STRONG MOTION SIMULATION OF PCSE

The most important application of PCSE is to apply it to estimating ground motions for seismic design. In this paper, as an example of application of PCSE, an improved empirical Green's function method (Luo, 1990) is used to synthesize ground motions on site S, the center of Shanghai city (see Figure 3), for one PCSE ($\overline{M}(p_0)$=6.90).

2.1 Empirical Green's function method

Since the appearance of empirical Green's function method (Harzell, 1978), in which the small earthquake record is treated as Green's function to synthesize large earthquake record, many researchers have applied this method and have made it more practical (Irikura, 1983, Dan *et al*, 1989, Luo *et al*, 1990, 1994). This method consists of three main steps: The first step is to decide the sub-fault numbers of a large earthquake fault. The second is to modify small earthquake record into that radiated from sub-fault event of large earthquake. The last is to add small event records together.

In this paper the records of Lulong earthquake (M_L5.3), which occurred in North China on 19, Aug, 1982, are chosen as Green's functions to synthesize the ground motions caused by large PCSE (M6.9), because Lulong earthquake rupture direction is *N*56°*E* that is almost as same as the directions of faults in potential source zone *A* (see Fig. 3). In North China and East China, many earthquakes are strike events (ESRI, 1994), so that the small and large events are assumed as strike events here. And the N_L, N_W and N_D, sub-event numbers along large fault length, width and dislocation, can be calculated from (Luo, 1990)

$$
\begin{aligned}
N_L &= \frac{L}{L_S} = \left(E\frac{M_0}{M_{0S}}\right)^{\frac{1}{3}} \\
N_W &= \frac{k}{k_s} N_L \\
N_D &= \frac{\overline{D}}{\overline{D_S}} = N_W \\
E &= \frac{k^2}{k_s^2}
\end{aligned}
\quad , \qquad (12)
$$

here the subscript s means the value of small earthquake event, *k* is ratio of the fault length to width, $\overline{D}$ is average dislocation. M_0 is seismic moment given by $\mu\overline{D}LW$. For rectangle strike fault event, it can be expressed as (Kanamori and Anderson, 1975)

$$M_0 = \frac{\pi}{2}\Delta\sigma LW^2 , \qquad (13)$$

here $\Delta\sigma$ is stress drop. Equation (12) is deduced from equation (13) and

$$M_0 = \mu\overline{D}LW . \qquad (14)$$

In this method the we apply the approximate source spectrum for the far-field shear wave displacement proposed by Brune (1970) to modify the observed small event motion into a motion radiated from an element fault of the large PCSE. The modification formula is described by (Dan, *et al* 1989, Luo and Dan, 1994, Luo and Hu, 1997)

$$A_{pqk}(\omega) = \left(\frac{r_s}{r_{pq}}\right)\sqrt{ab}\,d\left(\frac{\omega_{cs} + i\omega}{\omega_{cs}\sqrt{d}/\sqrt[4]{ab}\sqrt{c} + i\omega}\right)^2 \times \left(1 - \frac{2\pi}{Q}\right)^{\omega(r_{pq} - r_s)/4\pi\beta} A_s(\omega) . \qquad (15)$$

Here, the subscripts *s*, *pq*, and *pqk* indicate the values for the small event, the (*p*, *q*) sub-fault of the large fault and the (*p*, *q*, *k*) element of the large event, respectively. *r* is the hypocentral distance, μ is the rigidity, β is the shear-wave velocity, *i* is an imaginary unit and *Q* is the quality factor. *a*, *b*, *c* and *d* are ratios of the fault length *L*, the width *W*, the average dislocation $\overline{D}$ and the stress drop $\Delta\sigma$ of the large event to those of the small event, respectively. ω_c is the corner frequency given by $\omega_c = 2\beta\sqrt{\pi\lambda\Delta\sigma / M_0}$, and $\lambda = \sqrt{LW/\pi}$ is the size of the source. The geometric attenuation and intrinsic attenuation of the propagation wave are considered in terms of r_s / r_{pq} and *Q*, respectively. An estimated acceleration $a(t)$ of a large earthquake can then be written by

$$a(t) = \sum_{p=1}^{N_L}\sum_{q=1}^{N_W}\sum_{k=1}^{N_D} a_{pqk}(t - t_{pqk}) , \qquad (16)$$

here $a_{pqk}(t)$ is the Fourier inverse transform of $A_{pqk}(\omega)$, t_{pqk} is the travelling time lag for the rupture process, the wave propagation and the rise time for dislocation.

2.2 Source parameters

Two records recorded on TS-2/Beijiadian station are chosen as empirical Green's functions, because the focal distance from TS-2 station to Lulong earthquake epicenter is about 41 km, that is similar to the focal distance from site S to PCSE in Fig.3. The site soil is stiff, belong to B class soil (from Private letter from Prof. K. Peng, 1998). Its source parameters are chosen from Luo, *et.al* (1990) and shown in Table 1. By using the source parameters in Table 1 and Brune spectrum model mentioned above (Brune, 1970), the theoretical Fourier spectra of small event can be calculated. The comparison of the theoretical spectra and Fourier spectra of the observed record in Fig.4 implies that the chosen source parameters of the small event are acceptable. Acceleration time history of small event is shown in Fig. 5.

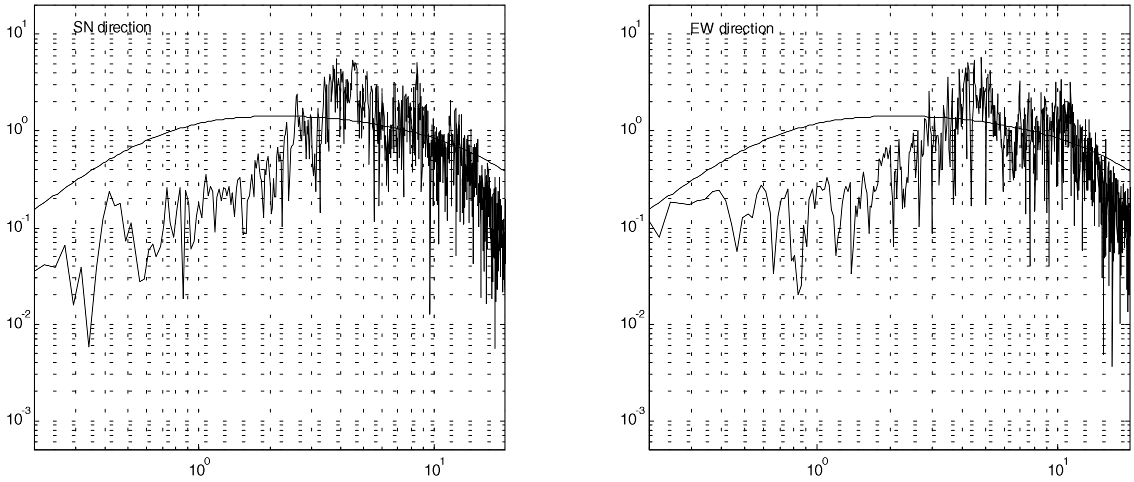

Figure 4 Comparison of theoretical spectra and observed Fourier spectra

Reference to equation (17) that is for magnitude between 5.5 to 8.5 in the East China proposed by R. Dong (ESRC,1994)

$$M = 4.04 + 1.69 \log_{10} L \quad (17)$$

and other materials, the fault length L of the PCSE M6.9 is chosen as 45 km. It is assumed that the fault width W of large event is the half of the fault length and the value of stress drop $\Delta\sigma$ is equal to small event. Other necessary parameters can be calculated from equations (12), (13), and (14). All the parameters of small and large events are listed in Table 1.

Table 1 Source parameters of small and large events

Magnitude	M_L5.3	M6.9
M_0(N·m)	3×10^{16}	7.1×10^{19}
$L\times W$(km^2)	3.4×3.4	45×22.5
$\Delta\sigma$(10^5Pa)	20	20
Depth(km)	9.6	15
$\overline{D}$ (m)	0.08	2.14
N_L	-	20
N_W	-	10
N_D	-	10
Shear wave β(km/s)		3.0
Rupture velocity V_R(km/s)		2.5
Quality Q		500

2.3 Synthetic accelerogram

The shear wave velocity β and the fault rupture velocity V_R adopted here are 3.0 km/s and 2.5 km/s respectively. The rise time τ of dislocation is calculated from $\tau = \mu\overline{D}/(\beta\Delta\sigma)$ (Geller, 1976). Bilateral rupture pattern is considered, peak values of synthesised accelerations of PCSE in SN and EW directions are 127 Gal and 138 Gal, respectively. Subsequently, the acceleration response spectra of synthesised results are calculated. Fig. 5 shows the observed small event records and synthesised accelerations. Fig. 6 shows the synthesised acceleration response spectra of PCSE.

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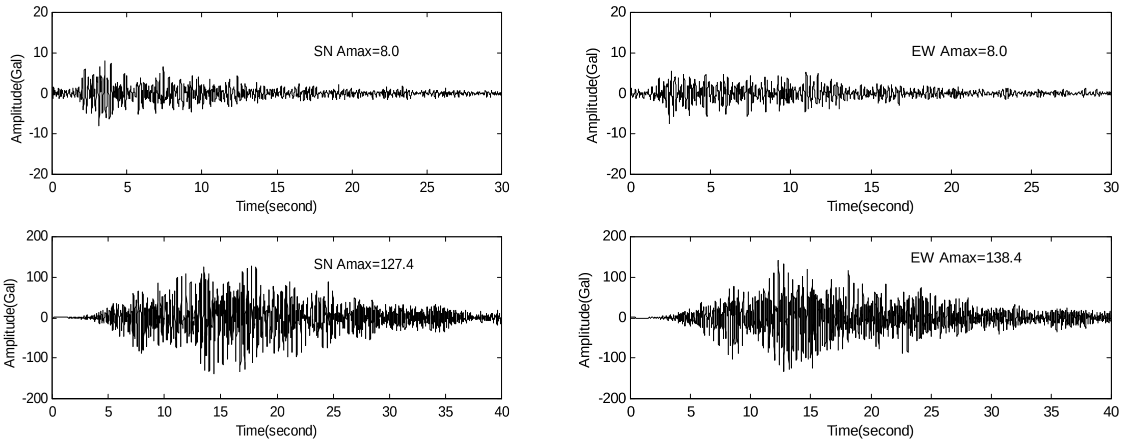

Fig.5. Observed small event records (UP) and Synthesized accelerations of PCSE

3. CONCLUSION

A definition of **P**robability-**C**onsistent **S**cenario **E**arthquake (**PCSE**) and its evaluation method were proposed in this paper. This definition is different from the former scenario earthquake definition, which is not consistent with exceeded probability p_0 calculated from conventional probability hazard analysis method. Because not only the exceeded probability of the ground motion intensity caused by PCSE is consistent with p_0, but also its magnitude, focal distance and orientation can be known, this definition is very useful for earthquake disaster mitigation.

The PCSE definition was applied in Shanghai region. The result shows that, corresponding to 3% probability of exceedance, the magnitude of PCSE near Shanghai area is *M*6.9, its focal distance is about 48 km and the orientation of the epicenter is *N*70.4°*E*. The application proves that the suggested evaluation method of PCSE is applicable.

The observed records of Lulong earthquake M_L5.3 in 1982 are chosen as empirical Green's function to synthesize ground motions for PCSE. The peak values of synthetic acceleragrams are about 140 Gal, which are almost equal to the results calculated by the probability hazard analysis. The result shows that PCSE is useful in estimation of ground motions for seismic design. The synthesized results also imply that the improved empirical Green's function method is valuable for strong motion simulation.

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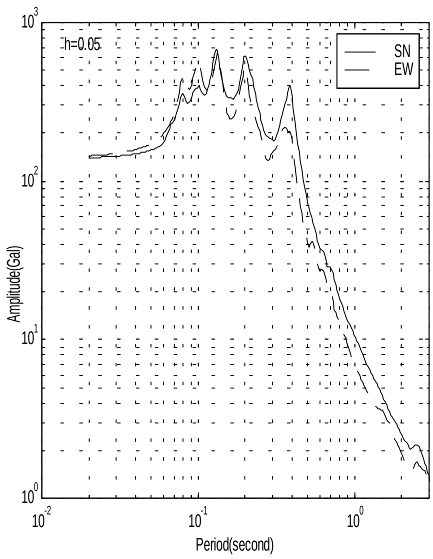

Figure 6 Response spectra

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