GROUND MOTION ATTENUATION RELATIONSHIP BASED ON STOCHASTIC METHOD

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ABSTRACT

For regions without adequate strong ground motion records, a method is developed to establish strong ground motion attenuation relationships, based on the stochastic method. Sendai area of Japan (N36°~40°, E138°~143°) is selected as the target, since there are enough data from seismographic observation for calculation, and those from strong ground motion observation and some empirical relationships for result testing.

Three parameters related to regional source and crustal medium are inversed by the micro-Genetic Algorithm. Total of 240 records from 77 small events (M_w=3.5~4.5, focal depth≤30 km) in two directions, recorded by F-net, are adopted for the inversion. Fourier spectra are adopted as the objective function. These parameters are then taken into the stochastic method to estimate the root-mean-square acceleration and velocity (A_{rms} and V_{rms}) and the peak factor (γ_m), PGA or PGV is the product of A_{rms} or V_{rms} and γ_m.

The regional ground motion attenuation relationships, for PGA and PGV, are compared with strong ground motion records from K-NET (M_w≥4.5, focal depth≤30 km, equivalent shear-wave velocity≥500 m/s) and empirical relationships. There is a great agreement, which can illustrate the reliability of this method.

Keywords: Attenuation relationship, Inversion, Regional parameters.

1. INTRODUCTION

Ground motion attenuation relationship is essential in the field of earthquake engineering, which describes the effects of source, path and local site condition on ground motion. Most relationships are empirical, strong ground motion observation records are the foundation. So, this kind of method is just effective for regions with enough data, like in western US and Japan.

Nowadays, more and more instruments for strong ground motion observation have been or are being installed in some earthquake-prone countries. However, it is difficult to install these instruments around the epicenters of future earthquakes, since it is impossible to predict the places. Moreover, even this kind of instruments have been installed, it could be a long time before big earthquakes occur, since it is impossible to predict the time. So, for most countries or regions without enough strong ground motion observation records, it is necessary and urgent to develop a method for establishing strong ground motion attenuation relationships. On the other hand, there are many digital broadband seismographic networks, even in China. For instance, the Global Seismographic Network (GSN), which is a globally distributed digital seismic network, and real-time data can be obtained.

The purpose of this study is to develop a method, which can establish strong ground motion attenuation relationships for regions with few or without strong ground motion records. Records from F-net in small earthquakes are adopted to inverse by the micro-Genetic Algorithm.

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2. DATA

Sendai area (N36°~40°, E138°~143°) is selected as the target region. In the target region, there are 12 F-net stations, Fourier spectra of last 10 records from each one, except some low-quality ones, are adopted as the objective function for inversion. These records are from 77 earthquakes (M_w=3.5~4.5, focal depth⩽30 km, Nov. 2006~Apr. 2010). However, in this database, there is no record on near field (Hypocentral distance < 50 km), and there is no earthquake with shallow focal depth (D < 5 km), and those with focal depth 10 km~20 km are less than others.

For comparison, there are 2743 records from 1325 earthquakes (M_w⩾4.5, focal depth⩽30 km, Jan. 1996~Apr. 2010), recorded by 29 K-NET bedrock stations ($\overline{V}_{S30}$ ⩾500 m/s) in this region. The database structures of F-net and K-NET are shown in Table 1, in which there is a little bit difference.

Table 1(a). Database structure - Hypocentral distance

Hypocentral distance (km)	F-net records	K-NET records
<100	17	1995
100~200	64	567
200~300	34	145
≥300	5	36

Table 1(b). Database structure - Depth

Depth (km)	Earthquake Number (F-net)	Earthquake Number (K-NET)
<10	36	347
10~20	12	666
20~30	29	312

3. THEORY AND METHODOLOGY

3.1. Stochastic Method

Assuming that the far-field accelerations on an elastic half space are band-limited, finite-duration and white Gaussian noise, and the approach is based on Brune ω^2 source spectrum, the Fourier spectrum on a site can be presented as (Boore, 2003),

$$FA(M_0,f,R)=\frac{R_{\theta\phi}FV}{4\pi R_0\rho_s\beta_s^3}\times\frac{M_0}{1+\left(\frac{f}{f_0}\right)^2}\times\exp\left(-\frac{\pi f R}{Q(f)\beta_s}\right)\times\frac{1}{\left[1+\left(\frac{f}{f_{\max}}\right)^8\right]^{-1/2}}\times(2\pi f)^z\times G(R)\times A(f) \tag{1}$$

where, $R_{\theta\square}$ is the radiation pattern of the shear excitation, with the assumption that the energy was equally partitioned into two horizontal components; F is the free surface effect; V is the vectorial partitioning of shear wave energy into two components of equal amplitude; R_0 is a reference distance; ρ_s is the density in the vicinity of the source; β_s is the shear-wave velocity in the vicinity of the source; M_0 is the seismic moment; f is the frequency; f_0 is the corner frequency, $f_0=4.9\times10^6\times\beta_s\times(\Delta\sigma/M_0)^{1/3}$, $\Delta\sigma$ is the stress drop; f_{max} is the high-frequency cutoff frequency; z is the index variable, z=0, 1 and 2 is for displacement, velocity and acceleration; R is the hypocentral distance; $Q(f)$ is the function of frequency, which describes the crustal medium, $Q(f)=Q_0f^\eta$; $G(R)$ is the geometric spreading function; $A(f)$ is the amplification factor of near surface amplitude as a function of hypocentral distance R and frequency f.

According to the relation between Fourier spectrum and power spectrum and the definition of spectral moment, the latter can be calculated by the following numerical integration,

$$m_k = 2\int_0^{f_{\max}} (2\pi f)^k \left|FA(M_0, f, R)\right|^2 df \tag{2}$$

where, k=0, 2 or 4 denotes the zero-order spectral moment, the second-order spectral moment and the fourth-order spectral moment of ground motion

According to the Parseval's Theorem and the definition of root-means-square (rms) acceleration, A_{rms} is

$$A_{rms} = \left(\frac{m_0}{T}\right)^{1/2} \tag{3}$$

where, T is the duration used in computing A_{rms}, which is the sum of source duration T_s and oscillator decay time (Boore and Joyner, 1984).

The peak factor γ_m, which describes the ratio of peak to rms motion, is calculated by the following numerical integration (Boore, 2003),

$$\gamma_m = 2\int_0^{+\infty} \left\{1 - \left[1 - \xi \exp\left(-z^2\right)\right]^{N_e}\right\} dz \tag{4}$$

where, ξ is the bandwidth factor; N_e is the number of extrema.

Then, PGA or PGV can be calculated as a product of the rms acceleration A_{rms} or the rms velocity V_{rms} and the peak factor γ_m.

3.2. Inversion Strategy and Results

Micro-Genetic Algorithm (μGA) is adopted for the inversion. Premature phenomenon and local optimum can be avoided and global optimum can be found quickly by this algorithm.

For large and shallow earthquakes, $\Delta\sigma$ varies from about 10 bars to 100 bars (Shearer, 2009), which is one inverse parameter. In some researches, $\Delta\sigma$ is set as 80 bars (Atkinson and Silva, 2000). Q is the frequency-dependent quality factor of shear waves, which describes the energy loss from anelastic processes or internal friction during wave propagation. Usually, η is 0.5~1.0 (Wang, 2007). For Tohoku area, Matsumoto (1989) suggests η equals to 0.6~1.2. Since Q is a factor related with the crustal medium rather than the size of earthquakes, Q_0 and η are other two inverse parameters.

The objective function is the residual sum of squares between the calculated Fourier spectrum and the objective spectrum from observed records, which describes the fitting. The objective function □$_j$ is

$$\phi_j = \sum_m \sum_n [FA_0(m,n) - FA_j(m,n)]^2 \tag{5}$$

where, m is observed records (one direction); n is the points on a Fourier spectrum; FA_0 is the objective Fourier spectrum; FA_j is the calculated Fourier spectrum from generation j.

Fitness is calculated from the objective function by Eq. (6), which is between 0 and 1.

$$F_j = e^{-\beta\phi_j} \tag{6}$$

where, β is the fitness coefficient, which effects the evolution of the μGA to a large extent.

In this inversion, Fourier spectra on the frequency range of 0.1 Hz~10 Hz, from 120 records in each direction, are adopted as the objective. The ranges of inverse parameters are determined as $\Delta\sigma$=70~150 bars, Q_0=150~300 and η=0.6~1.0. After searching among 2000 generations by μGA, the optimum solution is listed in Table 2.

Table 2. Inverse result

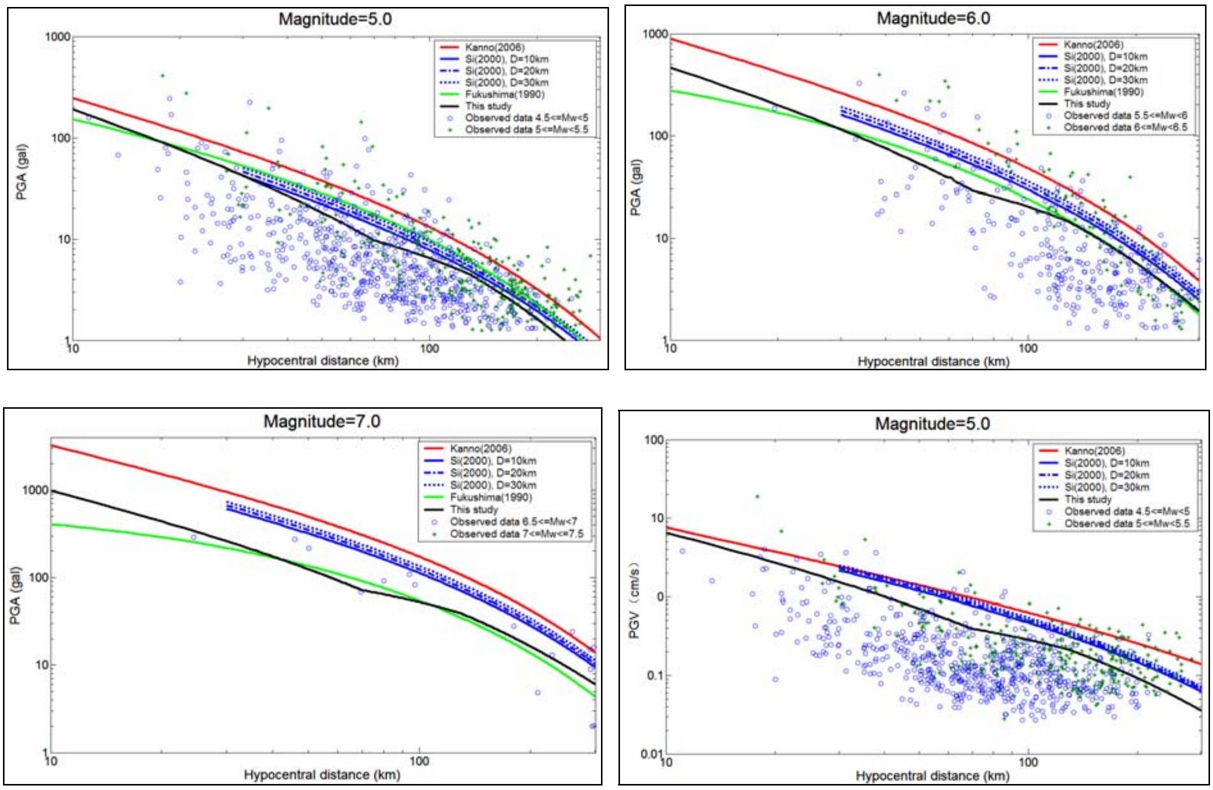
$\Delta\sigma$ (bars)	Q_0	η
89.1095	173.1040	0.6201

By taking these parameters into the stochastic method, the strong ground motion attenuation relationships for PGA and PGV are obtained, which are the maximum values in two horizontal directions.

4. COMPARISONS

4.1. PGA Attenuation Relationship

Strong ground motion attenuation relationships obtained above (PGA and PGV) are compared with strong ground motion records and some empirical relationships, as shown in Figure 1. Strong ground motion records are from K-NET and empirical relations are from Kanno (2006), Si (2000) and Fukushima (1990). The PGA and PGV of K-NET are the maximum values in two horizontal directions.



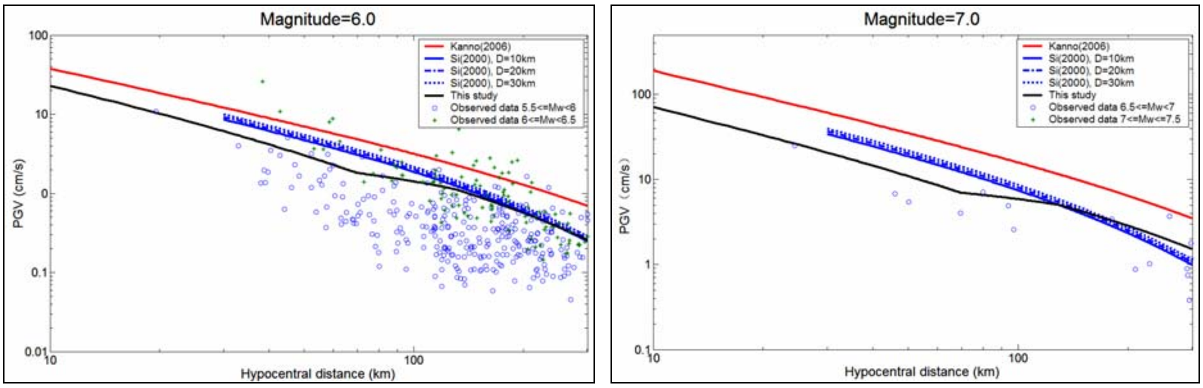


Figure 1. Comparison on attenuation relationships

It is shown that the results are lower than empirical relations on medium and far fields (hypocentral distance > 30 km), and on the near field, they are higher than Si's and Fukushima's relations, close to Kanno's. However, these results just pass through the strong ground motion records. It is reasonable, for instance, the relation for M_w=5 is compared with the records from earthquakes with M_w=4.5~5.5.

Comparisons between the mean residuals, defined by Eq. (7), from this thesis and empirical relations are shown in Table 3. These data are separated into three groups, $4.5 \le M_w < 5.5$ (M_w=5), $5.5 \le M_w < 6.5$ (M_w=6) and $6.5 \le M_w \le 7.5$ (M_w=7).

It is obvious that the residuals from this method are the lowest. So, compared with other relations, results from this study are closer to the observation data.

$$\overline{residual} = \frac{1}{N}\sum_{i=1}^{N}\log_{10}\left(\frac{predicted \quad value}{observed \quad value}\right) \tag{7}$$

Table 3. Comparison of mean residuals

	Relations	M_w =5	M_w =6	M_w =7
PGA	Kanno (2006)	0.3793	0.3896	-1.0288
	Si (2000)	0.0947	0.1324	-1.1666
	Fukushima (1990)	0.0500	-0.1189	-1.8428
	This study	0.0255	0.0172	-0.8191
	Relations	M_w =5	M_w =6	M_w =7
PGV	Kanno (2006)	0.5982	0.5709	0.2075
	Si (2000)	0.3338	0.2142	-0.6674
	This study	0.2087	0.1732	-0.1695

5. CONCLUSIONS

For the regions with few or without strong ground motion records, a method to establish strong ground motion attenuation relationships, based on the stochastic method, is developed. Sendai area in Japan is selected as the target. Regional source and crustal medium parameters, the stress drop $\Delta\sigma$, and the parameters indicating quality factor (Q_0 and η), are inversed by μGA from small earthquakes (M_w=3.5~4.5), recorded by a seismographic network F-net. The database involves 120 records on each horizontal component, from 77 earthquakes with focal depths less than 30 km. Then, these inverse parameters are taken into the stochastic method to calculate the root-mean-square acceleration and velocity, A_{rms} and V_{rms}, as well as the peak factor γ_m. Attenuation relationships for PGA and PGV are obtained. These results are compared with strong ground motion records from K-NET and some

Japanese empirical relationships. There is an excellent agreement between predicted values and observed data.

6. RECOMMENDATION

This method is proved primarily that it can establish strong ground motion attenuation relationships for regions without abundant strong ground motion records. However, there are still some parts can be improved:

(a) Observed records on the near-field or with shallow focal depth can be added to the database for the inversion;
(b) Values on the highest one or five frequencies can be adopted as the objective function, since PGA is mainly dominated by high-frequency values;
(c) Geometric parameters used in this thesis are empirical, so they can be other inverse parameters;
(d) The selection of the objective function can be more reasonable;
(e) Uncertainty from the selection and determination of parameters can be considered.

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