# The selection and scaling of ground motion records for great scenario earthquakes based on the condition mean spectrum

**Li Lin**
*Institute of Engineering Mechanics, China Earthquake Administration, Harbin， 150080 Heilongjiang， P.R.China*
*Harbin University，Harbin，150080 Heilongjiang，P.R.China*

**Wen Ruizhi，Zhou Baofeng & Shi Dacheng**
*Institute of Engineering Mechanics, China Earthquake Administration, Harbin， 150080 Heilongjiang， P.R.China*

**SUMMARY:**
In this paper, PEER Ground Motion Databases (PGMD) at the Pacific Earthquake Engineering Research Center (PEER) was updated by 141 groups of ground motion records in Japan Tohoku earthquake on March 11, 2011，which expanded the application of this database. Following the disaggregation results from probabilistic seismic hazard analysis, the scenario earthquake and the conditional mean spectrum (CMS) were set up as the target requirement and the selection and scaling of ground motions for the great scenario earthquake was addressed finally. The results show that the expanded database could make the different selection and scaling of strong motion records in great earthquakes, and the suggested method could be applied for the strong motion records selection in structural spectrum analysis.

*Keywords: magnitude 9.0 conditional mean spectrum selection and scaling*

## 1. INTRODUCTION

The code for seismic design of building requires that dynamic time-history analysis should be adopted in the seismic design of high-rise buildings and other important structures. Selection ground motion is a key step in defining the seismic load input of structural analysis[1,2]. Many scholars put forward that the variability of ground motion records play an important role in structure desgin. How to choose the ground motion is critical. At present, actual records or simulated ground motion was usually to match a target mean response spectrum, while the actual records can reflect more information of seismic, compared with the simulated. The Pacific Earthquake Engineering Research Center (PEER) ground motion NGA database includes 3551 sets of three-component records from 173 earthquakes from 1456 recording stations[3-6]. The PEER Ground Motion Database contains 3182 sets of three-component records and each of them has an unique order number and other related information : distance, site characterizations, earthquake source and so on. Their magnitude scale is from 5.0M to 8.0M, and distance scale is 0—200km. There are no records of magnitude above 8.0M. In addition, the ground motion prediction equation of acceleration response spectrum is the foundation of the target response spectrum's builing. So the NGA ground motion prediction equations should be verified to appropriate or modulated. The application of PGMD is still subjected by the data resource,and the selection of ground motion records for great earthquakes should be considered..

Based on the 141 groups of ground motion records in Japan Tohoku earthquake on Mar. 2011[7], a ground motion prediction equation of acceleration response spectrum was built. Following the disaggregation results from any PSHA calculation and the conditional mean spectrum (CMS) method, the selection and scaling of ground motions for the great scenario earthquake was addressed[8-10].

## 2. TARGET RESPONSE SPECTRUM

It is the consensus principle to select ground motion records matching target response spectrum. Target spectrum, including code spectrum, uniform hazard spectrum and condition mean spectrum, represents the demand of structure design. The code spectrum is the average of response spectrum of records in large quantity[11]. And it is a statistical average. For the general structure, it is used to determine the earthquake effect in the static analysis. In the structure dynamic analysis, code spectrum is not feasible to be target spectrum. Firstly, code spectrum in seismic code was not satisfied the period of tall building. Secondly, code spectrum was not considered the effect of nearly fault earthquakes[12]. So, it is difficult to predict the appropriate structure response in the future earthquakes.

Uniform hazard spectrum (UHS) is a site spectrum, based on the probability seismic hazard analysis. A uniform hazard spectrum is defined as the locus of points such that the spectral acceleration value at each period has an exceedance probability equal to the specified target probability form probability seismic hazard analysis(PSHA) [13]. UHS is only a set of response spectrum envelope with the same exceed probability at all period points. UHS is thus not representative of the spectra of any individual ground motion. It will make an unsatisfactory target spectrum. In structure time-history analysis using UHS as the target spectrum, the result will conservation, in contrast with a real ground motion recordings[6].

Baker (2005) proposed a target spectrum termed the conditional mean spectrum (CMS), which shows several improvements over the commonly used uniform hazard spectrum (UHS)[14]. The CMS consists of the mean values of the spectrum at all periods, conditional on a target spectral acceleration value at the period of interest[9]. The $\varepsilon$ ($T_1$) is defined as the number of standard deviations by which the log of the ground motion's spectral value differs from the mean log prediction at given period $T_1$[13]. To build a CMS, we can use the mean value of $\varepsilon(T_i)$ at other periods, given that we know the value of $\varepsilon(T_1)$. The $\varepsilon(T_i)$ value at any other period is equal to the $\varepsilon(T_1)$ multiplied by the correlation coefficient between the two $\varepsilon$ values[9]. The CMS can be computed using the mean from attenuation relationship plus standard deviation multiplied by the $\varepsilon(T_i)$. The shape of CMS associated with the $\varepsilon(T_1)$, so ground motions matching spectral shape can be treated that naturally have the target $Sa(T_1)$ value, which is PSHA and PDSA results. CMS requires existing ground motion attenuation relationship.

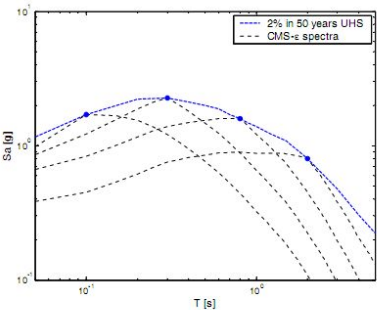


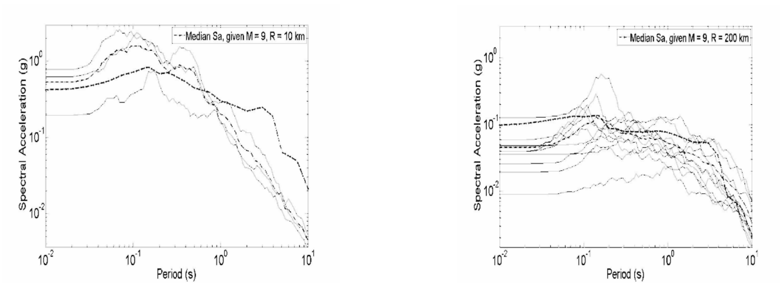

**Figure 1.** 2% in 50-years uniform hazard spectrum at Van Nuys site, along with several conditional mean spectra, considering ε (CMS-ε), conditioned on Sa(T) at four different values of T (0.1, 0.3, 0.8 and 2 sec)[13]

## 3. GROUND MOTION PREDICTION MODELS

Ground motion prediction models (equations) (GMPM) have inputs such as earthquake magnitude, distance from source to site, average shear-wave velocity, fault type and so on and the logarithmic mean and standard deviation of spectral acceleration (Sa) as the outputs. The PEER Next Generation Attenuation (NGA) Program has studied five groups different ground motion prediction models. We only choose two of them to be extrapolated to 9.0M. Then, we verify that weather it is suitable for great earthquake or not. Boore[15] and his colleagues published ground motion prediction equations (GMPEs) in 2007, which were derived as part of the PEER NGA project, using an extensive database of thousands of records. The regress analysis used 1,574 records from 58 main shocks in the distance range from 0 km to 400 km. Predicting ground motions equation is:

$$\ln Y = f_m(\mathbf{M}) + f_d(R_{jb},\mathbf{M}) + f_s(V_{s30},R_{jb},\mathbf{M}) + \varepsilon\times\sigma \quad (1)$$

The model is abbreviated as BA. In this equation, M is moment magnitude, $R_{jb}$ is the Joyner-Boore distance (defined as the closest horizontal distance to the surface projection of the fault plane), and Vs30 is the time-averaged shear-wave velocity from the surface to 30 m. ε is the fractional number of standard deviations of a single predicted value of lnY away from the mean value of lnY. All terms, including the coefficient σ, are period dependent [15]. The equations are applicable for M=5–8, RJB=0–200km, and VS30=180–1300$m^2$/s [15]. We will create a observed versus predicted spectral acceleration for the 2011 9.0M Japan earthquake. To see a summary of these values quickly, fig.2 (a) (b). For this example, $R_{jb}$ is 10km and 200km, respectively. Vs30 is 760m/s2. Unfortunately, recordings is not available in the 10km that would allow us to apply a mean of similar distance (from 0km to 20km) recordings, see figure2 (a). In the 200km, we apply a mean of similar distance (from 190km to 210km) recordings, see figure 2 (b). BA ground motion prediction models extrapolated to 9.0 magnitude，the mean observed spectral acceleration is bigger than predicted spectral acceleration at short periods and smaller at long periods, figure 2(a). When $R_{jb}$ is 200km，the mean observed spectral acceleration is bigger than predicted spectral acceleration at short periods while resemblant at long periods, figure 2(b).



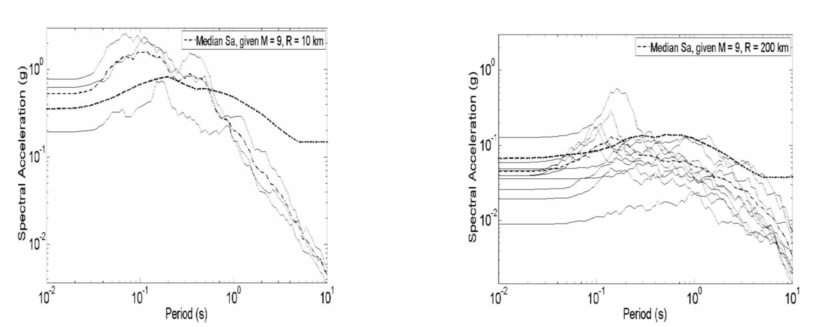

(a) (b)

**Figure 2.** Compared with 9.0 magnitude ground motion records in Japan and BA attenuation model of acceleration response spectrum (a) R=10Km, (b) R=200Km

K. W. Campbell and Y. Bozorgnia [16,17] published ground motion prediction equations (GMPEs) in 2008, as part of the PEER NGA project, using thousands of records, abbreviated as CB. Predicting ground motions equation is:

$$\ln Y = f_1(M) + f_2(R) + f_3(F) + f_4(HW) + f_5(S) + f_6(D) + \varepsilon \quad (2)$$

In this equation, f1(M), f2 (R), f3 (F), f4 (HW), f5 (S) and f6 (D)represent the magnitude scaling, distance function, faulting earthquakes mechanism and hanging wall sites effect, site amplification and deep soil depth scaling respectively. We also create a observed versus predicted spectral acceleration for the 2011 9.0M Japan earthquake, figure 3 (a) (b). For this example, the predictor variables are 9.0M, $R_{jb}$=10/200km, and $V_{S30}$=760m2/s. We apply a mean of similar distance (from 0km to 20km) recordings, instead of 10km compared with CB predicted spectral, see figure 3 (a). In the 200km, we apply a mean of similar distance (from 190km to 210km) recordings, see figure 3 (b). CB ground motion prediction models extrapolated to 9.0 magnitude，the mean observed spectral acceleration is bigger than predicted spectral acceleration at short periods while smaller at long periods, figure 3(a). In the 200km，it is similar at short periods. The mean observed spectral acceleration is bigger than predicted spectral acceleration at long periods, figure 3 (b).




(a) (b)

**Figure 3.** Compared with 9.0 magnitude ground motion records in Japan and CB attenuation model of acceleration response spectrum (a) R=10Km, (b) R=200Km

As mentioned before, there are big differences between the observed value and the predicted spectral acceleration for 9.0M, especially at short periods. The ground motions predicted spectral acceleration models are not suitable for 9.0M earthquakes. So we analyze the database coming from the Japan 2011 to get ground motion prediction equation.

## 4. GROUND MOTION PREDICTION EQUATIONS OF JAPAN 9.0M

There is 9.0M earthquake in Japan Tohoku on Mar. 2011. K-NET seismic station network obtain a lot of strong vibration observation data, which would be downloaded on the K-NET wet. We get 273groups ground motions records published by K-NET. But only 141groups have the integral seismic parameters. In the data, moment magnitude is 9.0M, and the closest horizontal distance to the surface projection of the fault plane is from 10km to 643km, and $V_{s30}$ the time-averaged shear-wave velocity from the surface to 30 m is from 210m/s to 2270m/s. The PGMD was expanded by 141 groups of ground motion records in Japan Tohoku earthquake on Mar. 2011. Based on the Tohoku ground motion records, an attenuation model of acceleration response spectrum was built.

In the study, the records were processed with TSPP program, strong vibration data processing method, proposed by David Boore [18]. Butterworth filter is used, and usable frequency is 0.1Hz--25Hz. We computed the peak acceleration (PGA), peak velocity (PGV), peak displacement (PGD), and pseudo spectral accelerations (5%-damped) at 105 periods as the parameters to select ground motion records. Pseudo spectral acceleration is in units of g. The value is the geometric average of the two orthogonal horizontal components orientated randomly. Figure 4 is the distribution of K-NET strong-motion stations.

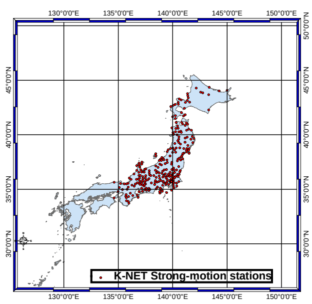
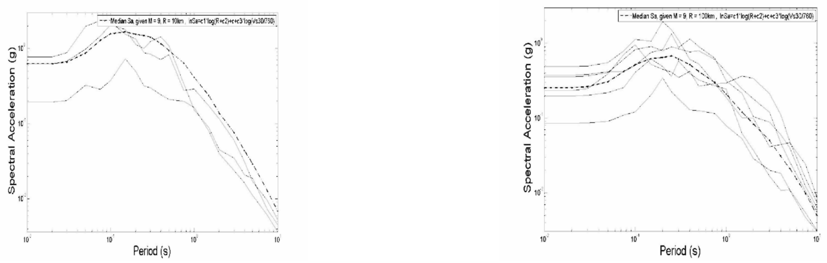



**Figure 4.** The distribution of K-NET strong-motion stations

Based on the Tohoku 9.0M ground motion records, an attenuation model of acceleration response spectrum was built, see formula (3). This paper proposes a ground motion prediction equations which is a function of two independent variables, distance from source to site and local average shear-wave velocity. This equation is for pseudo spectral accelerations (5%-damped) at periods between 0.01 s and 10 s. Regression coefficients of the model are determined by the regression analysis, nonlinear Gauss-Newton least squares method in our study. In addition, PGA is from 0.001 to 1.9048g.To simplify the regression analysis, magnitude is considered as constant, and the correlation between the magnitude and distant is eliminated. So this ground motion prediction equation is only applied to 9.0M thrust fault earthquake, and it is an addition to current ground motion prediction equations. Predicting ground motions equation is:

$$\ln Y=c+c1\times\ln(R+c2)+c3\times\ln(V_{s30}/760) \qquad (3)$$

In this equation, R is the distance from source to site, and $V_{s30}$ is the time-averaged shear-wave velocity from the surface to 30m represented site amplification. The regressing coefficients are c, c1, c2, c3. The equation is abbreviated as LL. All terms are period dependent. Table1 is the regression coefficients of LL ground motion prediction equation of acceleration response spectrum. Compared with acceleration response spectrum value of ground motion record 9.0 magnitude in Japan and LL attenuation model with $V_{s30}$=760m/s$^2$ , R=10km and R=200km, see Figure 5(a) (b). We get LL –GMPM as the basis for the CMS.




(a) (b)

**Figure5.** Compared with 9.0 magnitude ground motion records in Japan and LL attenuation model of acceleration response spectrum (a) R=10Km, (b) R=200Km

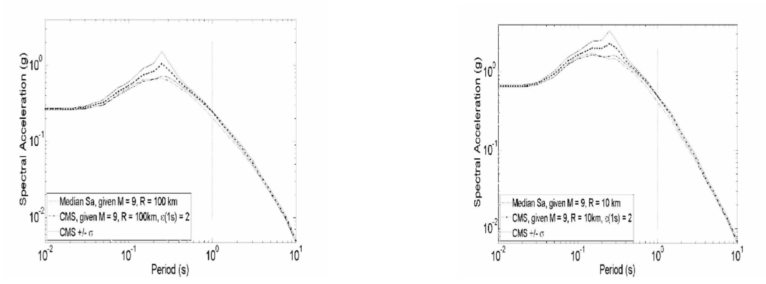
**Table 4.1.** Regression coefficients of LL-GMPM of acceleration response spectrum

| *period* | *c1* | *c2* | *C* | *c3* | *Err* |
|---|---|---|---|---|---|
| 0.00 | -25.15 | 2448.77 | 195.91 | 0.51 | 0.03 |
| 0.05 | -24.03 | 2014.24 | 182.79 | 0.78 | 0.09 |
| 0.075 | -24.39 | 1916.31 | 184.71 | 0.59 | 0.12 |
| 0.10 | -24.21 | 1911.29 | 183.48 | 0.48 | 0.11 |
| 0.15 | -25.61 | 2291.24 | 198.8 | 0.44 | 0.21 |
| 0.20 | -26.14 | 2656.27 | 206.65 | 0.43 | 0.27 |
| 0.25 | -27.23 | 3083.8 | 219.23 | 0.4 | 0.44 |
| 0.30 | -26.84 | 2828.49 | 213.79 | 0.16 | 0.28 |
| 0.40 | -25.51 | 2780.75 | 202.53 | 0.33 | 0.14 |
| 0.50 | -24.04 | 2651.77 | 189.56 | 0.21 | 0.06 |
| 0.75 | -24.05 | 2789.68 | 190.41 | -0.06 | 0.03 |
| 1.00 | -22.35 | 2895.64 | 177.33 | -0.07 | 0.01 |
| 1.50 | -18.97 | 2467.82 | 146.83 | -0.32 | 0.01 |
| 2.00 | -19.2 | 3349.84 | 153.95 | -0.07 | 0.01 |
| 3.00 | -19.83 | 4234.92 | 163.04 | -0.11 | 0.01 |
| 4.00 | -19.21 | 4904.74 | 160.12 | -0.18 | 0.01 |
| 5.00 | -18.14 | 5204.28 | 151.7 | -0.19 | 0.01 |
| 7.50 | -16.8 | 5395.14 | 140.07 | 0 | 0.01 |
| 10.00 | -17.3 | 4697.81 | 141.31 | -0.05 | 0.01 |

## 5. EXAMPLES

Shome et al proposed that the most efficient way to estimate the nonlinear structure response of a given earthquake is to estimate the mean spectral acceleration by GMPM, and then to scale the ground motion records to the mean value as inputs to dynamic analysis [19]. Matching a target response spectrum is a common selection ground motions method. The target spectrum representing ground motion intensity and structure characteristics can give realistic estimates of structural response. The PEER Ground Motion Database is to select ground motion records that are for dynamic structure analysis. The PGMD selects acceleration records from the PEER-NGA database that satisfy the user-specified selection criteria and provide good fits to the target response spectrum [1,2]. The PGMD provides three methods to generate the target spectrum. Three options are (1) PEER-NGA Model; (2) User defined spectrum; (3) ASCE/SEI Standard 7-05 code specified spectrum [1,2]. PEER-NGA Model is defined for a specific scenario earthquake defined in terms of magnitude, distance and site conditions, based on five groups NGA GMPM[9-13]. CMS is the target spectrum developed from the PEER-NGA models. It can be constructed using ground motion models and the value of epsilon at a interest period and the expected values of epsilon at other spectral periods which are used to computed by using the correlation model developed by Baker and Jayaram (2008). Scale the record to match the target spectrum over a period range. Record scaling by applying a linear scale factor does not change the shape of the response spectrum of the ground motion records. A basic criterion with the best-matching records is that the mean squared error (MSE) of the difference between the spectral accelerations of the record and the target spectrum is the lowest MSE. There is an example of selection ground motion records, given a specific scenario earthquake, based on expanded PGMD by 9.0M, to generate CMS as the target spectrum and select best-matching records.

We take formula(3) LL ground motion prediction models instead of NGA ground motion prediction models, to generate CMS as the target spectrum of 9.0M. There are the examples:(a) A specific scenario earthquake using probabilistic seismic hazard analysis (PSHA), is 9.0M thrust fault earthquake of the seismic source. Distance from the site to the fault rupture is Rjb=100km, and VS30 is 760m/s2 used to describe the site condition. For example, the ground motion levels are two standard deviation above the median at interest periods T=1s (epsilon = 2.0) by probabilistic seismic demand analysis (PSDA). (b) Rjb=10km，other conditions are the same as (a). Figure 6(a) shows a CMS created for the example (a) of an epsilon value of 2.0 at a spectral period of 1.0s. Figure (b) shows a CMS created for the example (b).




(a) (b)

**Figure 6.** 9.0 magnitude conditional mean spectrum

We adopt the algorithm to select ground motions that match the CMS spectrum mean and variance [8]. First of all, generate CMS as the target spectrum, given a specific scenario earthquake in terms of magnitude, distance and site conditions and based on LL GMPM. The selection algorithm, which was proposed by Jayaram N. et al, first used Monte Carlo simulation to probabilistically generate multiple response spectra from a distribution parameterized by the target means and variances. For each simulated response spectrum, a ground motion with a similar response spectrum is then selected[8]. We take the spectrum in figure 6 (a), as a target spectrum, with the above selecting ground motion method, from the added PGMD and PGMD respectively, select a set of 10 ground motions for the scenario earthquake earlier (magnitude = 9.0M, $R_{bj}$ = 10km, $V_{s30}$=760$m^2$/s, $T_1$ = 1s and $\varepsilon(T_1)$ = 2).The result of selection records and scale factor can be seen from table 2, 3. The measure of matching is represented the MSE between the target spectrum and the response spectrum of a record. From Table 2, it can be seen that there are three 9.0M records in ten, and their scale factor(SF) are 1.01,2.78,1.44. From figure 7（a）, we can see the correlations of the magnitude and SF. The SF is smaller for 9.0M compared with other magnitude. We can see the correlations of the magnitude and distant or the time-averaged shear-wave velocity from figure 7(b)(c). From figure 7(d)(e)(f), we can see the correlations of the magnitude and PGD, and $R^2$ , the coefficient of determination between SF and PGA, is 0.736. The coefficient of determination between and PGV is almost zero, but R2 is 0.567with M<8, and 0.999 with M=9.0. The coefficient of determination between SF and PGV is 0.911， and the correlations of SF and PGA, PGV, PGD are significant. No constraints on the SF for selection are used, but such constraints are easily accommodated by simply restricting the PGA, PGV, and PGD of the selected recordings.

**Table5.1** The results of selection ground motion records from PGMD expanded by 9.0M records

| *Record Number* | *Sequence Number* | *Scale Factor* | *Magnitude* | *R* | *soil_Vs30* | *PGA* | *PGV* | *PGD* |
|---|---|---|---|---|---|---|---|---|
| 1 | 410 | 2.82 | 5.77 | 8.5 | 376.1 | 0.3 | 18.24 | 3.03 |
| 2 | 413 | 2.84 | 5.77 | 7.7 | 376.1 | 0.3 | 17.88 | 4.24 |
| 3 | 3679 | 1.01 | 9.0 | 51 | 560.0 | 0.71 | 9.38 | 9.38 |
| 4 | 957 | 4.6 | 6.69 | 15.87 | 821.7 | 0.14 | 9.09 | 2.05 |
| 5 | 1089 | 4.28 | 6.69 | 10.31 | 376.1 | 0.26 | 13.76 | 3.13 |
| 6 | 3784 | 2.78 | 9.0 | 110 | 1080 | 0.31 | 3.42 | 3.42 |
| 7 | 1078 | 1.98 | 6.69 | 1.69 | 715.1 | 0.25 | 16.06 | 5.96 |
| 8 | 3725 | 1.44 | 9.0 | 11 | 2020 | 0.78 | 7.23 | 7.23 |
| 9 | 763 | 2.49 | 6.93 | 9.19 | 729.7 | 0.33 | 26.94 | 5.33 |
| 10 | 3549 | 5.56 | 6.69 | 15.46 | 659.6 | 0.19 | 8.1 | 2.31 |

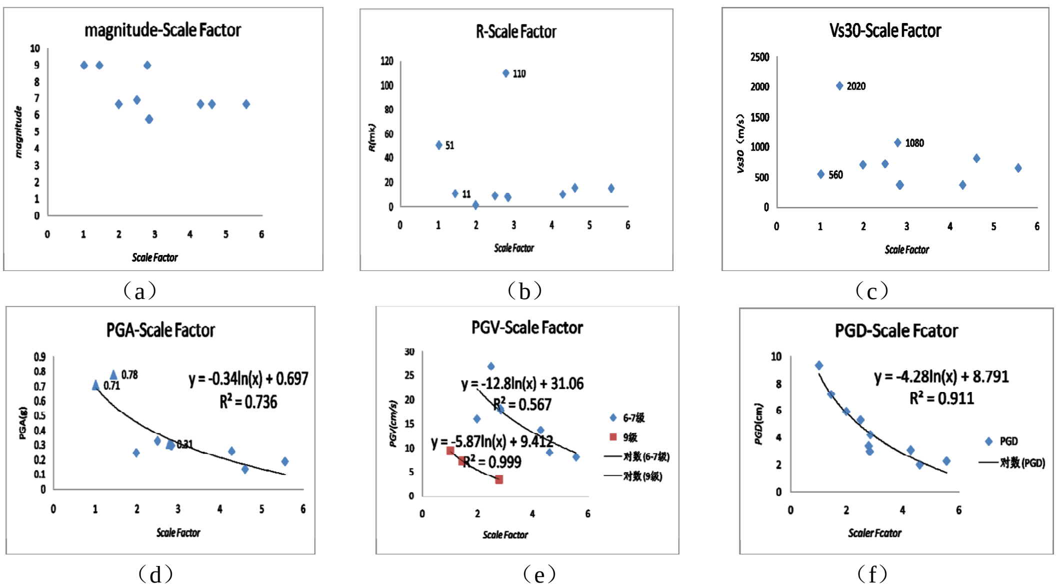
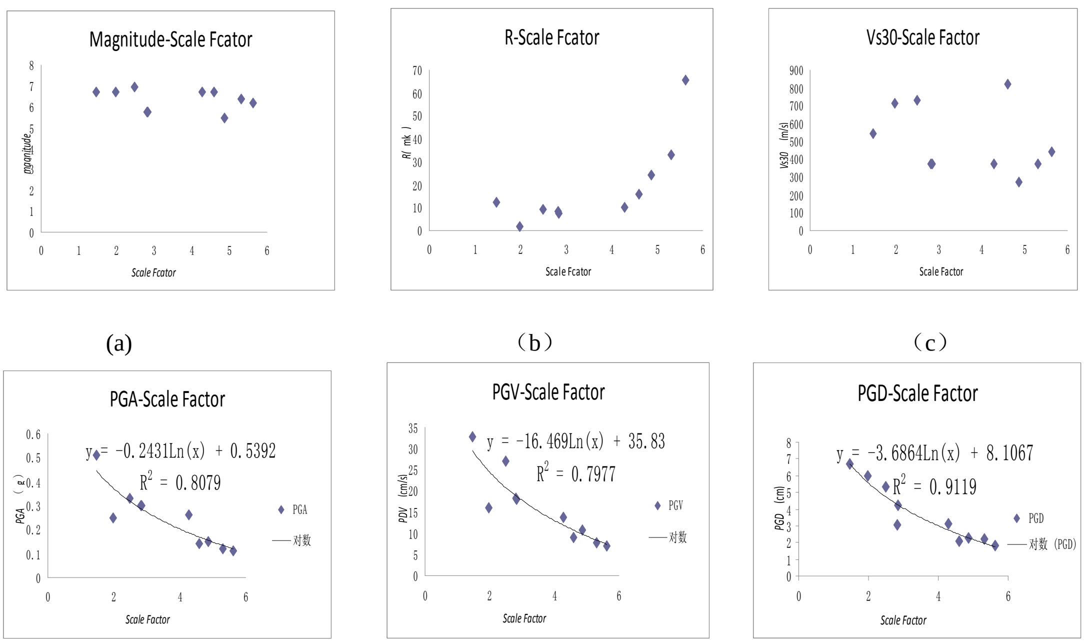



**Figure 7.** Logarithmic linear correlation between scalar factor and earthquake intensity parameters(PGMD expanded by 9.0M records)

The result of selection records and scale factor can be seen from table 3, with the above selecting ground motion method and target spectrum from PGMD. The correlations of the SF and earthquake or ground motion intensity parameter can be seen from figure 8(a-e). Compared with table 2 and 3, the mean of SF is 2.98 and 3.63 respectively, and the mean of PGA is 0.357and 0.247 respectively. The results show that 9.0 magnitude ground motion records in Japan expand the magnitude application of PGMD which could be applied to the probability spectrum analysis.

**Table 5.2** The results of selection ground motion records from PGMD

| *Record Number* | *Sequence Number* | *Scale Factor* | *Magnitude* | *R* | *soil_V$_{s30}$* | *PGA* | *PGV* | *PGD* |
|---|---|---|---|---|---|---|---|---|
| 1 | 410 | 2.82 | 5.77 | 8.5 | 376.1 | 0.3 | 18.24 | 3.03 |
| 2 | 413 | 2.84 | 5.77 | 7.7 | 376.1 | 0.3 | 17.88 | 4.24 |
| 3 | 2954 | 5.63 | 6.2 | 65.81 | 442.2 | 0.11 | 6.98 | 1.83 |
| 4 | 957 | 4.6 | 6.69 | 15.87 | 821.7 | 0.14 | 9.09 | 2.05 |
| 5 | 1089 | 4.28 | 6.69 | 10.31 | 376.1 | 0.26 | 13.76 | 3.13 |
| 6 | 763 | 2.49 | 6.93 | 9.19 | 729.7 | 0.33 | 26.94 | 5.33 |
| 7 | 1078 | 1.98 | 6.69 | 1.69 | 715.1 | 0.25 | 16.06 | 5.96 |
| 8 | 952 | 1.47 | 6.69 | 12.39 | 545.7 | 0.51 | 32.82 | 6.67 |
| 9 | 562 | 4.87 | 5.44 | 24 | 271.4 | 0.15 | 10.66 | 2.29 |
| 10 | 357 | 5.31 | 6.36 | 32.81 | 376.1 | 0.12 | 7.87 | 2.22 |




(d) (e) (f)

**Figure 8.** Logarithmic linear correlation between scalar factor and earthquake intensity parameter(PGMD)

## 6 CONCLUSIONS

This study built an attenuation model of acceleration response spectrum based on the Tohoku ground motion records. Following the conditional mean spectrum (CMS) method, the selection and scaling of ground motions for the great scenario earthquake was addressed from PGMD expanded by 9.0M ground motion records. Here are some advices. First, it is necessary to add the current mete using the great earthquake. Second, adjust the current Ground motion prediction models of acceleration response spectrum to increase the attenuation relationship of the applicability of the earthquake so as to build a reasonable target spectrum.

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