Ground motion attenuation relation for small to moderate earthquakes in Fujian region, China^{*}

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Abstract

We collect 1974 broad-band velocity records of 94 earthquakes ($M_L=2.8\sim 4.9$, $\Delta=13\sim 462$ km) from seven stations of the Fujian Seismic Network from March 1999 to March 2007. Using real-time simulation, we obtain the corresponding acceleration and then adopt different models to analyze the seismic data. As a result, a new attenuation relationship between PGA and PGV of the small and moderate earthquakes on bedrock site in Fujian region is established. The Yongchun earthquake occurred recently verifies the attenuation relationship well. This paper provides a new approach for studying the ground motion attenuation relationship using velocity records.

Key words: real-time simulation; peak ground acceleration; peak ground velocity; regression analysis; attenuation relationship

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Introduction

The research on the earthquake attenuation relation plays a significant role in engineering construction. It provides scientific and reasonable parameters of resisting earthquake for design of some important structure. Recently, the researches in this field develop exponentially, and the research results in this field mostly include:

Firstly, for few regions with plenty of strong seismic ground motion records, *e.g.*, US and Japan, more parameters are considered in the research on attenuation relation. From 1970s to 1980s, some scholars had already made some researches on the statistical attenuation relationship of ground motion parameters (PGA, PGV, PGD, response spectral acceleration), such as the influence of specific site on the parameters, the attenuation model, the regression method and so on (Trifunca *et al*, 1976; Mcguire and Hanks, 1980; Mcguire and Hanks, 1980; Sadigh *et al*, 1997). In recent years, with the monitoring network of strong ground motion rapidly expanding, the studies in this field had an integration analysis concerning multi-factors, such as distinguishing fault style, hanging wall/footwall effects in fault and so on; these achievements are great helpful for people in

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recognizing the physical essence of the attenuation relationship.

Secondly, for regions with poor record of strong ground motion, such as Chinese mainland *etc.*, it is very difficult to research attenuation relation of strong ground motion. HU and ZHANG (1984), HU *et al* (1996) brought forward a mapping method to estimate the parameters of ground motion for region with poor record. Assuming the same intensity and ground motion parameters in the US and China, on the condition of the same magnitude and same epicentral distance, the ground motion attenuation relationship of China can be deduced by referring to the attenuation relationship of seismic intensity and the ground motion attenuation relationship of Western America, and the attenuation relationship of seismic intensity in China. Hereafter, HUO (1989), WANG (2001), LI *et al* (2005) have studied in this field mainly including researches on the attenuation model, the multi-parameter demarcating, uncertainty amendment method, regression method *etc.*

Fujian is a region where earthquake is intensive with distinct characteristics in the southeastern China. Although there are poor PGA record, a plenty of velocity data of small and moderate earthquakes were recorded by Fujian Seismic Network. In this paper, using real-time simulation proposed by JIN *et al* (2004), we obtain the corresponding acceleration and then adopt different models to analyze the seismic data. As a result, a new attenuation relationship between PGA and PGV of the small and moderate earthquakes on bedrock site in Fujian region is established.

1 Data collection and analysis

After transformation in Ninth Five-year and Tenth Five-year, Fujian Seismic Network are equipped with new broadband, large dynamic and high resolution velocity seismograph, which has accumulated a great number of velocity data. Fujian lie in Wuyi-Daiyun upfold zone, which belongs to the South China fold zone, adjoining to annulus Pacific Ocean seismic zone, and is one of the active seismicity zones in China. In plate tectonics, Fujian is on the margin of southeastern Eurasian Plate and the inside of subduction zone of Pacific (Philippine Sea) Plate to the Eurasian Plate, with the opposite side of Taiwan where seismic activity is intense and highly frequent. In this paper we collect 1974 broadband velocity records of 94 earthquakes (M_L 2.8~4.9, Δ =13~462 km) obtained by seven stations in Fujian Seismic Network from March 1999 to March 2007. There are seven bedrock stations which are equipped with FBS-3B broadband seismograph, of which parameters are listed in Table 1. The magnitude and epicentral distance distributions are listed in Table 2, the epicentral distribution of earthquake is shown in Figure 1.

Table 1 Main character of FBS-3B broadband seismograph

Serial No.	Capability index	Capability parameter
1	Sensor type	Triplet direction assembly seismetrics
2	Frequency band	0.05~20 Hz velocity record
3	Sensitive measure	over 1 000 V·s/m and the voltage export at both end
4	Demarcate function	Demarcate loop damp is 70 Ω , Sensitive measure is 1.2 V·s/m
5	Power	D.C. power supply +11~+15 V, power dispersion less than 0.6 W
6	Work circumstance	-20°C~+50°C

Four aspects are considered when collecting and sorting out the records.

1) The selected records should be universal and representative, the distribution of magnitude and epicentral distance of earthquake should be wide and the amount of earthquake should be huge. Both records with epicentral distance inside Fujian Seismic Network and on margin are

Table 2 Seismic record number of different ranges on magnitude and epicentral distance

Epicentral distance/km	Magnitude (M_L)			
	2.8~3.2	3.3~3.7	3.8~4.2	4.2~4.9
10~100	246	102	3	24
100~200	423	162	15	42
200~300	366	141	18	45
>300	246	78	27	36

chosen;

2) The horizontal (the two horizontal components are treated as two statistical objects) and vertical components should be calculated respectively;

3) The epicentral distance is adopted;

4) In the data collected, the magnitude is local magnitude M_L .

In order to research ground motion acceleration attenuation relationship of small and moderate earthquakes in Fujian region, this paper uses method proposed by JIN *et al* (2003a, b, 2004a, b, 2005) to change PGV records into PGA records.

2 Statistical model of earthquake parameter

The most popular attenuation model in China is one recommended by *Evaluation of Seismic Safety for Engineering Sites* (GB17741-2005), that is

$$\log Y = C_1 + C_2 M + C_3 M^2 + C_4 \log[\Delta + \Delta_0(M)] + C_7 \Delta + \varepsilon \quad (1)$$

Where Y is the peak ground motion or response spectrum in different periods; C_i ($i=1, 2, \dots, 7$) is regression coefficient; M is the local magnitude; R is the epicentral distance; $R_0(M)=C_5 \exp(C_6 M)$ is a saturation factor that has a correlation with the earthquake magnitude and can be predetermined; ε is the random variable.

When surface wave magnitude is under 8, the peak acceleration do not increase with magnitude increasing according to the HUO (1989), the $C_3 M^2$ term will not be introduced, because all of chosen earthquakes magnitudes are under 5. So this paper merely considers the saturation phenomenon in near field, which is related to the scale of source body, the effect degree is correlative with the focal depth and rupture scale. At the same time, in order to simplify the equation and make conveniently regression analysis, also considering that the focal depth is usually about 10 km, we assume R_0 is 10 km in the $C_4 \log[R+R_0(M)]$ term which is considered as geometrical diffusion to solve the saturation phenomenon in near field, finally the chosen attenuation model is

$$\ln Y = a + b \ln(\Delta + \Delta_0) + cR + dM \quad (2)$$

Figure 1 Epicentral distribution of earthquakes used in this study

People always use the least squares method when determining ground motion attenuation coefficients. On the basis of this method, some other methods are improved to fit the data distribution, for instance, weighted least squares method (TIAN *et al.*, 1986), coherent weighted least squares method (HUO, 1989) *etc.* Joyner and Boore (1981) proposed a two-step method to decouple the distance and magnitude for decreasing the influence of relativity between distance and magnitude on the regressive result. In the method, the first is regression on distance, and the second is that on magnitude. When determining model parameters, two regressive methods, least squares method and weighted least squares method, are used. Magnitude and epicentral distance are weighted separately in different ranges in two directions when using the weighted least squares method; the weighted coefficients in different ranges of magnitude and epicentral distance are listed in Table 3.

Table 3 Weighted coefficients in different ranges of magnitude and epicentral distance

Epicentral distance /km	Local magnitude (M_L)							
	Vertical seismic record				Horizontal seismic record			
	2.8~3.2	3.3~3.7	3.8~4.2	4.2~4.9	2.8~3.2	3.3~3.7	3.8~4.2	4.2~4.9
10~100	1	1	1	1	1	1	1	1
	16×82	16×34	16	16×8	16×2	16×2	16×2	16×2
100~200	1	1	1	1	1	1	1	1
	16×141	16×54	16×5	16×14	16×2	16×2	16×2	16×2
200~300	1	1	1	1	1	1	1	1
	16×122	16×47	16×6	16×15	16×2	16×2	16×2	16×2
>300	1	1	1	1	1	1	1	1
	16×82	16×26	16×9	16×12	16×2	16×2	16×2	16×2

For typical and common prediction equation, based on above-mentioned models and regressive methods, we choose five models to regress, and then name different models according to different regressive methods.

1) Two-step regression model

At first, considering the effect of epicentral distance on peak ground motion when the seismic intensity is homogeneous, we chose model as

$$\ln Y = a_0 + b_0 \ln(\Delta + 10) \quad (3)$$

Where a and b are function of the magnitude M , we simply regard there is a linear relation between magnitude and parameters a and b (Figure 2), and select model as

$$\begin{cases} a_0 = a + bM \\ b_0 = c + dM \end{cases} \quad (4)$$

Thus, the final regression model is

$$\ln Y = a + bM + (c + dM) \ln(\Delta + 10) \quad (5)$$

2) Unweighted multivariate regression model

The records are directly made regression by using the physical model (2), and thus the related parameter can be acquired.

Figure 2 Relation between value a , b and magnitude in two-step regression model

(a) Horizontal acceleration; (b) Vertical acceleration; (c) Horizontal velocity; (d) Vertical velocity; (e) Horizontal acceleration; (f) Vertical acceleration; (g) Horizontal velocity; (h) Vertical velocity

3) Weighted multivariate regression model

The records are directly made weighted regression by using the physical model (2) and the related parameter can be obtained. The weighted coefficients are listed in Table 3.

4) Unweighted multistep regression model

Suppose there is a set of reference earthquakes (Δ_0 , M_0 , Y_0) satisfying equation

$$\ln Y_0 = a + b \ln(\Delta_0 + 10) + c\Delta_0 + dM_0 \quad (6)$$

then many sets of earthquakes (Δ_i , M_0 , Y_i) with the same magnitude should follow the equation

$$\ln Y_i = a + b \ln(\Delta_i + 10) + c\Delta_i + dM_0 \quad (7)$$

Substituting equation (6) into equation (7), we can obtain

$$\ln Y_i = \ln Y_0 - b \ln(\Delta_0 + 10) - c\Delta_0 + b \ln(\Delta_i + 10) + c\Delta_i \quad (8)$$

Let $\ln Y_0 - b \ln(\Delta_0 + 10) - c\Delta_0 = A$, it can be obtained

$$\ln Y_i = A + b \ln(\Delta_i + 10) + c\Delta_i \quad (9)$$

The regression parameters b and c can be acquired by using least squares method; similarly, many sets of earthquake with the same epicentral distance should satisfy equation

$$\ln Y_i = a + b \ln(\Delta_0 + 10) + c\Delta_0 + dM_i \quad (10)$$

Substituting equation (6) into equation (10), we can obtain

$$\ln Y_i = dM_i + (\ln Y_0 - dM_0) \quad (11)$$

Let $\ln Y_0 - dM_0 = B$, then

$$\ln Y_i = dM_i + B \quad (12)$$

The regressive parameter d is acquired by using least squares method, and then the parameter a can be acquired as follows

$$a = \frac{1}{n} \sum_{i=1}^N \ln Y_i - b \ln(\Delta_i + 10) + c \Delta_i + d M_i \quad (15)$$

Finally the regression model is

$$\ln Y = a + b \ln(\Delta + 10) + c \Delta + d M \quad (14)$$

5) Weighted multistep regression model

The records are statistically weighed regressed by using multistep, and the each parameter can be acquired. The weighted coefficient is listed in Table 3.

3 Regression analysis result

The horizontal and vertical records of velocity and acceleration are regressed by using five different models above-mentioned respectively. The peak attenuation relationships at bedrock site in Fujian Province can be calculated as shown in Table 4.

Table 4 Regression coefficients of five model and standard deviation individually

Model	Earthquake parameter	a	b	c	d	δ
Two step regression model	PGA-H	-9.375 800	4.541 40	0.039 024 0	-0.547 21	0.330 920 0
	PGA-V	-6.474 300	3.391 30	-0.476 010 0	-0.351 38	0.139 750 0
	PGV-H	-12.638 000	4.239 00	-0.102 360 0	-0.457 61	0.009 580 4
	PGV-V	-10.858 000	3.225 10	-0.366 730 0	-0.294 71	0.003 876 7
Unweighted multivariant regression model	PGA-H	-0.320 670	-1.571 10	-0.002 059 9	1.586 50	0.371 830 0
	PGA-V	-1.556 900	-1.319 00	-0.002 603 2	1.531 40	0.160 810 0
	PGV-H	-5.675 900	-1.283 50	-0.002 197 7	1.718 60	0.006 347 3
	PGV-V	-6.949 200	-0.997 96	-0.002 432 9	1.625 80	0.003 651 3
Weighted multistep regression model	PGA-H	-0.044 824	-1.689 60	-0.003 480 0	1.772 20	0.291 770 0
	PGA-V	-1.000 300	-1.490 60	-0.003 459 3	1.686 30	0.127 090 0
	PGV-H	-5.907 800	-1.286 90	-0.003 603 8	1.876 90	0.005 460 2
	PGV-V	-7.148 000	-1.001 20	-0.003 588 2	1.766 10	0.003 375 9
Unweighted multistep regression model	PGA-H	0.073 808	-1.540 80	-0.001 594 1	1.387 50	0.417 830 0
	PGA-V	-1.206 400	-1.289 70	-0.002 153 6	1.348 60	0.186 730 0
	PGV-H	-5.390 600	-1.250 70	-0.001 693 2	1.546 70	0.007 409 1
	PGV-V	-6.731 100	-0.966 93	-0.001 955 6	1.479 20	0.004 109 7
Weighted multistep regression model	PGA-H	-1.192 600	-1.345 20	-0.005 111 8	1.683 20	0.321 960 0
	PGA-V	-2.124 400	-1.163 00	-0.005 012 0	1.606 20	0.138 150 0
	PGV-H	-7.203 300	-0.922 24	-0.005 332 0	1.805 20	0.005 866 2
	PGV-V	-8.419 200	-0.658 04	-0.005 214 4	1.707 00	0.003 468 3

Note: PGV-H: horizontal PGV; PGV-V: vertical PGV; PGA-H: horizontal PGA; PGA-V: vertical PGA.

The peak velocity and acceleration curves with epicentral distance are plotted when magnitude is 3.0, 3.4, 3.8 and 4.4 respectively by using above-mentioned five different models as shown in Figures 3 to 7, comparisons with original records are also given in this figure. It can be seen that

1) The values calculated by using five models are basically consistent with original records and reflect the attenuation trend of original data. The coefficient of magnitude term is positive in the regressive result, which shows that the peaks increase with increasing of magnitude M ; in addition, the coefficients of the logarithm of distance and distance term are negative, which shows the peaks decrease with increasing of distance. This trend can also be seen from figures.

Figure 3 Comparison between the result of two-step model (line) and original record (dot)
(a) Horizontal acceleration; (b) Vertical acceleration; (c) Horizontal velocity; (d) Vertical velocity

Figure 4 Comparison between the result of unweighted multiple model (line) and original record (dot)
(a) Horizontal acceleration; (b) Vertical acceleration; (c) Horizontal velocity; (d) Vertical velocity

2) The regressive results in far field are consistent with the original data, while that in near field show a little discrepancy, which maybe result from less records in near field and thus result in conservative estimate.

3) The weighted models are better consistent with the original records. The reason is mainly that the weighted models increase the influence of less record in near field, avoiding domination

Figure 5 Comparison between the result of weighted multiple model (line) and original record (dot)
(a) Horizontal acceleration; (b) Vertical acceleration; (c) Horizontal velocity; (d) Vertical velocity

Figure 6 Comparison between the result of unweighted multiple-step model (line) and original record (dot)
(a) Horizontal acceleration; (b) Vertical acceleration; (c) Horizontal velocity; (d) Vertical velocity

of wide distribution data to result.

4) Under the same magnitude, the vertical acceleration attenuates more rapidly than the horizontal record, which is in accordance with that the attenuation of high frequency component is more rapid.

Figure 7 Comparison between the result of weighted Multiple-step model (line) and original record (dot)
(a) Horizontal acceleration; (b) Vertical acceleration; (c) Horizontal velocity; (d) Vertical velocity

It can be seen from Table 4 that for both acceleration and velocity, both horizontal and vertical records, the standard deviations in the weighted multivariate models are the least, showing less measure of dispersion. Therefore we suggest that the regressive result from weighted multivariate model should be adopted.

4 Comparison with small to moderate ground motion attenuation relationships currently available

For the data of small and moderate earthquakes used in the study are from far field, we select several ground motion attenuation relationships currently available to make comparison, which are attenuation relationships by Liu and Tsai (2005) as well as Bragato and Slejko (2005) respectively. The two attenuation relationships are briefly introduced as follows.

1) The attenuation relationship by Liu and Tsai (2005), including the attenuation relation of PGA and PGV, use records of bedrock, hard soil and soft soil in shallow earthquake in Taiwan from 1993 to 2002, with magnitude range from 4.0 to 7.1, and distance less than 275 km. The relation is

$$\ln Y = a \ln(\Delta + h) + b\Delta + cM_w + d \quad (15)$$

Where M_w is moment magnitude, Δ is epicentral distance, h is a saturation coefficient of near field.

2) The attenuation relationship by Bragato and Slejko (2005) includes attenuation relationship of peak and acceleration response spectrum, using records of bedrock and hard soil at the eastern Alps in shallow earthquake from 1993 to 2002, with magnitude range from 2.5 to 6.3, and distance less than 134 km. The attenuation relation is expressed as

$$\log_{10} Y = a + (b + cM)M + (d + eM^3) \log_{10} \Delta \quad (16)$$

Where M is local magnitude and Δ is epicentral distance.

Figure 8 is a comparison between these three models when M is 3.5, 4.0, 4.5 and 5.0, respectively. It can be seen that the estimation in this study is the least in near field, while it is between the other two in far field; with magnitude increasing, the acceleration attenuation curve gradually approach that of Liu and Tsai (2005), the velocity attenuation curve gradually approach that of Bragato and Slejko (2005) curve. The discrepancy is attributable to different data distribution for statistic and regressive analysis method, besides different regions. In this study, data from near field and large earthquake are less; on the one hand, the effect of near field and great magnitude can be ensured by using the weighted least squares method; on the other hand, the method produce error when extrapolating to near field for the same reason. Liu and Tsai (2005) ignored site effect and made a statistic on epicentral distance and magnitude term respectively to reduce effect of the correlation between magnitude and epicentral distance on regression analysis. However, because of too much great earthquake records, the estimation value is magnified. Bragato and Slejko (2005) also ignored the site effect and merged bedrock and soil data for statistic using multistep method; however, for there were more small earthquake records used, the regression result in near field was closer to observation records, whereas the regression result in far field and great earthquake were underestimated.

5 A verification to the attenuation relationship through $M_L 4.6$ Yongchun earthquake

25 new-built wide-frequency band bedrock stations have been put into operation during the 11th Five-year Plan Period in Fujian Seismic Network, which include 18 stations of CMG-3ESP seismometer with frequency band range from 60 s to 40 Hz; 5 stations of BBVS-60 seismometer, with frequency band range from 60 s to 40 Hz; 1 station of CTS-1 seismometer with frequency band range from 120 s to 40 Hz; one else of KS2000 seismometer, with frequency band range from 120 s to 40 Hz; All new stations have recorded an $M_L 4.6$ earthquake of Yongchun, Quanzhou at 7:28 on August 29, 2007. We select all velocity records in this earthquake, simulate the velocity records with a frequency range from 0.05 Hz to 20 Hz using real-time simulation method proposed by JIN *et al* (2003), and then the relevant acceleration records are obtained by using the above-mentioned method to pick up the PGV and PGA; finally the results are compared with the weighted multivariant regression attenuation curve as showed in Figure 9.

It can be seen from Figure 9 that the calculated results of weighted multivariant regression model is basically in accordance with the original records, especially in horizontal distribution, suggesting the method is of better practicability

6 Conclusions

We collect 1974 broad-band velocity records of 94 earthquakes ($M_L 2.8 \sim 4.9$, $\Delta = 13 \sim 462$ km) from seven stations of the Fujian Seismic Network from March 1999 to March 2007. Using real-time simulation, we obtain the corresponding acceleration and then adopt five models to analyze the seismic data. As a result, five attenuation relationships on bedrock site in Fujian region are established, of which the standard deviation of weighted multivariant model is the least, therefore the model is recommended. According to research in this paper, the model is applicable in

Figure 8 Comparison between the result in this paper and other results

(a) Horizontal acceleration; (b) Vertical acceleration; (c) Horizontal velocity; (d) Vertical velocity

Figure 9 Comparison between the result of weighted multivariate model (line) and original record (dot)

(a) Horizontal acceleration; (b) Vertical acceleration; (c) Horizontal velocity; (d) Vertical velocity

following range

- 1) Epicentral distance: 13~462 km;
- 2) Magnitude: M_L 2.8~4.9;
- 3) Site: bedrock.

In addition, the multivariate regression model is compared with international popular ground motion attenuation relationships, and some possible reasons for their difference are presented. Comparison between Yongchun M_L 4.6 earthquake records and the multivariate regression model shows a basically consistence, suggesting the multivariate regression model is of better practicability.

On the basis of this study, we will expand small and moderate earthquake to strong one. At present, only PGA and PGV are statistic regressed, study about some other parameters will be introduced in other paper.

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