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The first peak ground motion attenuation relationships for North of Vietnam

Le Minh Nguyen [a,d], Ting-Li Lin [a,f,*], Yih-Min Wu [a], Bor-Shouh Huang [b], Chien-Hsin Chang [c], Win-Gee Huang [b], Tu Son Le [d], Quoc Cuong Nguyen [d], Van Toan Dinh [e]

[a] Department of Geosciences, National Taiwan University, Taipei 106, Taiwan
[b] Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei 115, Taiwan
[c] Central Weather Bureau, Taipei 100, Taiwan
[d] Institute of Geophysics, Vietnamese Academy of Science and Technology, Hanoi, Viet Nam
[e] Institute of Geological Sciences, Vietnamese Academy of Science and Technology, Hanoi, Viet Nam
[f] Department of Earth Sciences, National Cheng Kung University, Tainan 701, Taiwan

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ABSTRACT

The first attenuation relationships of peak ground acceleration (PGA) and peak ground velocity (PGV) for northern Vietnam are obtained in this study. Ground motion data are collected by a portable broadband seismic network in northern Vietnam as a part of cooperation between the Institute of Geophysics, Vietnamese Academy of Science and Technology, Vietnam and Institute of Earth Sciences, Academia Sinica, Taiwan. The database comprises a total of 330 amplitude records by 14 broadband stations from 53 shallow earthquakes, which were occurred in and around northern Vietnam in the period between 01/2006 and 12/2009. These earthquakes are of local magnitudes between 1.6 and 4.6, focal depths less than 30 km, and epicentral distances less than 500 km. The new attenuation relationships for PGA and PGV are:

$$\log_{10}(PGA) = -0.987 + 0.7521M_L - \log_{10}(R) - 0.00475R,$$

$$\log_{10}(PGV) = -3.244 + 0.9008M_L - \log_{10}(R) - 0.00322R,$$

where PGA is in cm/s^2, PGV is in cm/s, and R is the epicentral distance in kilometers. The site corrections are also derived in this study. These site corrections are very suitable with the station corrections for M_L and imply the qualification of the resulting attenuation relationships.

1. Introduction

Vietnam is located in South East Asia and bounded by the Pacific belt and Mediterranean–Himalaya seismic belt on its eastern, western and southern sides, respectively. Vietnam is strongly affected by the relative movement between the belts, and also suffers the consequence of the spreading process that is taking place in East Vietnam Sea. The dynamic tectonic processes are dragging the territory of Vietnam and adjacent areas into intensive movements in a variety of directions and making the regional tectonic structure very complicated. The tectonic conditions have led this territory to a moderate seismic activity and complicated geological structure at many zones such as the Lai Chau–Dien Bien (LC–DB) fault zone, and Red River fault zone (Fig. 1). During the last century, two earthquakes (Fig. 1) of M_S 6.7, 1935 and M_S 6.8, 1983 (International Seismological Centre (ISC) catalog) and more than 20 earthquakes of M_S 5.0–5.6 (Vietnam and ISC catalog) had occurred in the territory of Vietnam and caused great damages to houses, infrastructure, and also losses of human life. The Vietnam earthquake catalog is compiled by the Institute of Geophysics, Vietnamese Academy of Science and Technology (Nguyen et al., 2004). Although the seismicity is not as high as in the countries situated right on the seismic belts such as Indonesia and Philippine the earthquake hazard prevention and mitigation should be seriously considered in Vietnam. For this purpose, more studies on the regional seismic hazard assessment and local microzonation to the urban and industrial areas in or near the seismic zones are most needed.

Over the recent decades, there are some major earthquake hazard assessment projects such as *study on earthquake prediction and ground motion in Vietnam* (Nguyen et al., 2004), *Seismic hazard*

* Corresponding author at: Department of Earth Sciences, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan. Tel.: +886 6 2757575x65436.
E-mail address: mulas62@gmail.com (T.-L. Lin).

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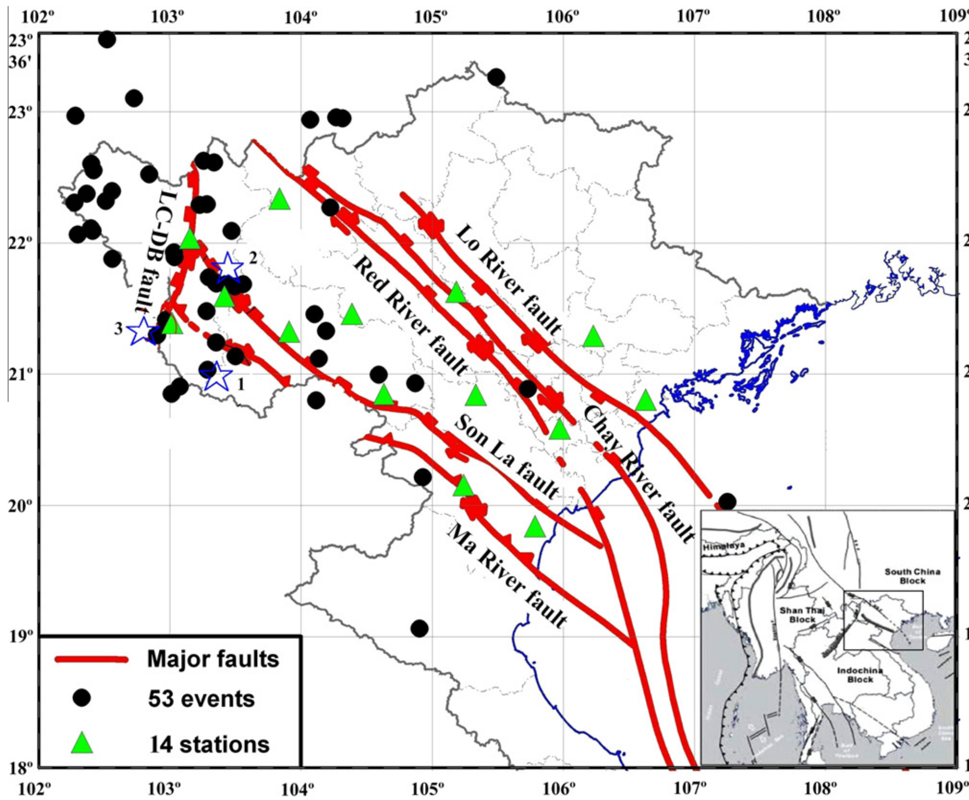

Fig. 1. Map of the major fault systems, 53 events used in this study and the 14 portable broadband stations in North of Vietnam. The two strongest recorded earthquakes (in 1935 and 1983) in the last century as well as the 2201 DienBien earthquake are indicated by the three open stars labeled as Nos. 1, 2, and 3, respectively.

assessment of construction areas of SonLa, Lai Chau Hydropower projects (Nguyen et al., 2001) in broad Vietnam and many relatively small projects in North Vietnam had been done. In all of these projects, because Vietnam does not have its own ground-motion distance attenuation relations, the Campbell (1997) equation for global, and Xiang and Gao (1994) equation for the Yunnan region, where neighbors on Vietnam, are used in the ground motion prediction. For two recently decades, the economy of Vietnam grows very fast especially in North of Vietnam. Many buildings and important constructions have been constructing since then. Hence it is very urgent and important to find the attenuation relations specifically for North Vietnam for the urban development plans and earthquake hazard assessments in the near future. More accurate ground motion predictive equations will be essential in assessing earthquake hazards for a fast economic growing region as for northern Vietnam.

One of the most important fundamental of earthquake hazard assessment is to express ground motions (such as PGA or PGV) as a function of distance and earthquake magnitude that is often referred as ground motion attenuation relationships. A common way to build up these relationships is to make the model expressed as mathematical functions relating the strong motion parameter to parameters characterizing the earthquake, the propagation medium and the local site geology. Nowadays, many predictive equations have been proposed for different regions in the world such as Campbell (1997) for global; Atkinson and Boore (1997) for eastern North America; Ambraseys et al. (1996a); Ambraseys and Simpson (1996b) for Europe; and Frisenda et al. (2005) for North-western Italian.

In fact, Nguyen and Tran (1999) have built a PGA attenuation relationship for Vietnam. This relationship was indirectly inferred from the formula of the intensity attenuation curve and the relationship between intensity and acceleration. They pointed out that the intensity–acceleration relationship used in their study is quite dispersive since intensity is a more qualitative measure than acceleration. In this study, by using PGA and PGV values from broadband seismic data, the first attenuation relationships for both PGA and PGV values for northern Vietnam are obtained. The correlation between site correction values in this study and station correction values in North Vietnam's M_L scale (Nguyen et al., 2011) was also evaluated.

2. Seismic data

Waveform data are collected by a portable broadband seismic network, which is a part of the cooperation between the Vietnam Institute of Geophysics and the Institute of Earth Sciences at Academia Sinica, Taiwan. This network has been deploying in northern Vietnam since 2005 initially with 14 stations (Fig. 1). This network uses two types of velocity seismometers: STS-2 and Trillium 40, which have flat responses approximately from 0.008 to 50 Hz and 0.025 to 50 Hz, respectively (Huang et al., 2009). Although the number of events used in this study is relatively limited due to the short observation period of only 4 years, they still provide the valuable data to build the ground motion attenuation relationships for northern Vietnam.

The peak ground motion values used in this study are derived from 53 shallow earthquakes (Table 1) occurred in and around north-western Vietnam from 01/2006 to 12/2009 and comprise a total of 330 amplitude readings recorded by a portable broadband seismic network of 14 stations (Fig. 1). Since the ground motions are recorded by the three-component seismometers, the peak ground motions are the maximum values among the three components. Originally, a much larger number of events is possible during this recording period. However, for the sake of maintaining data quality we restrict the events of those with good recording quality,

Table 1
List of 53 earthquakes used in this study.

No	Origin time (UTC)		Lat (°N)	Long (°E)	Depth (km)	M_L
1	1/6/2006	11:50:03	22.951	104.316	10.0	3.9
2	1/6/2006	18:28:08	22.091	102.411	2.7	4
3	1/6/2006	18:43:03	22.113	102.398	2.4	3.8
4	1/15/2006	14:29:47	21.738	103.297	10.7	3.1
5	1/16/2006	17:58:01	22.296	103.282	13.0	2.7
6	1/23/2006	21:09:20	22.29	103.227	11.0	2.3
7	2/3/2006	1:08:44	20.886	105.728	9.6	2.4
8	2/19/2006	13:16:52	21.687	103.431	10.0	2.5
9	2/26/2006	16:12:37	21.242	103.351	8.3	3.6
10	3/9/2006	22:04:52	22.615	103.336	10.8	2.8
11	3/16/2006	16:22:32	22.27	104.222	7.2	3.1
12	3/18/2006	20:18:04	21.24	103.354	7.9	2.0
13	4/3/2006	17:06:56	20.029	107.252	10.9	3.8
14	4/9/2006	21:55:31	21.48	103.278	6.5	1.6
15	4/13/2006	13:24:57	21.402	102.973	8.8	2.4
16	6/30/2006	18:18:56	22.092	103.47	14.2	1.8
17	8/15/2006	20:49:06	21.691	103.353	6.4	3.4
18	8/15/2006	21:24:16	21.695	103.349	5.0	1.9
19	8/26/2006	4:20:40	21.296	102.903	14.2	1.6
20	8/30/2006	22:36:19	20.216	104.927	6.3	2.7
21	9/2/2006	18:16:53	22.308	102.271	17.1	3
22	9/6/2006	19:24:17	22.97	102.28	15.0	3.1
23	9/6/2006	19:28:19	23.103	102.727	17.1	2.7
24	9/17/2006	6:10:38	21.033	103.287	11.2	2.9
25	9/18/2006	16:18:39	20.905	103.075	17.3	2.5
26	9/18/2006	16:33:10	20.85	103.012	20.0	2.7
27	9/23/2006	20:07:13	21.415	102.969	4.4	2.1
28	10/16/2006	19:38:23	22.064	102.296	8.5	3.1
29	11/11/2006	18:46:02	23.554	102.521	8.9	4.1
30	11/23/2006	16:30:02	22.605	102.401	10.0	4.5
31	11/24/2006	0:05:20	22.9593	104.267	10.0	4
32	3/31/2007	3:15:56	22.376	102.364	18.2	3.8
33	5/31/2007	15:44:31	22.525	102.841	17.1	3.2
34	6/7/2007	5:31:13	21.929	103.029	0.5	3.4
35	7/21/2007	8:47:11	21.456	104.102	0.5	3.1
36	9/6/2007	18:51:48	23.266	105.487	15.1	4.6
37	1/3/2008	6:00:31	19.062	104.904	0.7	3.1
38	2/10/2008	2:44:46	21.686	103.558	28.0	2.8
39	2/16/2008	20:27:47	21.668	103.495	10.0	2.8
40	8/7/2008	19:09:56	20.995	104.593	11.4	3.2
41	8/30/2008	20:20:41	21.117	104.134	0.7	2.3
42	10/19/2008	20:58:09	21.892	103.035	6.6	3.1
43	11/16/2008	16:21:13	21.683	103.426	17.1	2.6
44	11/17/2008	11:04:47	22.626	103.255	1.5	3.1
45	2/1/2009	4:53:07	21.88	102.56	26.0	3.4
46	3/7/2009	7:28:07	22.94	104.07	5.0	4.1
47	3/21/2009	18:31:33	22.554	102.418	9.5	2.7
48	3/27/2009	14:43:31	22.396	102.557	17.1	3.1
49	4/22/2009	18:46:39	21.135	103.5	11.7	2.6
50	5/19/2009	0:02:50	20.798	104.114	12.3	2.8
51	8/19/2009	2:25:25	22.32	102.51	1.0	3.7
52	9/6/2009	20:49:13	20.93	104.87	16.0	3.2
53	11/26/2009	13:59:06	21.33	104.19	7.0	4.4

epicentral distances less than 500 km, and been recorded by at least three stations. The earthquakes used in this study have local magnitudes in the range of $1.6 < M_L < 4.6$, epicentral distances ranging between 5 and 500 km, and focal depths shallower than 30 km. Since the magnitudes of the events used in this study are rather small and the epicentral distances reach to 500 km, we have checked the quality of data by considering the signal-to-noise ratio. We have selected three typical records of small magnitude events with the furthest epicentral distances. Fig. 2 shows the seismograms and the respective signal-to-noise spectra for events with magnitudes of 3.1, 2.8, and 2.0 and epicentral distances of 457 km, 208 km, and 91 km, respectively. Fig. 2 shows that the signal-to-noise ratios of these records are higher than 1.5 in frequencies less than 15 Hz suggesting that the data used in this study have a suitable data quality.

In Table 2, we also compare the station corrections from the North Vietnam's M_L study (Nguyen et al., 2011) and the site corrections obtained in this study to check their correlation and the qualification of the resulting attenuation relationships.

3. Methods and results

The relationship between amplitude of seismic waves with distance from hypocenter or epicenter can be expressed as the functional form $Amp \sim e^{-\gamma R}/R^{n}$, where Amp, R, n and γ are amplitude, hypocenter or epicenter distance, geometrical spreading coefficient and anelastic attenuation coefficient, respectively (Wu et al., 2005). Taking the logarithm, we derived:

$$\log_{10}(Amp) = c_s - (\gamma/\ln 10)R - n\log_{10}(R) \tag{1}$$

where c_s is a constant. Assuming $n = 1$ for body wave propagation. Therefore, in this study we use the linear regression model such as:

$$\log_{10}(A) = a + bM_L - \log_{10}(R) + cR \tag{2}$$

where A is either PGA or PGV, M_L is local magnitude and R is the epicenter distance.

We have tested a second-order magnitude term (Frisenda et al., 2005; Akkar and Bommer, 2007) and replaced epicentral distance (Wu et al., 2001; Massa et al., 2008) by hypocentral distance in Eq. (2). We find that the results presented in this study are not significantly changed. Interestingly, the corresponding standard deviations become larger than those of Eq. (2), which might be partly due to that the depths of the earthquakes were not correctly computed or the measured amplitudes are the amplitudes of the surface waves. For shallow earthquakes, which often cause more seismic loss than deeper ones, the use of epicentral distance is efficient in describing the wave propagating distance. We also neglect the influence of rupture type in this study because there were no studies in focal mechanism for most earthquakes in Vietnam before 2010. Besides that, most of the faults in North Vietnam are dominant in the strike-slip type.

To establish the attenuation relationship, we substitute the data of 330 records from 53 events recorded by 14 stations into the Eq. (2) such as:

$$\log_{10}(A_{ij}) = a + bM_i - \log_{10}(R_{ij}) + cR_{ij}, \quad i = 1, 2 \ldots n \tag{3}$$

where A_{ij} is either PGA or PGV of the ith event at the jth station, M_i is the local magnitude of ith event, R_{ij} is epicenter distance from the ith event to the jth station, m is number of events ($m = 53$) and n is number of stations ($n = 14$). The coefficients a, b, c are to be determined by solving Eq. (3). Eq. (3) can be rewritten in matrix form as (Alsaker et al., 1991; Miao and Langston, 2007)

$$\begin{bmatrix} 1 & M_1 & R_{11} \\ 1 & M_1 & R_{12} \\ & \vdots & \\ 1 & M_1 & R_{1n} \\ & \vdots & \\ 1 & M_m & R_{11} \\ & \vdots & \\ 1 & M_m & R_{mn} \end{bmatrix}_{(mn)\times(3)} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} y_{11} \\ y_{12} \\ \vdots \\ y_{1n} \\ y_{21} \\ y_{22} \\ \vdots \\ y_{mn} \end{bmatrix}_{(mn)\times 1} \tag{4}$$

or G.**u** = **d** with $y_{ij} = \log_{10}A_{ij} + \log_{10}R_{ij}$. The vector of unknowns (**u**) can be found through the generalized inverse matrix of G (G^{-g}) using singular value decomposition (Menke, 1984) as proposed by Miao and Langston (2007). Miao and Langston (2007) adopted a one-step linear inversion without iteration (Hutton and Boore, 1987; Langston et al., 1998) for a typical over-determined inversion problem such as presented in Eq. (4). For deriving the standard deviations

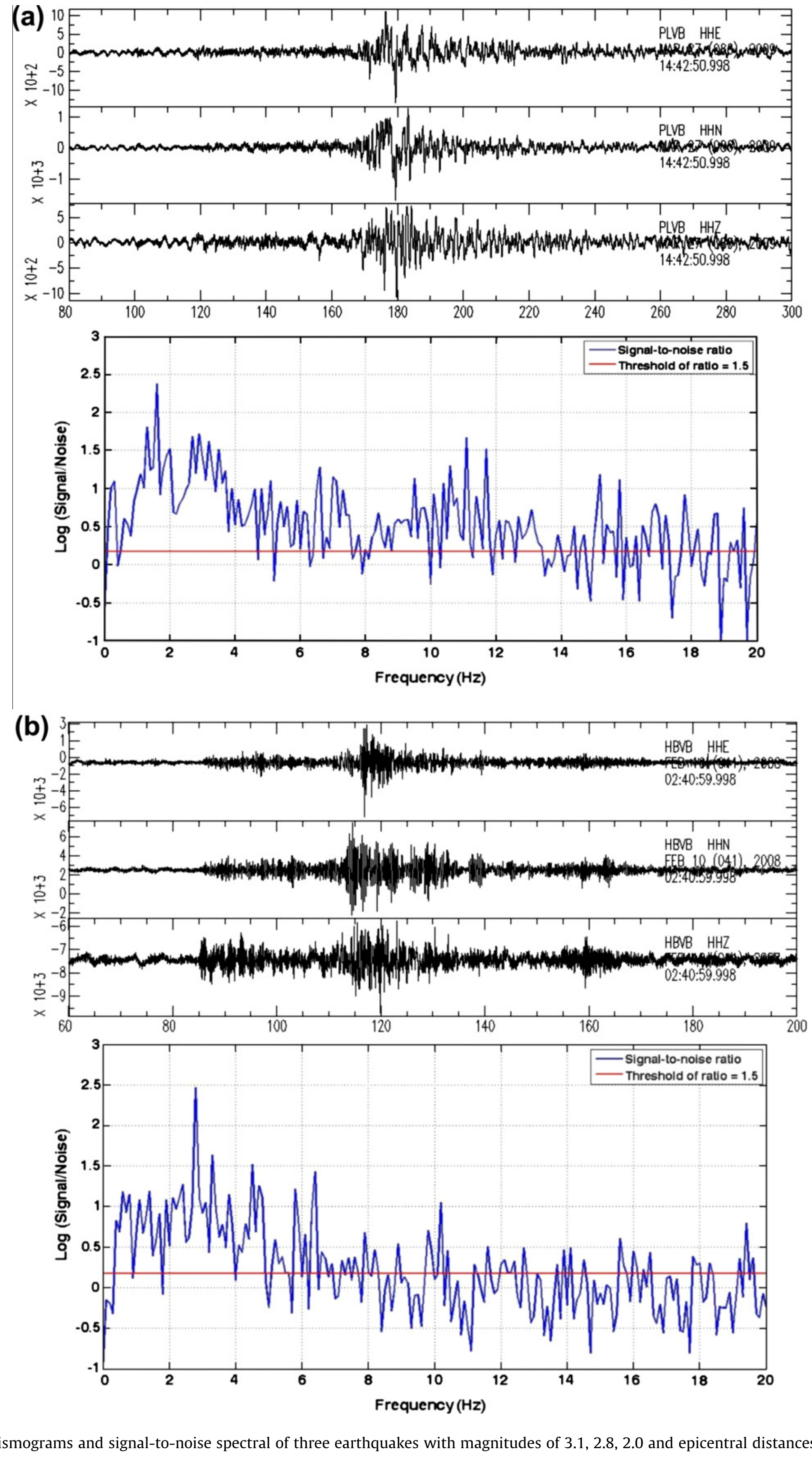

Fig. 2. (a–c) shows the seismograms and signal-to-noise spectral of three earthquakes with magnitudes of 3.1, 2.8, 2.0 and epicentral distances of 457 km, 208 km, 91 km, respectively.

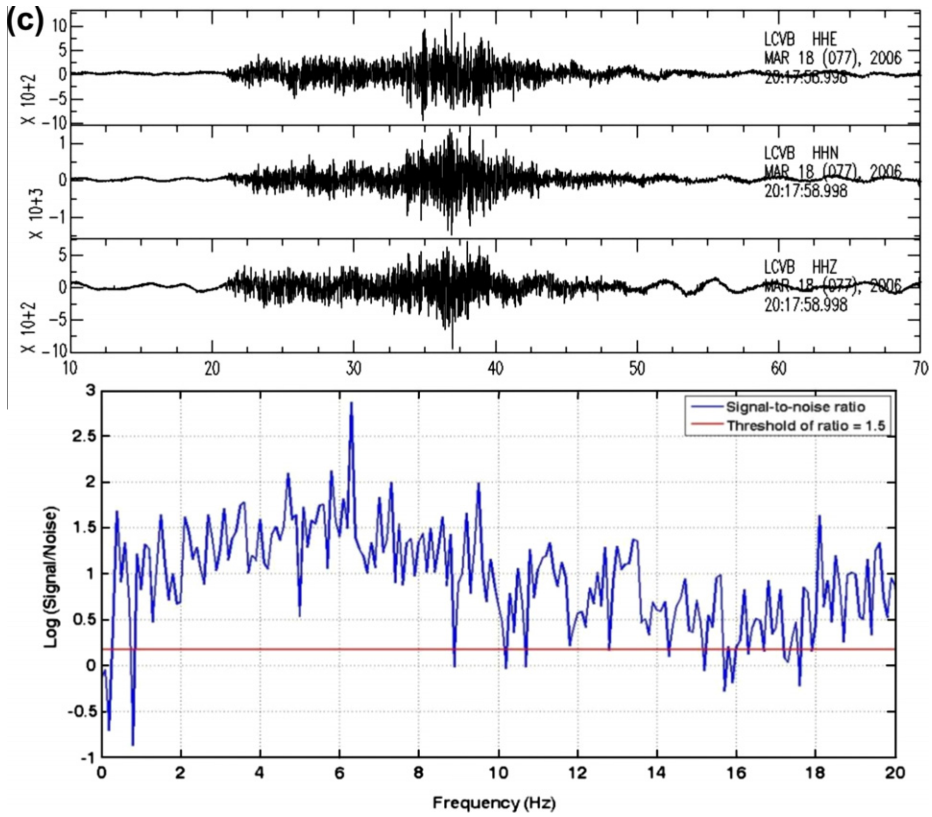

Fig. 2 (*continued*)

Table 2
List of 14 stations and their parameters used in this study. Sta. crt – station correction for M_L, Site crt – site correction factor for PGA and PGV.

Name	Sta. code	Long	Lat	Elev (m)	Sensor	Number of recordings	Sta. crt	PGA Site crt	PGV Site crt
Sapa	SPVB	103.835	22.338	1582	STS-2	39	−0.09	1.29	1.34
Lai Chau	LCVB	103.152	22.038	250	Trillium40	36	−0.04	1.35	1.33
Tuan Giao	TGVB	103.416	21.595	580	Trillium40	48	0.20	0.71	0.73
Hoa Binh	HBVB	105.333	20.842	50	Trillium40	20	−0.38	2.64	2.49
Bac Giang	BGVB	106.228	21.29	50	Trillium40	9	−0.18	3.00	2.05
Doi Son	DSVB	105.974	20.587	70	Trillium40	7	−0.10	2.17	1.70
Lang Chanh	LAVB	105.24	20.157	80	Trillium40	8	−0.04	2.10	1.75
Phu Lien	PLVB	106.628	20.805	18	STS-2	12	0.15	1.21	0.96
Thanh Hoa	THVB	105.784	19.843	20	Trillium40	13	0.16	1.25	0.93
Tram Tau	TTVB	104.388	21.46	600	Trillium40	30	0.17	0.52	0.61
Moc Chau	MCVB	104.631	20.847	800	Trillium40	21	0.13	0.57	0.78
Doan Hung	DHVB	105.185	21.628	70	Trillium40	13	−0.33	5.72	3.00
Dien Bien	DBVB	103.018	21.39	490	STS-2	39	0.03	1.02	1.03
Son La	SLVB	103.909	21.323	590	Trillium40	35	0.30	0.34	0.40

of that attenuation curves, we use the residuals between the observed values and predicted values as following (Wu et al., 2001):

$$\text{res} = ln(A_i)\text{- }\ln(\overline{A_i}) \tag{5}$$

where A_i and $\overline{A_i}$ are observed and predicted PGA or PGV data derived from the attenuation relationship, respectively.

In this study, the site correction for the stations are separately determined with the coefficients by taking the average of the residuals between the observed data and predicted data as following equation (Wu et al., 2001):

$$S = \exp\left(\frac{1}{n}\sum_{i=1}^{n}\ln(A_i/\overline{A_i})\right) \tag{6}$$

The site peak ground motion can be expressed as $S \times A_i$.

With 330 records from 53 events recorded at most by 14 stations in North of Vietnam, the first ground motion attenuation relationships are derived as:

$$\log_{10}(PGA) = -0.987 + 0.7521M_L - \log_{10}(R) - 0.00475R \tag{7}$$

$$\log_{10}(PGV) = -3.244 + 0.9008M_L - \log_{10}(R) - 0.00322R \tag{8}$$

where the PGV and PGA units are in cm/s and cm/s^2, respectively, R is epicentral distance in kilometer. Figs. 3 and 4 show the 330 observed PGA and PGV with the predicted curves by Eqs. (7) and (8), respectively. In this study, by using the definition of the residuals between observed and predicted values as Eq. (5), the standard deviations of residuals for PGA and PGV attenuation relationships are 0.914 and 0.663, respectively. The derived site correction values are shown in Table 2. After applying the site corrections in the

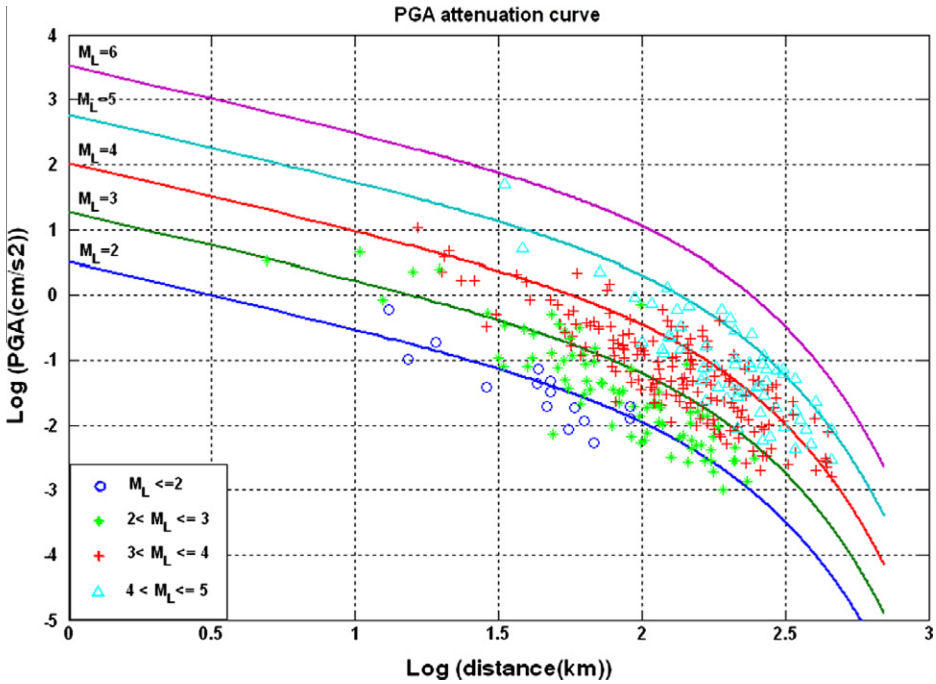

Fig. 3. The PGA attenuation curves and the observed data.

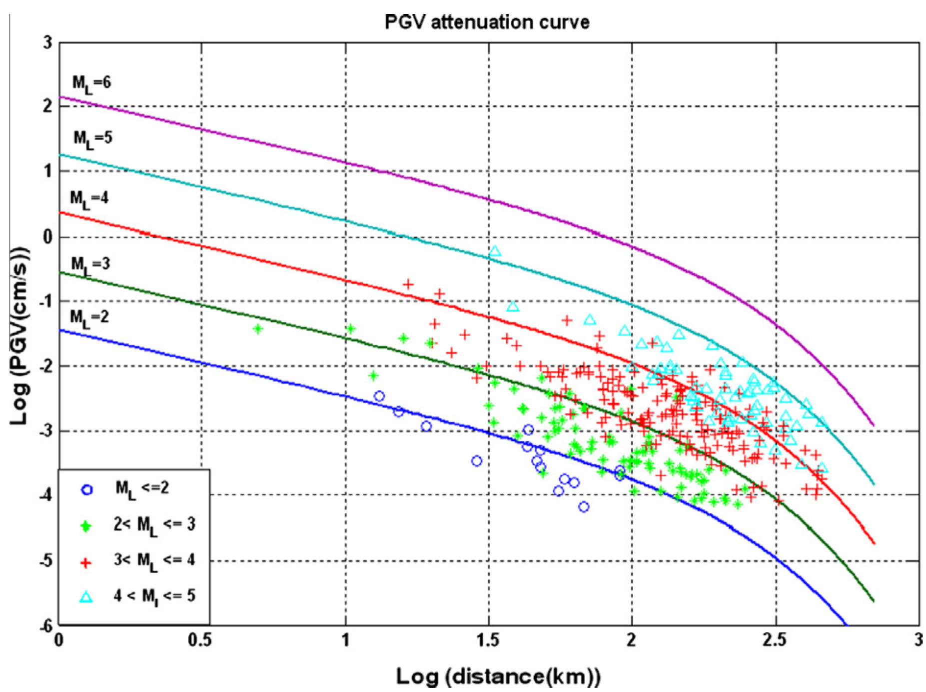

Fig. 4. The PGV attenuation curves and the observed data.

amplitude data, the standard deviations reduce to 0.716 and 0.455 for PGA and PGV, respectively (Fig. 7a and b).

4. Discussion and conclusion

In Figs. 5 and 6, we compare our new attenuation relationships with the PGA and PGV values of nine events (Table 4) occurred in the period of 04/1997–08/1999 (Dinh, 1999), and the DienBien earthquake and its 16 aftershocks (Table 3) from 19/02/2001 to 05/03/2001 (Le and Nguyen, 2003). Note that those PGA and PGV values are not used in the regression analysis (Eqs. (7) and (8)). The DienBien earthquake was occurred in the DienBien province at 22:51 local time, 19/02/2001 with magnitude 5.3 (Vietnam catalog) and has affected many structures. The ground motions of those events are recorded by the three-component strong-motion seismometer SSA-1. These observed PGA and PGA are comparable to those predicted by our new attenuation curves (Figs. 5 and 6) suggesting the qualification of the new attenuation relations.

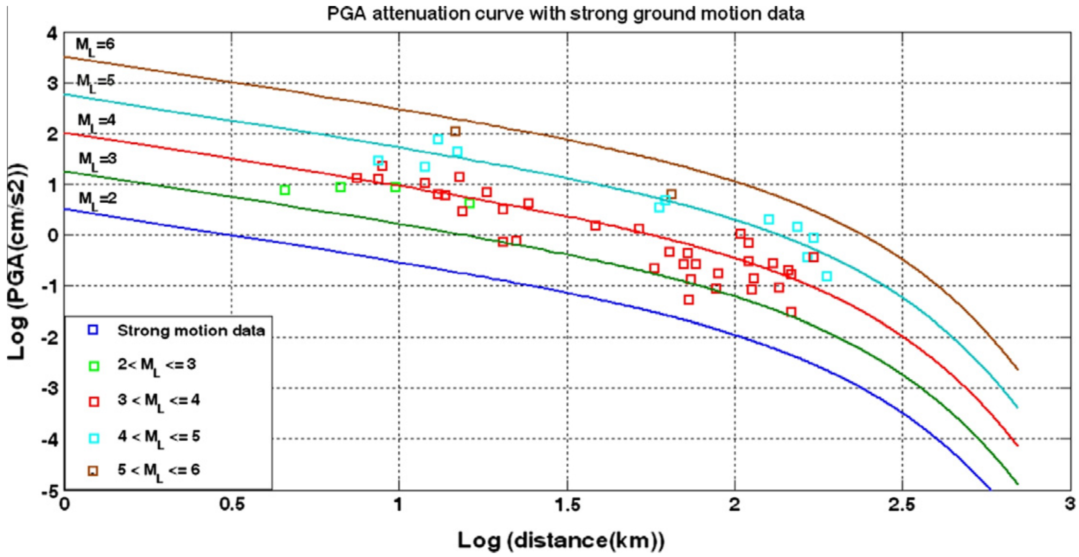

Fig. 5. The PGA attenuation curves and the strong motion data of nine earthquakes in 04/1997–07/1999 (Table 4), the DienBien earthquake 2001 and 16 aftershocks (Table 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

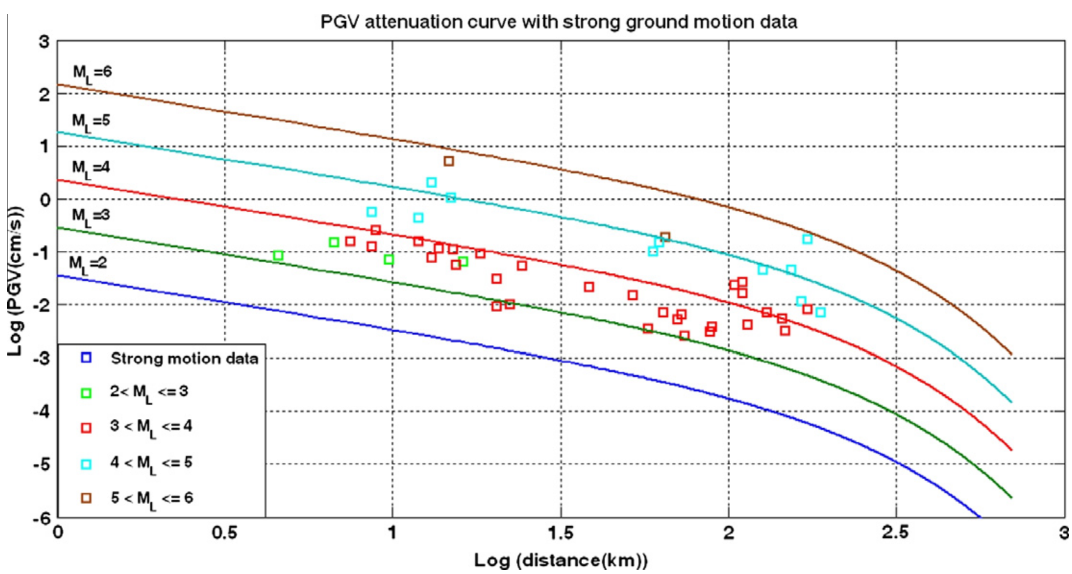

Fig. 6. The PGA attenuation curves and the strong motion data of nine events in 04/1998–07/1999, DienBien's earthquake and 16 its aftershock. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We have compared the PGA attenuation relationship obtained in this study with the other attenuation curves, which are adopted for the current seismic hazard assessments in North of Vietnam such as Campbell (1997), Xiang and Gao (1994), Nguyen and Tran (1999). Because there is not any M_W scale in Vietnam, the seismologists in Vietnam have to use M_S when they apply these relationships for seismic hazard analysis for Vietnam. For reference purpose, we also compare it with those for the other regions such as Wu et al. (2001) for Taiwan and Zhao et al. (2003) for Yunnan. Before comparing all of these relationships, the M_W in Eq. (4) of Wu et al. (2001) is converted to M_L by using Eq. (1) in Wu et al. (2001). For relationships of Campbell (1997), Xiang and Gao (1994), and Nguyen and Tran (1999), M_S is converted to M_L by using their correlations in Nguyen et al. (2011). The comparisons are shown in Fig. 8a–d with magnitude 4, 5, 5.5, and 6, respectively. For distances over 100 km and magnitude less than or equal to 5.0, our new PGA attenuation curve consistently has the values less than the others' used in North Vietnam. While for distances from 10 to 100 km and magnitudes greater or equal to 5.5, the attenuation curves for North of Vietnam come closer to each others. Because the regional earthquakes and a denser seismic network are adopted in this study, the new attenuation curves are expected to be more favorable for North of Vietnam. Comparing the derived PGA attenuation curve in this study with the one for Taiwan (Wu et al., 2001), the PGA values from magnitude greater than five earthquakes are almost equal in distance range of 10–100 km, but show difference in distances less than 10 km. This difference can be explained by the effect of near-source observation term as mentioned in Wu et al. (2001). This term is not considered in this study owing to the lack of the near-source recordings and there is no evaluation of this term for northern Vietnam before.

Table 3
The information and observed peak ground motion of DienBien's earthquake and its aftershocks.

No	Event type	Origin time (UTC)		Lat	Long	Depth (km)	Mag	Station	PGA (cm/s^2)	PGV (cm/s)
1	Mainshock	19/2/2001	15:51:34	21.34	102.9	12	5.3	DienBien	109,76	4.994
		19/2/2001	15:51:34					TuanGiao	6.24	0.186
2	Aftershock	19/2/2001	15:57:02	21.39	102.9	11	3	DienBien	7.64	0.083
3	Aftershock	19/2/2001	16:06:02	21.38	102.9	6	3.1	DienBien	8.84	0.145
4	Aftershock	19/2/2001	16:14:51	21.41	102.9	5	3.3	DienBien	12.47	0.125
5	Aftershock	19/2/2001	16:40:17	21.42	102.9	5	4.2	DienBien	22.12	0.426
6	Aftershock	19/2/2001	19:02:49	21.4	102.9	5	4.8	DienBien	75.71	2.042
		19/2/2001						TuanGiao	3.38	0.099
7	Aftershock	19/2/2001	22:58:30	21.42	102.9	5	3	DienBien	4.18	0.064
8	Aftershock	21/2/2001	11:04:45	21.42	102.9	5	3.8	DienBien	10.62	0.155
9	Aftershock	22/2/2001	11:36:33	21.43	102.9	8	3.4	DienBien	22.49	0.254
10	Aftershock	23/2/2001	17:53:28	21.42	102.9	5	3.2	DienBien	10.28	0.109
11	Aftershock	23/2/2001	18:26:00	21.48	103	5	3.1	DienBien	8.81	0.071
12	Aftershock	24/2/2001	22:14:31	21.36	102.9	5	4.2	DienBien	29.13	0.563
13	Aftershock	4/3/2001	20:18:49	21.39	102.9	8	4.7	DienBien	43.35	1.052
		4/3/2001						TuanGiao	4.69	0.148
14	Aftershock	4/3/2001	20:41:54	21.39	102.9	5	3.4	DienBien	6.23	0.075
15	Aftershock	5/3/2001	2:12:25	21.44	102.9	5	3.5	DienBien	7.01	0.089
16	Aftershock	5/3/2001	14:23:39	21.42	103	5	3.2	DienBien	13.16	0.154
17	Aftershock	5/3/2001	15:06:58	21.48	102.8	6	3.7	DienBien	5.94	0.116

Table 4
List of nine events, which were recorded by strong ground motion instrument in period of 04/1997–07/1999.

No	Date	Time	Lat	Lon	Depth (km)	M_L	Recording
1	04/22/1997	18:43:52	23.17	105.25	10	4.3	7
2	05/19/1997	14:19:05	20.66	104.24	19	3.4	5
3	06/07/1997	21:07:35	21.09	104.82	9	3.9	4
4	07/16/1997	11:47:31	21.91	104.81	10	3.3	5
5	07/24/1997	13:21:51	21.11	104.84	15	3.5	4
6	12/23/1997	13:09:45	21.62	106.14	5	3.5	4
7	12/29/1997	20:25:54	21.14	106.23	13	3.2	3
8	02/10/1998	15:18:04	21.07	104.8	17	3.3	2
9	07/08/1999	4:11:48	20.76	104.78	1	3.4	2

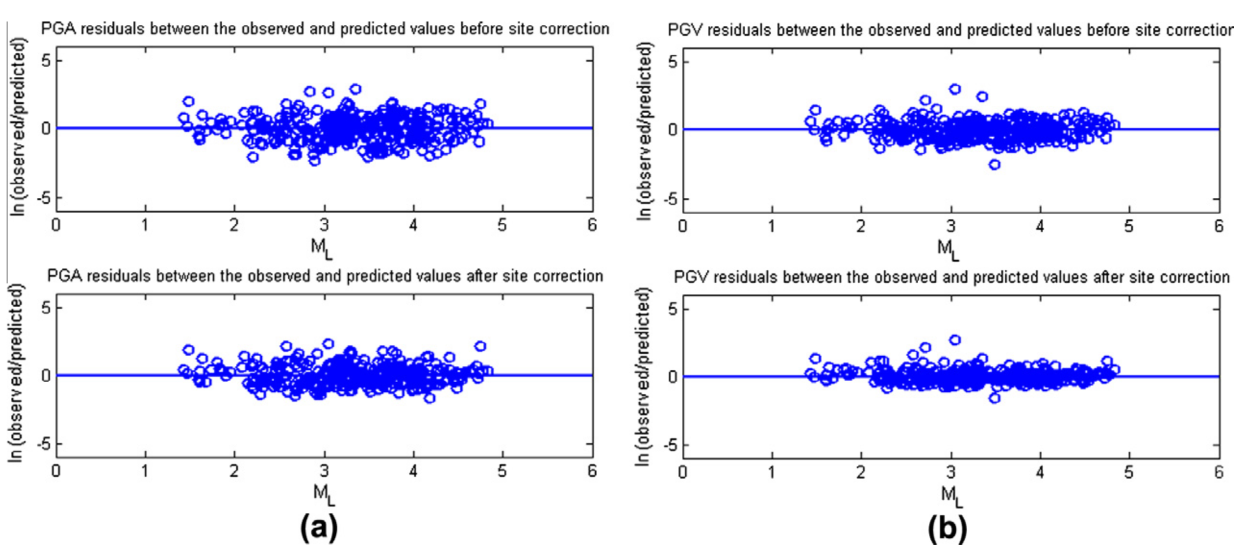

Fig. 7. The standard deviation of residuals before and after use the site correction: (a) for PGA and (b) for PGV.

Site corrections ranging from 0.34 to 5.72 for PGA curve and 0.4 to 3.0 for PGV curve (Table 2) are observed in the study. As indicated in Eq. (6), site correction, derived by the observed and predicted values, can reflect the soil condition beneath the recording station. In fact, there are some previous studies have pointed out this relation (Miao and Langston, 2007; Wu et al., 2001). In general, the stations located in the northwestern portion of North Vietnam have smaller site corrections (less than 1.25 and 1.0 for PGA and PGV, respectively) while ones located in the south-eastern portion of North Vietnam have larger site corrections (larger than 2.0 and 1.5 for PGA and PGV, respectively) (Figs. 8 and 9). Most of the stations with a small site correction are located in the mountain area, whereas the stations located in the plain have relatively large site corrections. Exceptionally, there are two stations in the southeastern portion, PLVB and THVB, have small PGA and PGV site correction values, and two

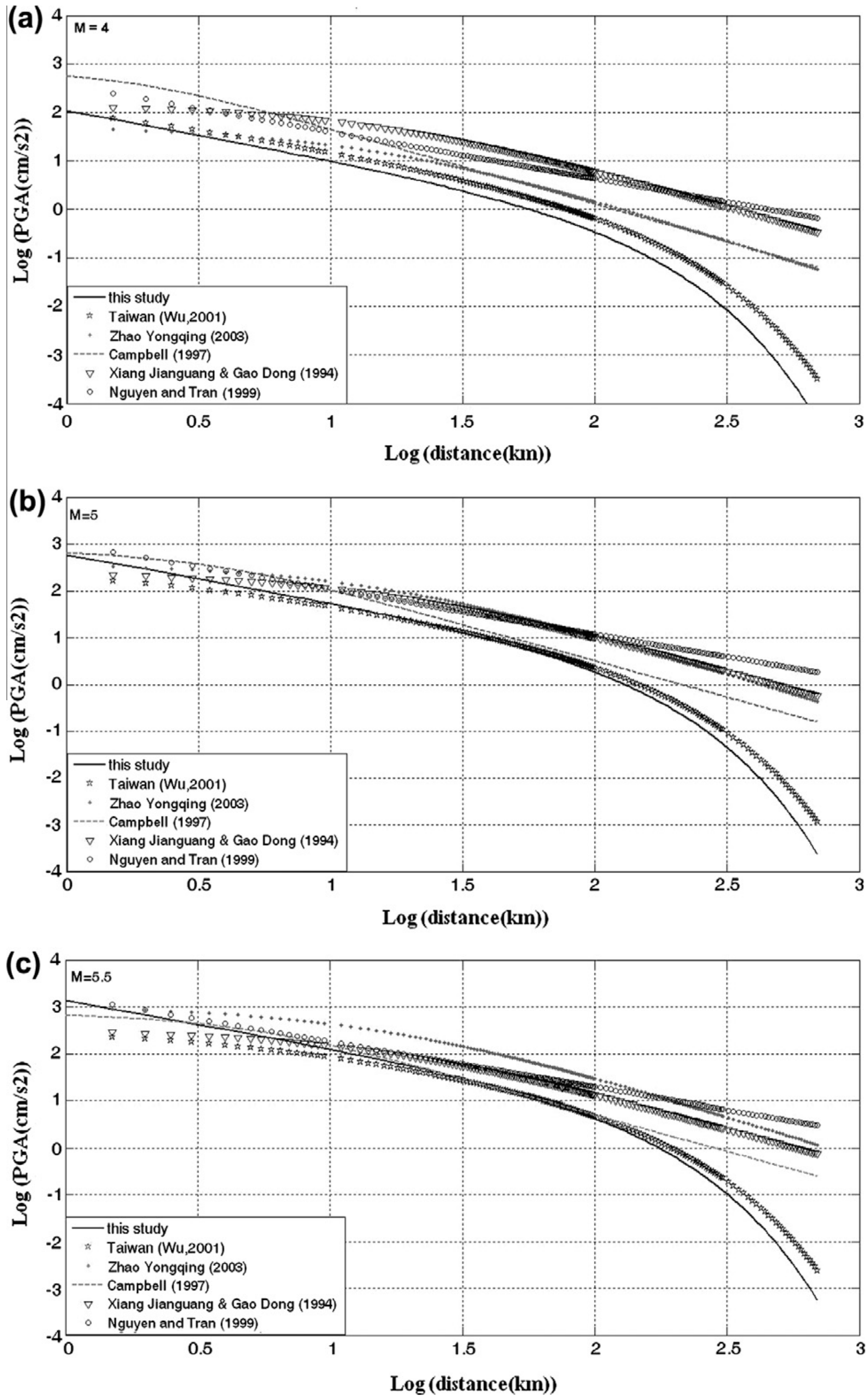

Fig. 8. (a–d) shows the plots of the comparison between PGA attenuation curve in this study and those from different regions in magnitude 4.0, 5.0, 5.5, and 6.0, respectively.

stations in the northwest, LCVB and SPVB, have the PGA and PGV site correction values larger than 1.25 and 1.0, respectively. We have checked these exceptions by considering the level of the ambient noise and the quality of the raw seismograms. It shows that the quality of recordings for two stations PLVB and THVB are very well. However, for the stations LCVB and SPVB, the quality of recordings is not as good as the other mountain stations indicated by their lower signal-to-noise ratios. We also compare the site corrections with the station corrections determined in the study of the northern Vietnam's M_L scale (Nguyen et al., 2011), which also reflect the site condition (Figs. 9 and 10). The stations, located in the mountain areas, have the small site corrections and the positive station corrections both indicating the minor effect of the site condition on ground motions. In opposite,

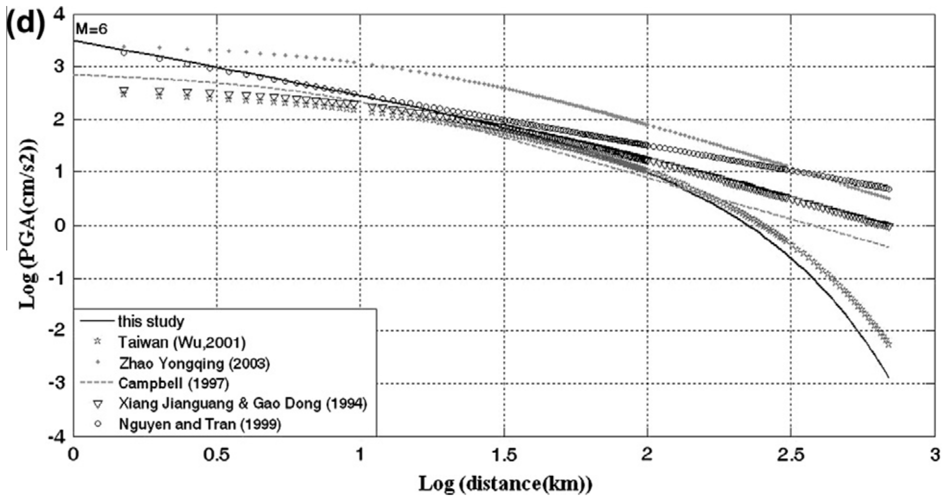

Fig. 8 (*continued*)

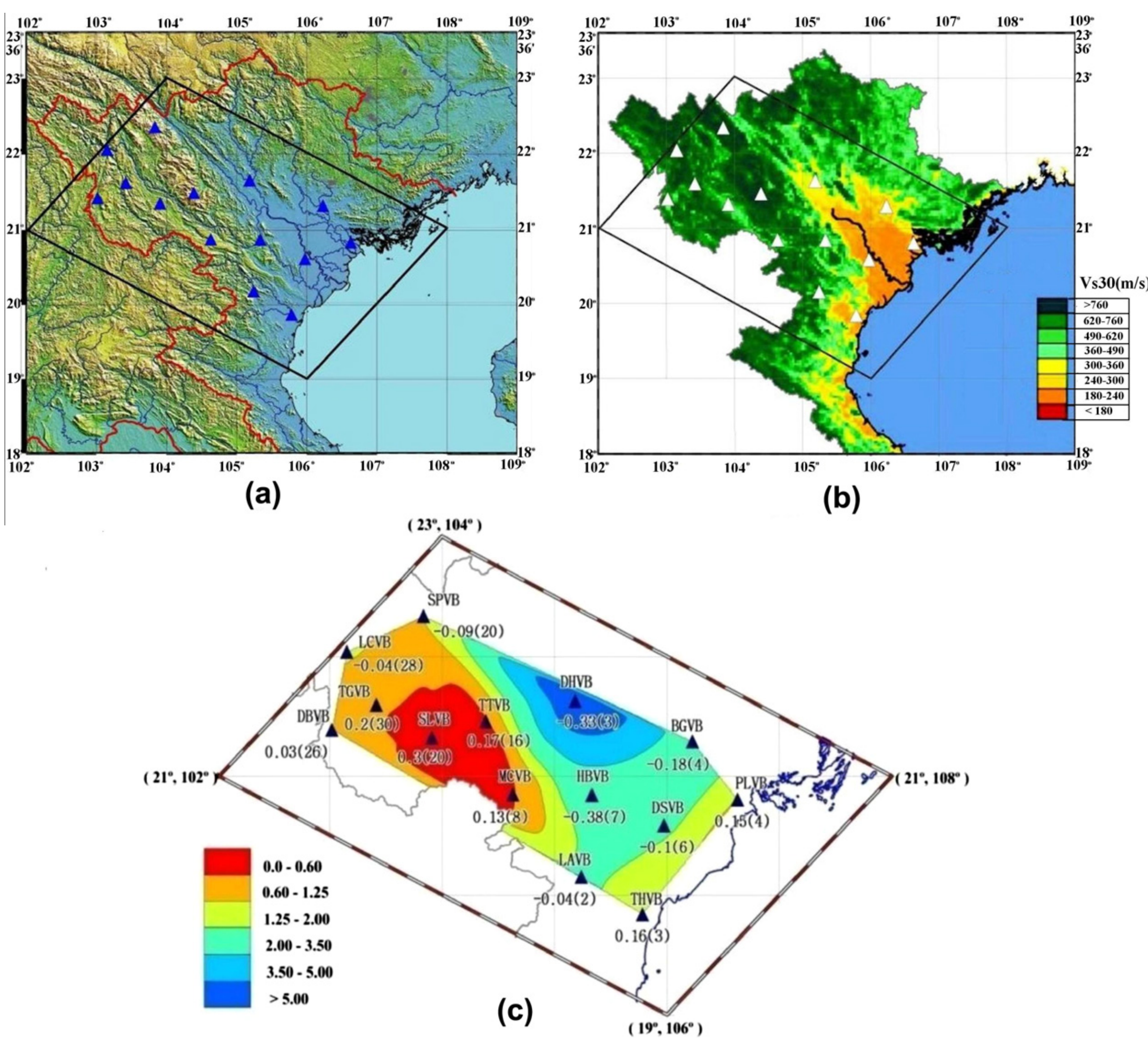

Fig. 9. (a) The topographic map, (b) the seismic site conditions V_S^{30} map, and the contour map of the site corrections for PGA (cm/s^2) attenuation. In the contour map, the values inside and outside the bracket are the number of recordings and the station correction, respectively. The values of site correction can be referred to the contour bar. Both site correction and station correction for each station are listed in Table 2.

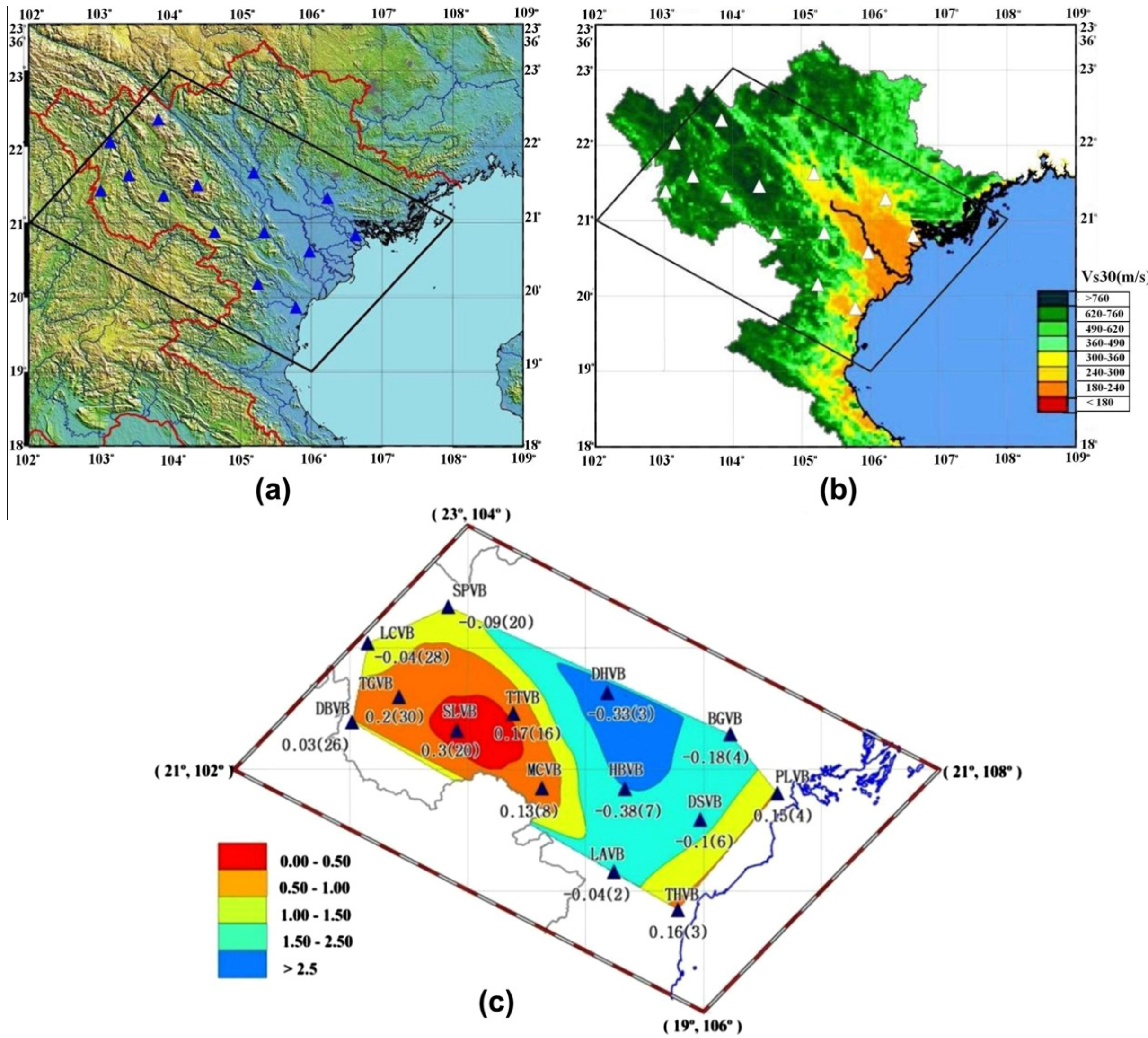

Fig. 10. Similar to Fig. 9 except the lower portion of the figure is for PGV (cm/s) attenuation.

the stations with large site corrections and negative station corrections are consistently located in the plain areas, which tend to have a higher degree of site amplification.

Finally, we compare the contour map of site correction with the seismic site conditions – V_S^{30} (average shear-wave velocity down to 30 m) map. The V_S^{30} values for northern Vietnam is derived from USGS's website (http://earthquake.usgs.gov/hazards/apps/vs30/, last accessed on May, 2011), which estimates the Global V_S^{30} map based on the topographic slope as a proxy (Wald et al., 2004; Wald and Allen, 2007; Allen and Wald, 2009). Figs. 9 and 10 generally indicate that the high site corrections are corresponding to the low V_S^{30} values in the plain areas and vice versa for the high site correction stations in the mountain areas. The total agreement between the station corrections (Nguyen et al., 2011), seismic site conditions map (V_S^{30}) and the site corrections (in this study) implies that the results in this study are reasonable.

Rapid and yet accurate estimation on the peak ground motion spatial distribution is essential in the earthquake emergency response operation. However, the station density in North Vietnam is not dense enough to provide a whole regional shake map, either PGA or PGV spatial distribution. While more stations are planning to be installed in the future, we presently can fill the station gap by estimating the predicated peak ground motion through the neighboring observed values and the site correction. These shake maps can be done based on the equation (Wu et al., 2001):

$$P = \overline{A} \times S \times \frac{A_{obs}}{A_{cal}} \tag{9}$$

where P is the peak ground motion value of the map at a specified site, $\overline{A}$ is either predicted PGA or PGV value determined by the attenuation curves at the specified site, S is the site correction value at the specified site, which was derived from the site correction contour map. A_{obs} is the observed peak ground motion value at the nearest station to the specified site and A_{cal} is the calculated peak ground motion value by using the attenuation relationship and the site correction at the nearest station. In the Eq. (9), the factor $\frac{A_{obs}}{A_{cal}}$ is considered as the weighting factor to determine the true peak ground motion value of the specified site.

Because of the scattering of the recording stations for the DienBien earthquake occurred in 02/2001, we could not apply this equation for creating a regional shake map. However, two stations, DienBien and TuanGiao stations, with station distance less than 50 km have recorded ground motions during the DienBien earthquake. We have calculated the predicted PGA values for DienBien

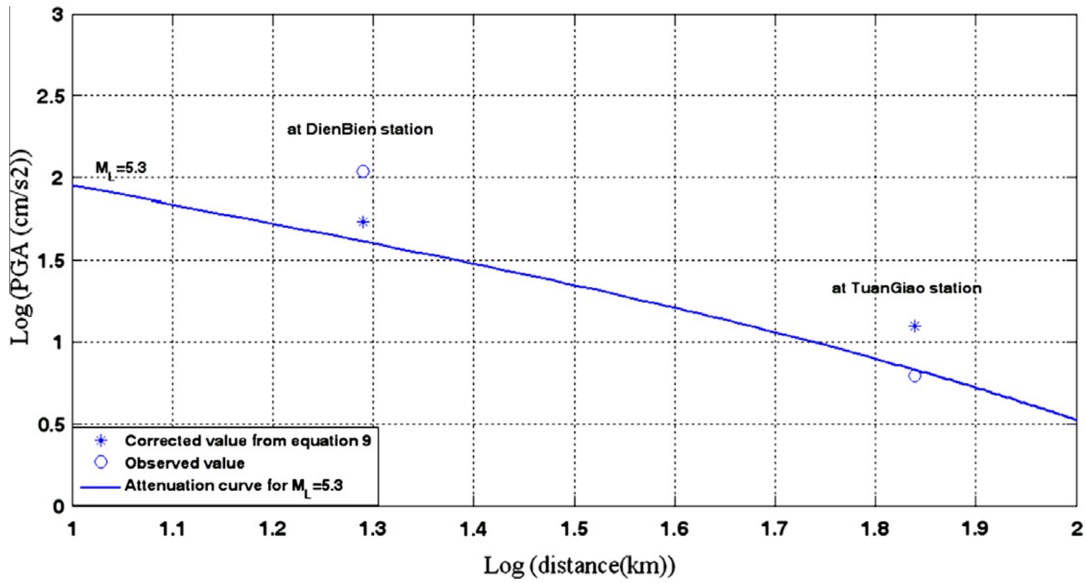

Fig. 11. The observed and the corrected PGA of the DienBien earthquake at the stations DienBien and TuanGiao and the corresponding attenuation curve.

and TuanGiao stations by using the observed PGA of TuanGiao and DienBien stations, respectively. The result is shown in Fig. 11. Although having some difference between the corrected and observed values, the corrected values still could be useful for creating a shake map. In the future, more stations in northern Vietnam is expected to be installed, we can create a more accurate shake map by combining more observations and predicted values by Eq. (9) after an occurrence of a strong earthquake.

In this study, we have derived the first ground motion attenuation relationships for northern Vietnam. Because the events used in this study are small, the new attenuations obtained in this study should be best applied to the earthquakes of magnitudes less than 5.0 and epicentral distances less than 500 km. Although there are only 330 amplitude records from 53 shallow earthquakes used in this study, the first attenuation curves for northern Vietnam proposed in this study still provide a reasonable and more accurate tool needed in the seismic hazard assessments such as for Probabilistic Seismic Hazards Assessment (PSHA) and earthquake shaking map.

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