SITE AMPLIFICATION MODELS OF PEAK GROUND ACCELERATION AND VELOCITY FOR THE BOGOTÁ BASIN, COLOMBIA

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Abstract

In this study, we developed site amplification models of PGA and PGV for the Bogotá basin, Colombia by analyzing the observed strong motion records. The amplification factors are defined as the PGAs and PGVs observed at surface divided by the reference PGAs and PGVs from the existing attenuation relationship. Several attenuation relationships including Uchiyama and Midorikawa (2006) are examined for evaluating reference bedrock intensities. The relationships between the Vs30 of the observation sites and the amplification factors for surface and body wave type records are modeled through regression analysis. The modeled site amplifications are discussed by comparing with the previous amplification models, and would be incorporated to real-time strong motions and building damage estimation system developing in Bogotá D.C.

Keywords: site amplification, peak ground acceleration, peak ground velocity, Vs30, Bogotá

1. Introduction

Colombia is located at the boundaries between the Nazca, Caribbean, and South American plates and has experienced many large earthquakes in the past. Severe structural damage caused by gigantic earthquakes occurring in the subducting zones between the plates such as the 1906 Mw 8.8 Colombian–Ecuador and the 1979 Mw 8.2 Tumaco earthquakes has been widely observed mainly in coastal areas. In the inland areas of Colombia, crustal earthquakes have been triggered by active faults widely distributed along the Andes Mountains. The Mw 6.1 Quindío earthquake on 25 January 1999 occurred in the central coffee-growing region and brought about destructive damage with ~ 1100 deaths, more than 50,000 buildings destroyed, and a direct economic loss of $1.5 U.S. Billion.

Bogotá, the capital of Colombia, is one of the largest metropolitan cities in Latin America with a population of approximately eight million. Many old masonry buildings are concentrated in the center of Bogotá, and the urbanized areas surrounding the city expanded as a result of rapid population growth. Bogotá has been affected by magnitude 6–7 class crustal earthquakes at intervals of approximately 100 year. Because such a large earthquake has not been recorded since 1917 in Bogotá, a destructive magnitude 7 class earthquake is expected to occur in the near future. Strong ground-motion prediction and structural damage estimation for future large earthquakes are indispensable to develop appropriate earthquake disaster mitigation plans.

In a previous study we developed average shear-wave velocity in upper 30 m (Vs30) -based empirical site amplification models of response spectra for the Bogotá basin, Colombia [1]. Since the surface waves and body waves were clearly observed in shallow and deep earthquakes, respectively, we developed the amplification models for both wave types by classifying the observation records. The amplifications were modeled from the response spectrum observed at surface dividing by the reference spectrum calculated from the exiting Japanese attenuation relationship by Uchiyama and Midorikawa [2]. Whereas response spectra would be useful for evaluating seismic design and structural damage, peak ground acceleration (PGA) and peak ground velocity (PGV) are also important for understanding strong motion intensities in a target area.

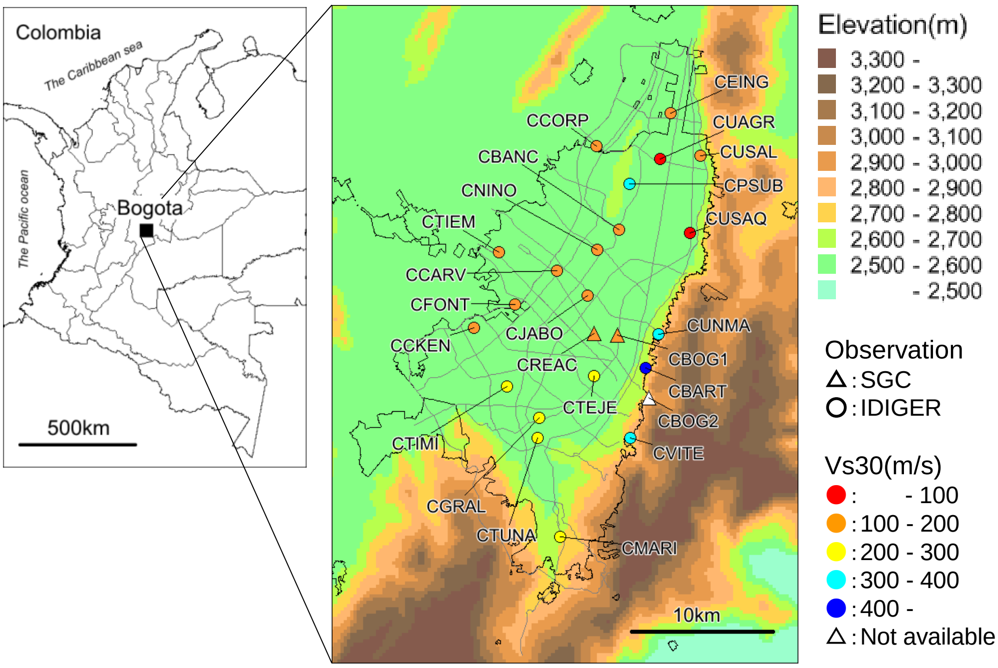

Fig. 1 - Locations of earthquake observation sites in Bogotá, Colombia [1]

Table 1 - Earthquake observation sites in Bogotá and their Vs30 [1]

No.	Code	Institute	Latitude (deg.)	Longitude (deg.)	Elevation (m)	Survey	Surveyed depth (m)	Vs30 (m/s)
1	CBOG1	SGC	4.6410	-74.0800	2,556	PS logging	45	115.6
2	CBOG2		4.6010	-74.0600	2,683	-	-	-
3	CREAC		4.6420	-74.0950	2,551	PS logging	92	175.6
4	CBANC	IDIGER	4.7085	-74.0789	2,552	Microtremor	302	136.6
5	CBART		4.6199	-74.0619	2,671	Microtremor	64	526.4
6	CCARV		4.6823	-74.1188	2,556	Microtremor	120	102.5
7	CCKEN		4.6458	-74.1723	2,548	Microtremor	259	186.8
8	CCORP		4.7619	-74.0937	2,554	Microtremor	166	110.8
9	CEING		4.7835	-74.0459	2,562	Microtremor	270	103.6
10	CFONT		4.6608	-74.1456	2,546	Microtremor	188	139.5
11	CGRAL		4.5879	-74.1301	2,566	Microtremor	268	257.4
12	CJABO		4.6664	-74.0993	2,554	Microtremor	138	101.0
13	CMARI		4.5120	-74.1170	2,689	Microtremor	168	240.1
14	CNINO		4.6959	-74.0930	2,555	Microtremor	137	106.9
15	CPSUB		4.7378	-74.0725	2,588	Microtremor	145	306.4
16	CTEJE		4.6147	-74.0949	2,566	Microtremor	124	206.7
17	CTIEM		4.6943	-74.1559	2,552	Microtremor	275	105.7
18	CTIMI		4.6083	-74.1510	2,559	Microtremor	340	202.4
19	CTUNA		4.5752	-74.1311	2,563	Microtremor	281	221.4
20	CUAGR		4.7541	-74.0527	2,561	Microtremor	227	91.4
21	CUNMA		4.6416	-74.0539	2,679	Microtremor	64	305.5
22	CUSAL		4.7558	-74.0266	2,567	Microtremor	261	104.5
23	CUSAQ		4.7064	-74.0334	2,565	Microtremor	324	93.9
24	CVITE		4.5752	-74.0717	2,777	Microtremor	37	383.7

In this study, we developed site amplification models of PGA and PGV for Bogotá by analyzing the observed strong motion records. The amplification factors are defined as ratios of PGAs and PGVs observed at surface divided by the reference PGAs and PGVs from the existing attenuation relationship. Several attenuation relationships including Uchiyama and Midorikawa [2] are examined for evaluating reference bedrock intensities. The relationships between the

Vs30 of the observation sites and the amplification factors for surface and body waves are modeled through regression analysis.

2. Vs30 Data and Earthquake Observation Records in Bogotá

As introduced in Miura et al. [1], PS-loggings were performed at two seismic observation stations operated by SGC, and microtremor explorations have been conducted at the seismic observation stations in Bogotá to reveal three-dimensional (3D) S-wave velocity structure model of the basin [3, 4]. The Vs30s at the stations were calculated from the obtained Vs structure models. Figure 1 shows the distribution of the seismic observation stations in Bogotá with their Vs30 values and the elevation map. Whereas the Vs30 at the western basin edge such as CBART is higher than 400 m/s, the Vs30s in the northern basin sites show smaller than 100 m/s. Although the Vs30 at CBOG2 located in the western basin edge was not investigated, the site class is expected to be nearly bedrock because of the geological and topographical conditions.

The seismic observation networks in Bogotá have been operated by SGC and IDIGER. As shown in Table 1, the seismic observation records at three sites of SGC and 21 sites of IDIGER are analyzed in this study. Figure 2 shows acceleration and velocity waveforms of NS component observed at CBOG1 during an earthquake (Mw=5.9 and depth=0 km) at Quetame region on May 24, 2008 and an earthquake (Mw=6.2 and depth=154 km) at Los Santos region on March 10, 2015. The spectral characteristics of the records are remarkably different. Although the ground motion with the periods of around 0.5s and 1 s is predominant in the record of the 2015 event, the ground motion with the period of 2 s is significantly dominant in the record of the 2008 event. Miura et al. [1] revealed that such longer period motions mainly consist of basin-edge-induced surface waves travelling in the basin from shallow earthquakes whereas the shorter period motions are vertically propagated body waves in deep earthquakes. Since the spectral characteristics of the ground motions are different between the surface and body waves, the site amplification models need to be

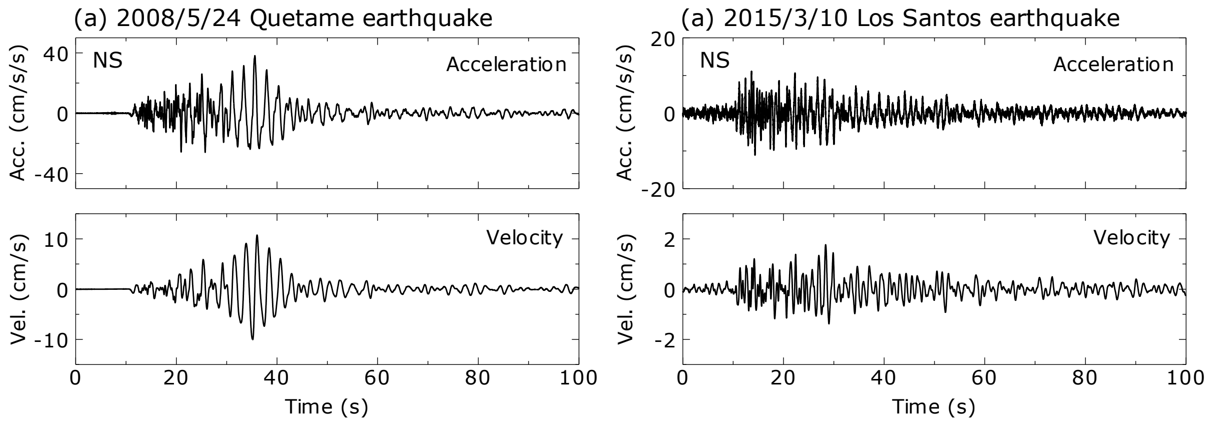

Fig. 2 - Accleration and velocity waveforms observed at CBOG1 during the 2008 and 2015 events

Table 2 - List of earthquake records used in this study [1]

Date (yyyy/mm/dd)	Time (hh:mm) (UTC)	Latitude (°)	Longitude (°)	Depth (km)	M_L	M_w*	Distance to Bogotá (km)	PGA (cm/s/s)	Number of Data	Type
1999/07/17	12:21	6.07	−72.73	3	5.4	5.6	220	2.9	6	Surface wave
2002/11/23	23:56	3.73	−74.05	67	5.6	5.1	120	10.1	2	Surface wave
2003/01/22	15:55	3.57	−74.57	0	5.3	5.2	130	5.3	2	Surface wave
2008/05/24	19:20	4.40	−73.81	0	5.7	5.9	40	62.4	21	Surface wave
2010/07/29	19:34	3.96	−75.16	2	5.1	5.1	140	5.1	11	Body wave
2015/03/10	20:55	6.83	−73.13	154	6.3	6.2	300	30.1	21	Body wave
Total									63	

PGA, peak ground acceleration.
*Reference: Global Centroid Moment Tensor.

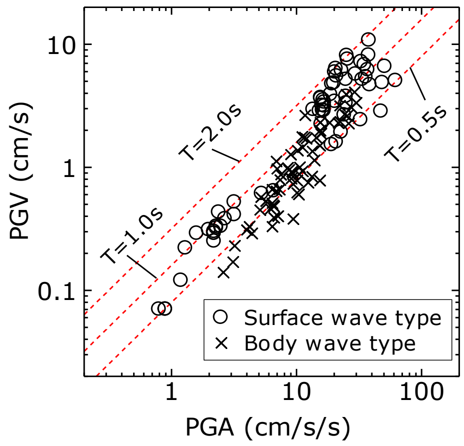

Fig. 3 - Relationship between PGA and PGV at ground surface analyzed in this study

developed for each seismic wave type.

Table 2 shows the list of the earthquake observation records analyzed in this study. The records are classified into surface wave type and body wave type considering the focal depth of the earthquakes and the spectral characteristics of the records. Whereas 31 records are analyzed for surface wave type, 32 records are used for body wave type. Since the maximum PGA and PGV of the records are 60 cm/s/s and 10 cm/s, respectively, nonlinear seismic response of the ground is not considered in the analysis. Figure 3 shows the relationship between PGA and PGV observed at ground surface analyzed in this study. Dotted lines indicate the relationships for equivalent natural periods of 0.5s, 1.0s, and 2.0s in harmonic oscillations, respectively. Although the relationships of body wave type records almost correspond to 0.5 to 1.0s, the relationships of surface wave type records mostly distribute around 1.0 to 2.0s, indicating that the surface wave type records include much longer predominant periods in the observation data.

3. Estimation of PGA and PGV at Reference Rock

In order to obtain site amplification factor, ground motion intensity at reference rock site is indispensable. Since the number of the observation records in Bogotá is limited, non-reference site approach is adopted in modelling site amplifications for PGA and PGV. In the non-reference site approach, the site amplification is evaluated on the basis of ratio of a PGA or PGV observed at a target site to that obtained from an attenuation relationship. Miura et al. [1] adopted the attenuation relationship proposed by Uchiyama and Midorikawa [2] (UM06) for modelling amplification of response spectra. Although the attenuation relation provide response spectra at reference rock with the Vs30 of approximately 550 m/s, it did not provide other peak ground motion parameters. Therefore, PGAs and PGVs on reference rock are estimated from the obtained response spectra. We adopted the equations for estimating PGA and PGV on reference rock (PGA_R and PGV_R) from response spectra proposed by Booth [5] (B07) as shown below.

$$PGA_R = \frac{SA_R(T_{Peak})}{2.65} \tag{1}$$

$$PGV_R = \frac{SV_R(T_{Peak})}{2.3} \tag{2}$$

Here, SA_R indicate acceleration response spectrum calculated from the attenuation equation of Uchiyama and Midorikawa [2] at the smoothed peak period, T_{Peak}. The peak period was defined from multiple peak periods and their spectral peaks in observed response spectrum. Since only one peak is calculated in the reference response spectrum by the attenuation relationship, the peak periods are accepted as the T_{Peak} in the Eq. (1) and (2). Pseudo velocity response spectra calculated from SA_R are used as SV_R in Eq. (2).

4. Site Amplification Models for PGA and PGV

The site amplification factors are defined as the ratio of the ground motion parameters observed at surface to the parameters at reference rock estimated as attenuation relationship. Figure 4 shows the relationships between the Vs30 at the site and the derived site amplifications of PGA and PGV for surface wave and body wave type. Although large variation is found in the amplification for PGA, significant Vs30 dependence is found especially in the amplification for PGV. Regression lines for the site amplifications as a function of the Vs30 are modeled as

$$\log Amp = a + b \log Vs30 \quad (3)$$

in which the regression coefficients a and b indicate the intersection with the vertical axis and the gradient of the relation, respectively. The derived coefficients for the ground motion parameters are shown in the Eq. (4) and (5) and in the figure. The correlation coefficients between Vs30 and amplification factor, r, are also shown in the equations.

For surface wave type:

$$\begin{aligned} \log Amp_{PGA} &= 0.44 - 0.25 \log Vs30 \quad (r = 0.27) \\ \log Amp_{PGV} &= 1.56 - 0.70 \log Vs30 \quad (r = 0.75) \end{aligned} \quad (4)$$

For body wave type:

$$\begin{aligned} \log Amp_{PGA} &= 1.40 - 0.46 \log Vs30 \quad (r = 0.47) \\ \log Amp_{PGV} &= 2.18 - 0.75 \log Vs30 \quad (r = 0.73) \end{aligned} \quad (5)$$

Since the correlation coefficients of PGV for surface and body wave types are higher than 0.7, the regression lines well represent the trends of the derived amplifications. On the contrary, the correlation coefficients of PGA are lower than 0.5. Especially Vs30 dependence of PGA for surface wave type is remarkably low because surface wave generally produce long-period ground motion and would not contribute short-period ground motion that control the amplitude of PGAs.

In order to discuss the applicability of the attenuation relationship used in this study, other typical attenuation relationships are also used to evaluate the site amplifications. The attenuation relationships for PGA and PGV proposed by Si and Midorikawa [6] (SM99) and Kanno et al. [7] (K06) are applied to estimate the ground motion intensities at the reference rock with the Vs30 of 550 m/s. These attenuation relationships are selected because they can apply not only for crustal shallow earthquakes such as the 2008 Quetame event but also for deep earthquakes such as the 2015 Los Santos event. The site amplifications are calculated and the regression lines are estimated by using these previous attenuation relationships.

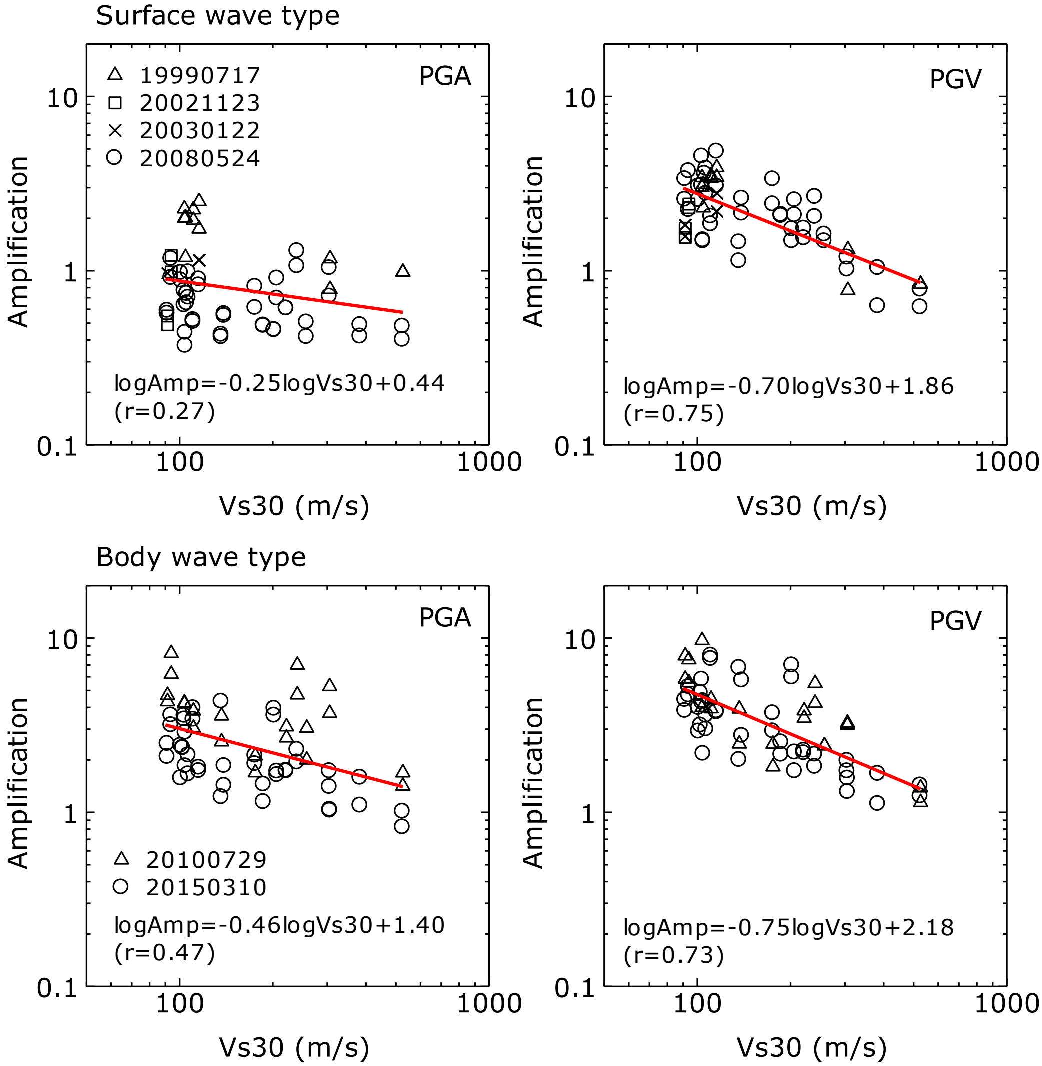

Fig. 4 – Model relationships between Vs30 and site amplification for surface wave type and body wave type.

The derived regression and correlation coefficients are summarized in Table 3. Compared with the site amplifications derived from UM06 and B07, no significant difference are found among the amplifications for the surface wave type. On the other hand, low correlation coefficient is found in the amplification derived from K06 for the body wave type, whereas the amplification derived from SM99 almost agree with the results by UM06 and B07. This indicates that the attenuation relationship of K06 could not well reproduce the ground motion intensities of a deep earthquake such as the 2015 event as discussed in Miura et al. [1]. The correlation coefficients derived from UM06 and B07 are higher than those of other relationships.

Vs30-dependent site amplification models have been proposed in previous studies. Figure 5 shows the comparison of the regression lines for the site amplifications derived in this study and those in Midorikawa et al. [8] and Yamaguchi and Midorikawa [9]. Although the amplifications of PGA for surface wave type are much smaller than those of the previous studies, the amplifications of PGV are similar to those of the previous studies. The amplifications of PGA and PGV for body wave type almost agree with the previous models since the previous models were developed to evaluate the site amplifications of S-waves.

Table 3 – Comparison of regression and correlation coefficients derived from different attenuation relationships

Used attenuation relationship						
Surface wave type	PGA			PGV		
	a	*b*	*r*	*a*	*b*	*r*
UM06 and B07	0.44	-0.25	0.27	1.86	-0.70	0.75
SM99	0.34	-0.24	0.36	1.76	-0.72	0.74
K06	0.31	-0.22	0.31	1.78	-0.72	0.67
Body wave type	PGA			PGV		
	a	*b*	*r*	*a*	*b*	*r*
UM06 and B07	1.40	-0.46	0.47	2.18	-0.75	0.73
SM99	1.02	-0.35	0.37	1.52	-0.54	0.50
K06	1.50	-0.41	0.37	1.53	-0.52	0.24

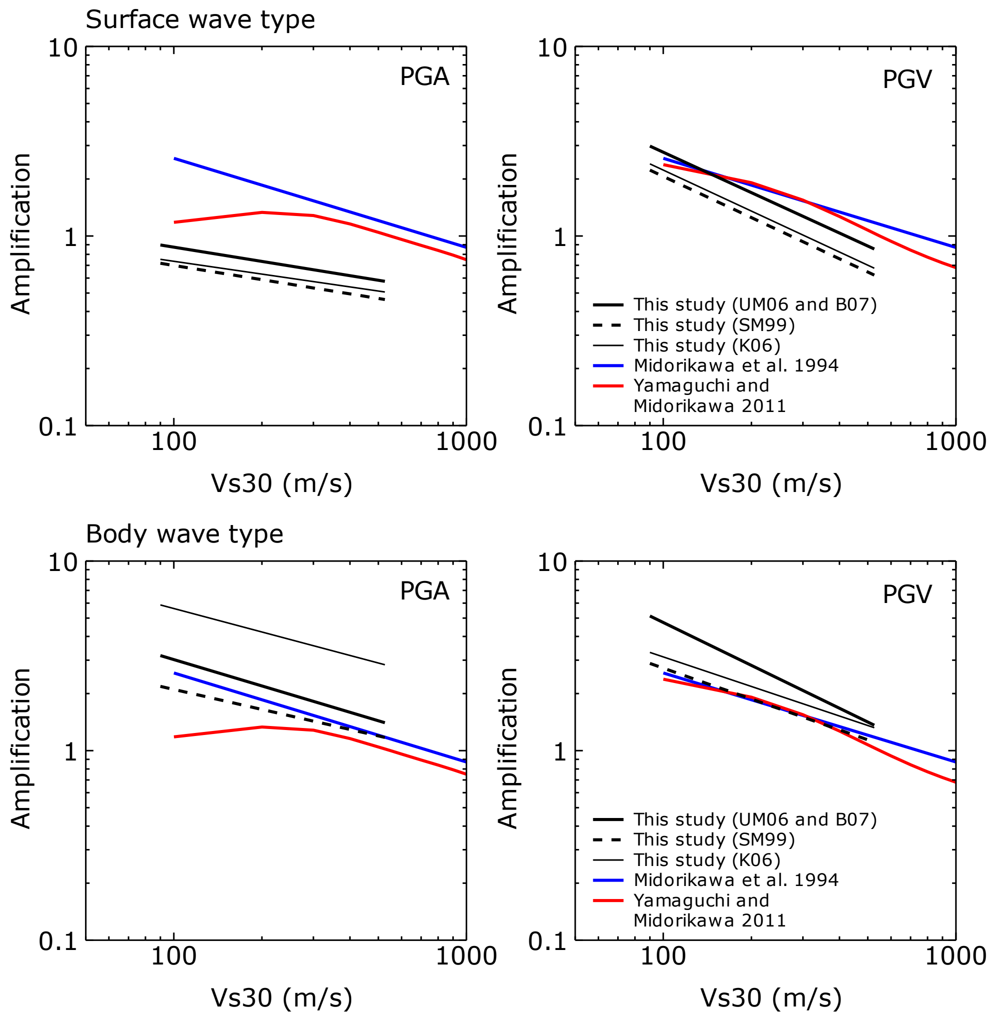

Fig. 5 – Comparison with site amplification models for PGA and PGV derived in previous studies

5. Concluding Remarks

This study introduced the Vs30-based site amplification models of PGA and PGV for the Bogotá basin, Colombia. The ground motion intensities at reference rock are evaluated from the attenuation relationship of response spectrum by UM06 and the estimation equations to PGA and PGV by B07. The site amplifications are evaluated by the ratio of the observed ground motion parameters to the estimated intensities at the reference rock. The site amplifications are modeled by classifying to surface wave type and body wave type because the spectral characteristic observed in shallow earthquakes are different from that in deep earthquakes. High correlations were found between Vs30 and PGVs for both wave types although the correlations were low between Vs30 and PGAs. The amplification models for PGA are similar to the previous models developed in Japan. These models can be applied to estimate ground motion distributions from observation records and Vs30 map, and would be incorporated to the real-time strong motion and building damage estimation system developing in Bogotá D. C.

6. Acknowledgements

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