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Estimation of Ground Shaking Distribution Based on Empirical Models and Vs30 Map in Bogota, Colombia

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Abstract

In order to develop empirical ground motion prediction equations (GMPEs) applicable to Bogota, Colombia, average shear wave velocity upper 30m (Vs30) -based site amplification model is proposed. The attenuation relation for acceleration response spectra on engineering bedrock developed in Japan is applied to evaluate the observed response spectra at rock sites observed in the 2008 Quetame earthquake. The period-dependent site amplification equations are derived from the Vs30 values at the sites and the spectral ratio of the observed response spectra at surface to the computed response spectra at the engineering bedrock. We confirmed that the developed GMPEs well reproduce the observed response spectra not only for the rock sites but for the soil sites. The Vs30 map in Bogota is developed from the topographic slope-derived Vs30 map by applying the relation between the topographic Vs30 and the measured Vs30. By using the GMPEs and the modified Vs30 map, the distribution of response spectra in Bogota due to an M7.0 scenario earthquake area is estimated.

Keywords: Ground motion prediction equations, Response spectra, Vs30, Colombia

1. Introduction

Colombia, located between the South-American plate and the Nazca plate, has been historically suffered by many earthquakes. The 1906 Ecuador-Colombia earthquake (M8.9) and the 1979 Tumaco earthquake (M7.8) occurred in the subduction zone produced severe tsunami damage in the southern part of Colombia. Due to the tectonic movement, many active faults are distributed in the central part of Colombia. The inland urban areas have been affected by the large crustal earthquake such as the 1917 Bogota earthquake (Mw6.7), the 1999 Quindio earthquake (Mw6.2) and the 2008 Quetame earthquake (Mw5.9).

In Bogota, the capital of Colombia, dense urban areas are widely distributed with the population of approximately eight millions. Although damaging earthquake has not been occurred since the 1917 event, M7-class large earthquake triggered by the active faults in the Andes Mountain region is anticipated in near future. Earthquake damage assessments has been performed based on seismic hazard analysis in Bogota [e.g. 1]. However, probabilistic approach and simple soil classification based on the surface geology were adopted in the seismic hazard analysis. The scenario-based earthquake hazard assessment using quantitative soil information needs to be conducted in order to consider effective earthquake disaster mitigation planning and to accurately evaluate seismic performance of the buildings.

Empirical ground motion prediction equations (GMPEs) consist mainly of attenuation relation for ground motion intensity on bedrock and site amplification factors for surface soil. The time-averaged shear wave velocity upper 30m (Vs30) are now widely used to evaluate the site amplification. The GMPEs for response spectra are useful to evaluate period-dependent building seismic performance. In this study, the applicability of existing attenuation relation for acceleration response spectra on engineering bedrock is examined and Vs30-based site amplification model for response spectra applicable to Bogota area are developed by analyzing observed ground motion records in the 2008 Quetame earthquake. The proposed method is applied to a M7-class scenario earthquake near Bogota in order to estimate the strong shaking distribution.

2. Attenuation Relation for Response Spectra on Engineering Bedrock

In the 2008 Quetame earthquake (Mw=5.9, Depth=3km), ground motion data was recorded not only in Bogota are but also near source area. Figure 1 shows the locations of the observation sites in and around Bogota with the fault. The distribution of Vs30 estimated from topographic slope (herein topographic Vs30) expressed by 250m-mesh (7.5 arcsecond) based on the technique of Allen and Wald [2] (AW09) is also shown in Fig. 1. The observation codes, peak ground accelerations (PGA) and the closest distances to the fault are denoted in Table 1. The observation sites are classified into rock sites and soil sites from surface geology. CQUET is located in the near source area and strong ground shaking with the PGA of approximately 600cm/s/s was observed. In the rock sites, peak period from horizontal to vertical spectral ratio (T_{HVSR}) of observed ground motion are calculated. The Vs30 is estimated from the relation between peak period and Vs30 proposed in McNamara *et al.* [3] (herein HVSR Vs30) as shown in Table 1. The HVSR Vs30 and the topographic Vs30 shows the Vs30s at rock sites are approximately 500m/s or larger. Here we assume the Vs30s of the rock sites to be 550m/s.

The attenuation relation for acceleration response spectra on engineering bedrock (Vs30=550m/s) proposed by Uchiyama and Midorikawa [4] is applied to evaluate the ground motions at rock sites. The relation was developed from strong ground motion data observed from 1968 to 2003 in Japan. The 5%-damped acceleration response spectra $S_A(T)$ is computed by the equation below.

$$\log S_A(T) = a(T)M_W + b(T)X + g + d(T)D + c(T) \tag{1}$$

Here, M_W, X and D are moment magnitude, closest fault distance and focal depth, respectively. The period-dependent regression coefficients $a(T)$, $b(T)$, $c(T)$ and $d(T)$ are expressed by the quartic function shown below and Table 2.

$$x(T) = \sum_{i=0}^{4} x_i (\log T)^i \tag{2}$$

The focal depth-dependent coefficient g in Eq. (1) is expressed by the equation below.

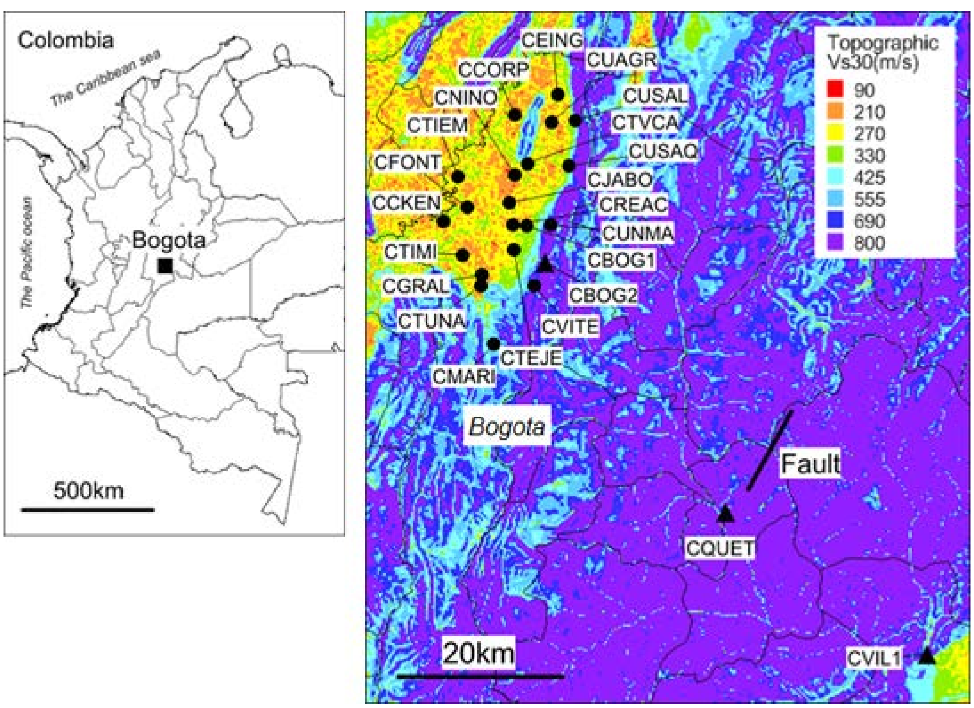

Fig. 1 Locations of observation sites and fault of the 2008 Quetame earthquake

(Triangle: Rock site, Circle: Soil site)

$$\begin{cases} g = -\log(X+e) & D \le 30\,\text{km} \\ g = 0.4\log(1.7D+e) - 1.4\log(X+e) & D > 30\,\text{km} \end{cases} \tag{3}$$

The near source saturation factor e is expressed by the equation below.

$$e = 0.006 \cdot 10^{0.5M_w} \tag{4}$$

The comparison of the observed and computed response spectra at rock sites is shown in Fig. 2. The observed spectra represents the geometric mean of two horizontal spectral accelerations. The site amplification is not considered in these sites. The computed response spectra shows good agreement with the observed ones not only in the near source region such as CQUET but in relatively far field region such as CVIL1 and CBOG2. It indicates that the attenuation relation developed in Japan is applicable to the ground motion at the rock sites in Bogota area.

Table 1 Characteristics of ground motion observation sites in and around Bogota

Geology	Institute	Code	PGA(cm/s/s)	Fault Distance(km)	Proxy Vs30	
					HVSR Vs30(m/s)*	Topographic Vs30(m/s)
Rock	SGC	CQUET	605.6	4	579	800
	SGC	CVIL1	71.8	30	NA	690
	SGC	CBOG2	72.6	35	462	800
					*: HVSR Vs30=51.9/T_{HVSR}+254.7	
Geology	**Institute**	**Code**	**PGA(cm/s/s)**	**Fault Distance(km)**	**Measured Vs30(m/s)**	**Topographic Vs30(m/s)**
Soil	IDIGER	CBANC	15.9	44	137	425
	SGC	CBOG1	38.2	39	116*	270
	IDIGER	CCKEN	15.8	48	187	270
	IDIGER	CCORP	16.5	49	111	270
	IDIGER	CEING	25.4	48	104	330
	IDIGER	CFONT	19.3	47	140	210
	IDIGER	CGRAL	20.4	41	257	270
	IDIGER	CJABO	37.3	43	101	270
	IDIGER	CMARI	62.4	36	240	425
	IDIGER	CNINO	36.1	44	107	210
	SGC	CREAC	33.1	41	176*	270
	IDIGER	CTEJE	38.8	39	207	270
	IDIGER	CTIEM	23.1	50	106	270
	IDIGER	CTIMI	16.8	44	202	270
	IDIGER	CTUNA	25.0	41	221	330
	IDIGER	CUAGR	20.8	46	91	210
	IDIGER	CUNMA	47.7	37	306	690
	IDIGER	CUSAL	16.3	44	105	425
	IDIGER	CUSAQ	48.7	40	94	330
	IDIGER	CVITE	24.3	35	384	555
					* From PS-logging	
					Others: From microtremor array observation	

Table 2 Regression coefficients of quartic function in Eq. (2)
(adopted from Uchiyama and Midorikawa 2006)

	x_0	x_1	x_2	x_3	x_4
a(T)	0.6692	0.3140	0.1199	-0.1135	-0.0541
b(T)	-0.0018	0.0029	-0.0010	-0.0006	0.0003
c(T)	-0.8028	-3.4501	-1.3750	1.0960	0.5136
d(T)	0.0025	-0.0054	-0.0004	0.0012	0.0001

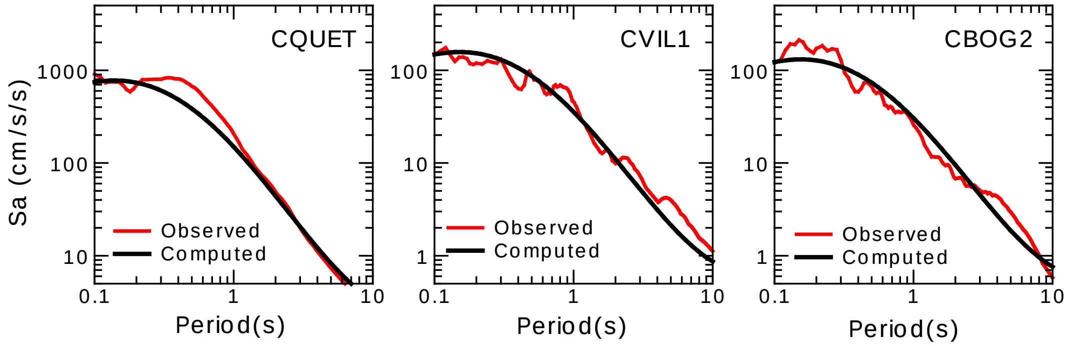

Fig. 2 Comparison of observed and computed response spectra at rock sites

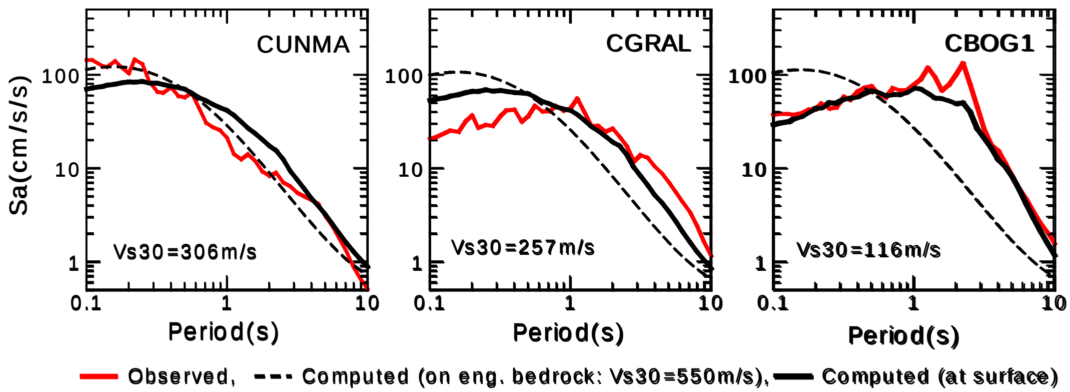

Fig. 3 Comparison of observed and computed response spectra at soil sites

3. Vs30-based Site Amplification Model

Bogota is located on several hundred meter thick soft soil deposit, indicating that strong site amplification is expected. In order to develop Vs30-based site amplification model, the measured Vs30 values at the observation sites are collected. PS-logging data is available at CBOG1 and CREAC. The microtremor array observations were conducted at the other soil sites to estimate the shear wave velocity (Vs) profile [5]. The Vs30s calculated from the profiles are shown in Table 1. The measured Vs30s in the most sites are 100 to 200m/s.

Figure 3 shows the comparison of the observed response spectra (solid red line) for various Vs30 sites in the 2008 event and the computed response spectra on the engineering bedrock by the attenuation relation (dotted black line). The observed response spectra in longer period range (>0.5s) are strongly amplified with the decreasing Vs30. This trend is consistent with the previous Vs30-based site amplification studies in U.S. and Japan [e.g., 6, 7]. On the contrary, the observed response spectra in shorter period range (<0.5s) are dramatically reduced from the computed spectra on the engineering bedrock, indicating that the spectral amplification in the soil sites would be smaller than a factor of 1. This trend was not observed in the previous Vs30 studies shown above.

In order to examine the spectral amplification characteristics in Bogota, theoretical transfer function is calculated from the microtremor-derived Vs profile. The Vs profile inverted from the microtremor array observation at CBOG1 is shown in Fig. 4(a). The PS-logging profile to the depth of 50m is also denoted in Fig. 4(a). The thickness of the soft soil deposit with the Vs of 200m/s or less is about 70m and the depth to the engineering bedrock with the Vs of 700m/s is approximately 220m. Figure 4(b) shows the theoretical transfer function (black line) from the engineering bedrock by giving the damping factor of 5% for all layers. The spectral ratio of the observed response spectra at surface to the computed response spectra on the engineering bedrock at CBOG1 is shown in Fig. 4(b) (red line). Although peak period of the spectral ratio is slightly longer than that of the theoretical transfer function, the shape of the spectral ratio is similar to the transfer function. It indicates that the spectral ratio almost represents the site amplification of the surface soil with the reference to the engineering bedrock.

In this study, the period-dependent site amplification is defined as the spectral ratio of the observed response spectra to the computed response spectra on the engineering bedrock. Figure 5 shows the relationship between the Vs30 at the site and the derived site amplification factor for each period. Strong period- and Vs30-dependency is observed in the site amplification. Linear regression analysis is performed to develop the Vs30-based site amplification (*Amp*) equation as shown below.

$$\log Amp(T) = p(T) \cdot \log Vs30 + q(T) \tag{5}$$

Here, period-dependent coefficients *p(T)* and *q(T)*, and the correlation coefficient r are shown in Table 3. Here the regression lines (red lines in Fig. 5) are modeled to pass through a point (*Vs30*=550, *Amp*=1). In longer

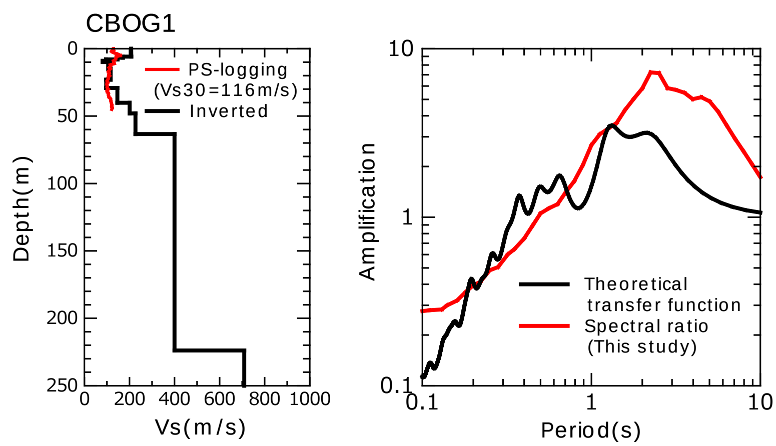

Fig. 4 (a) PS-logging and microtremor-derived Vs profiles, (b) Comparison of theoretical transfer function and spectral ratio of response spectra at CBOG1

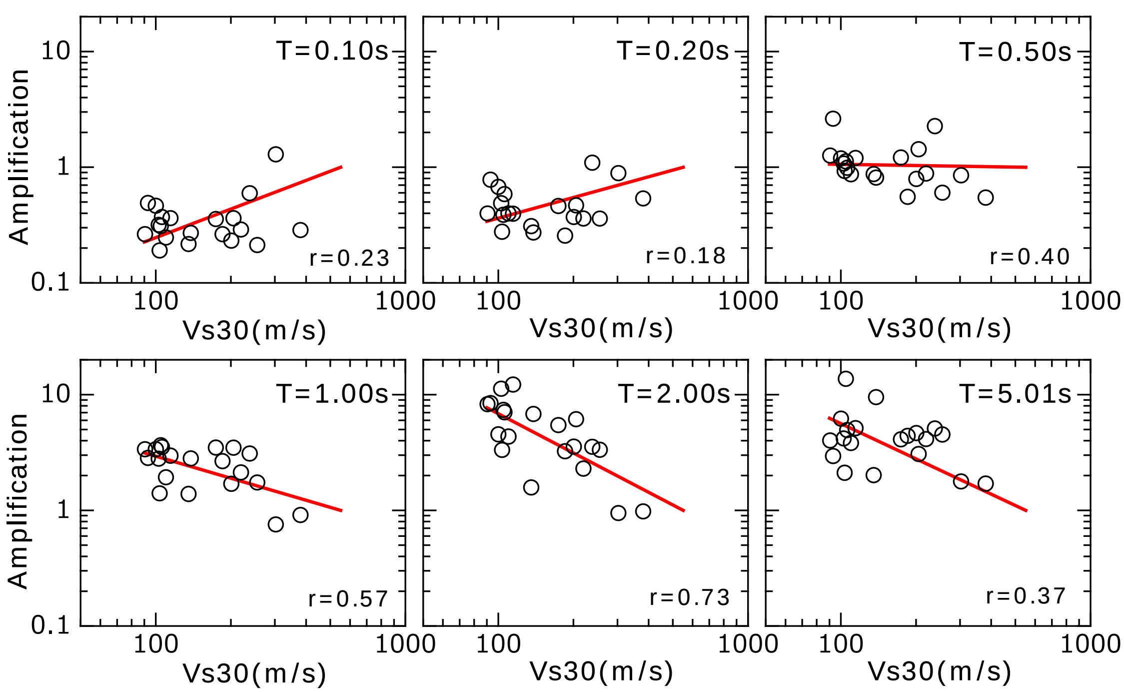

Fig. 5 Relationship between Vs30 and amplification of response spectra for typical periods

Table 3 Period-dependent regression coefficients for site amplification in Eq. (5)

Period(s) T	p	q	r	Period(s) T	p	q	r
0.10	0.822	-2.253	0.225	1.12	-0.727	1.992	0.547
0.11	0.815	-2.233	0.251	1.26	-0.778	2.132	0.630
0.13	0.808	-2.214	0.294	1.41	-0.827	2.266	0.740
0.14	0.771	-2.113	0.310	1.58	-0.939	2.573	0.821
0.16	0.730	-2.000	0.359	1.78	-1.038	2.844	0.774
0.18	0.655	-1.795	0.281	2.00	-1.128	3.091	0.732
0.20	0.595	-1.631	0.178	2.24	-1.269	3.478	0.803
0.22	0.566	-1.551	0.217	2.51	-1.261	3.456	0.830
0.25	0.465	-1.274	0.085	2.82	-1.131	3.099	0.814
0.28	0.436	-1.195	0.001	3.16	-1.114	3.053	0.698
0.32	0.325	-0.891	0.143	3.55	-1.090	2.987	0.547
0.35	0.279	-0.765	0.071	3.98	-1.033	2.831	0.431
0.40	0.186	-0.510	0.097	4.47	-1.051	2.880	0.393
0.45	0.070	-0.192	0.265	5.01	-1.013	2.776	0.367
0.50	-0.034	0.093	0.403	5.62	-0.927	2.540	0.303
0.56	-0.079	0.216	0.262	6.31	-0.805	2.206	0.179
0.63	-0.115	0.315	0.511	7.08	-0.690	1.891	0.162
0.71	-0.226	0.619	0.568	7.94	-0.576	1.578	0.206
0.79	-0.315	0.863	0.441	8.91	-0.468	1.282	0.240
0.89	-0.458	1.255	0.437	10.00	-0.355	0.973	0.278
1.00	-0.632	1.732	0.565				

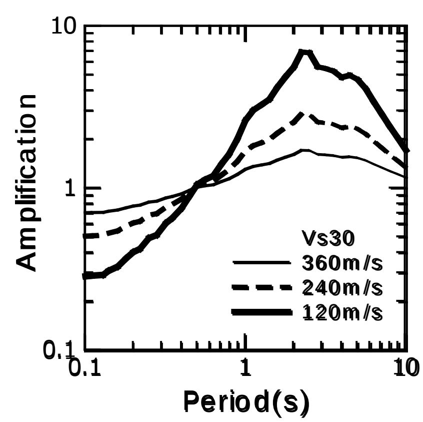

Fig. 6 Example of site amplification for each Vs30 value

period range (>0.5s), the coefficient *p(T)* indicating the slope of the line shows negative. On the contrary, in shorter period range (<0.5s), the coefficient *p(T)* turns positive. As described above, the trend was not observed in the previous studies. Figure 6 shows the examples of the site amplifications for the Vs30 of 360m/s, 240m/s and 120m/s. The amplification factor becomes remarkably larger in longer period and smaller in shorter period with the decreasing of Vs30. Solid black lines in Fig. 3 show the response spectra at surface computed from the attenuation relation and the proposed site amplification model. The results show that the site amplification model well reproduce the observed response spectra at the soil sites.

The proposed amplification model is validated by comparing with the response spectra observed at Bogota in the Quindio earthquake on Jan. 25, 1999 (Mw6.4, depth=10km). Red lines in Fig. 7 show the observed acceleration response spectra at CBOG2 and CBOG1 (see Fig. 1) whose shortest fault distances of the sites are approximately 180km. The assumed Vs30 of 550m/s for CBOG2 and the measured Vs30 of 116m/s for CBOG1 are used in applying the empirical model. Black lines in Fig. 7 show the response spectra computed by the empirical model proposed in this study. In order to show the applicability of the model, the existing GMPEs

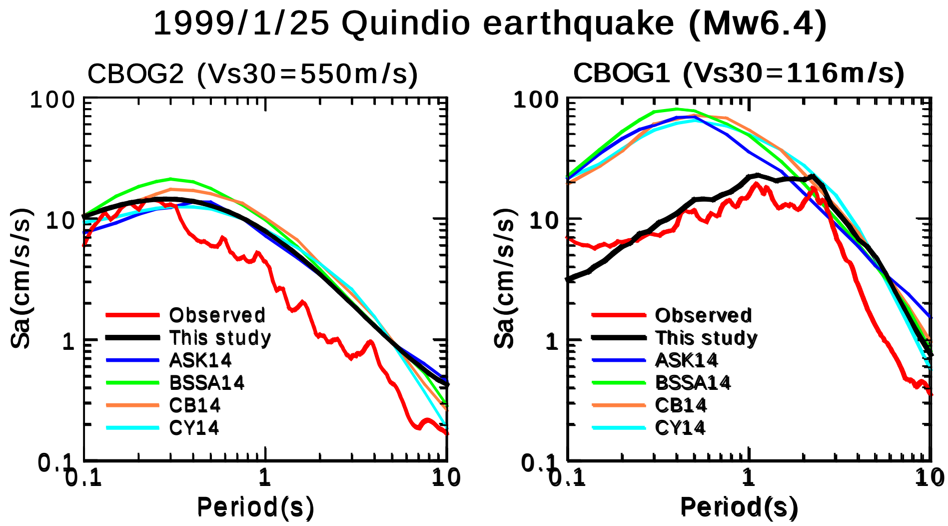

Fig. 7 Comparison of observed and computed response spectra at CBOG2 (rock site) and CBOG1 (soil site) in the 1999 Quindio earthquake

developed in the NGA-West2 [8-11] are also applied to compute the response spectra for the sites. Since the Vs30 range of the NGA-West2 models are more than 150m/s or 180m/s, the Vs30 of 116m/s at CBOG1 is out of the model range. The NGA-West2 models are applied to understand the difference of the amplification models. The blue, green orange and light blue lines in Fig. 7 show the response spectra computed by the NGA-West2 models [8-11]. The result at CBOG2 shows that all the empirical models produced similar response spectra. The computed response spectra almost agree with the observed one, indicating that all the models can be applicable for rock sites in Bogota. On the contrary, the computed response spectra at CBOG1 are completely different. The response spectra computed by the proposed model well reproduced the observed one. The NGA-West2 models, however, produced overestimated response spectra especially in shorter period range because the existing models expect stronger amplification in short period for smaller Vs30 sites. These results indicate that the proposing site amplification model would be more suitable for evaluating the ground motion at soil sites in Bogota.

4. Estimation of Vs30 Map and Scenario Ground Motion Map

In order to estimate the distribution of response spectra by the GMPEs, the reliable Vs30 map is needed. As shown in Fig. 1, the topographic Vs30 map by AW09 is available in Bogota. In order to discuss the relationship between the topographic Vs30 and the measured Vs30, downhole PS-logging data for 50 sites were collected in Bogota and the Vs30 at each site is calculated from the Vs profile. The relationship between the topographic Vs30 and the measured Vs30 is shown in Fig. 8. The dotted red line denotes the relation derived from the data in California by Yong [12] (Y16). The measured Vs30 values in Bogota are approximately half of the topographic Vs30, and are much smaller than in California. The solid red line and the equation in Fig. 8 indicate the regression line derived from the data in Bogota. Although the correlation coefficient is not high (r=0.42), the topographic Vs30 correlate with the measured Vs30. In this study, the regression equation is applied to modify the Vs30 from the topographic Vs30 map. When the modified Vs30 becomes smaller than 90m/s, the Vs30 are set to 90m/s. Figure 9 shows the modified Vs30 map with the downhole sites (solid circle). The result shows that the soft soil area with the Vs30 of 160m/s or smaller are widely distributed in Bogota.

A scenario earthquake with M_W=7.0 is considered in this study. The fault plane of the earthquake is illustrated in Fig. 9. The source area is determined at the same location of the 2008 Quetame earthquake. The strike angle (N230E deg.) is set to be parallel to the Andes mountain range and the dip angle (30deg. to horizontal) is determined from the geological cross-section of the region [13].

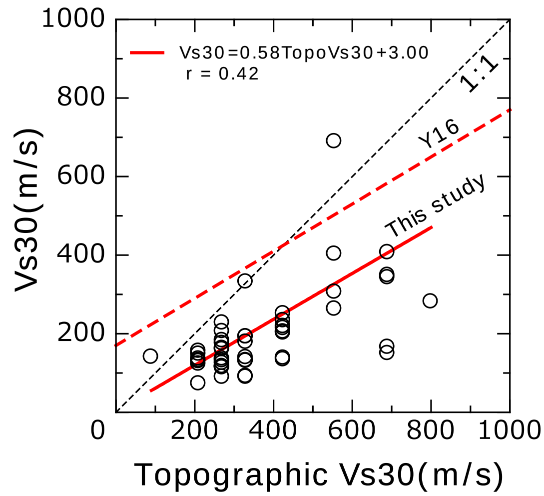

Fig. 8 Relationship between topographic Vs30 and measured Vs30

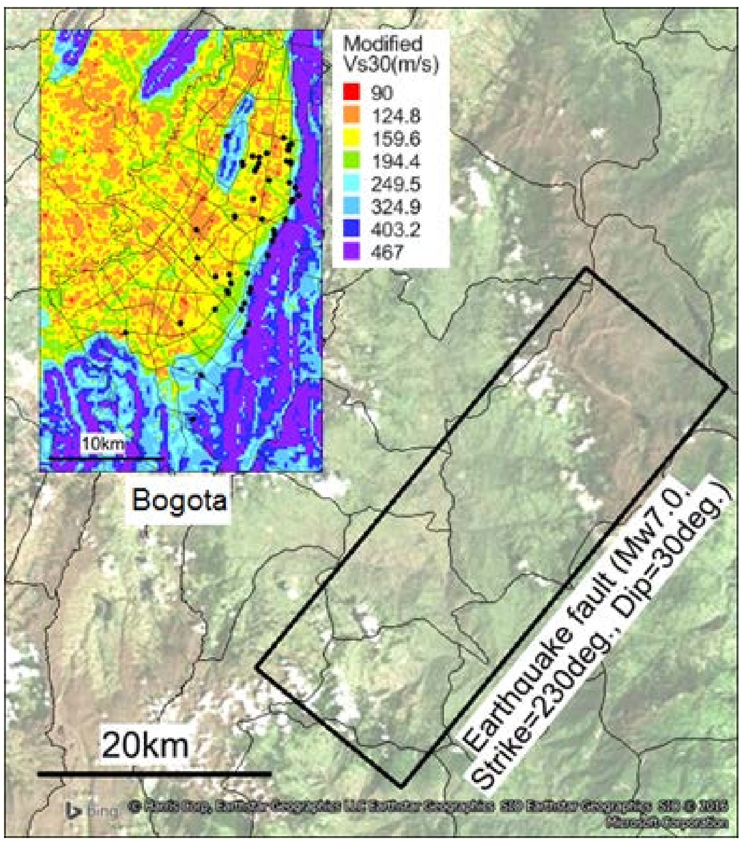

Fig. 9 Modified Vs30 map in Bogota and fault plane of scenario earthquake

In the simulation of strong ground shaking, nonlinear site amplification have to be considered. Since the nonlinear behavior of the soil in Bogota is still unknown, empirical vs30-based nonlinear site amplification model proposed by Yamaguchi and Midorikawa [14] (YM14) is applied in this study. In the YM14 model, the strain-dependent reduction factor *k* by Eq. (6) is multiplied to the site amplification to include the nonlinear effect by strong ground shaking.

$$\begin{cases} \log k(T,\gamma_{eff}) = 0 & (\gamma_{eff} < 3.0\times10^{-4}) \\ \log k(T,\gamma_{eff}) = \dfrac{1}{-6.2-11.7\log T-7.5(\log T)^2}\left\{\log(\gamma_{eff})-\log(3.0\times10^{-4})\right\} & (\gamma_{eff} \geq 3.0\times10^{-4}) \end{cases} \tag{6}$$

Here, γ_{eff} indicates effective strain during ground shaking. The equation means that the nonlinear site effect is excited if the effective strain exceeds $3.0\text{x}10^{-4}$. The effective strain is estimated from peak ground velocity (PGV) at surface and Vs30 as shown by Eq. (7).

$$\gamma_{eff} = \left\{\frac{0.4PGV}{Vs30}\left(\frac{1}{3.0\times10^{-4}}\right)^{-0.13}\right\}^{0.885} \tag{7}$$

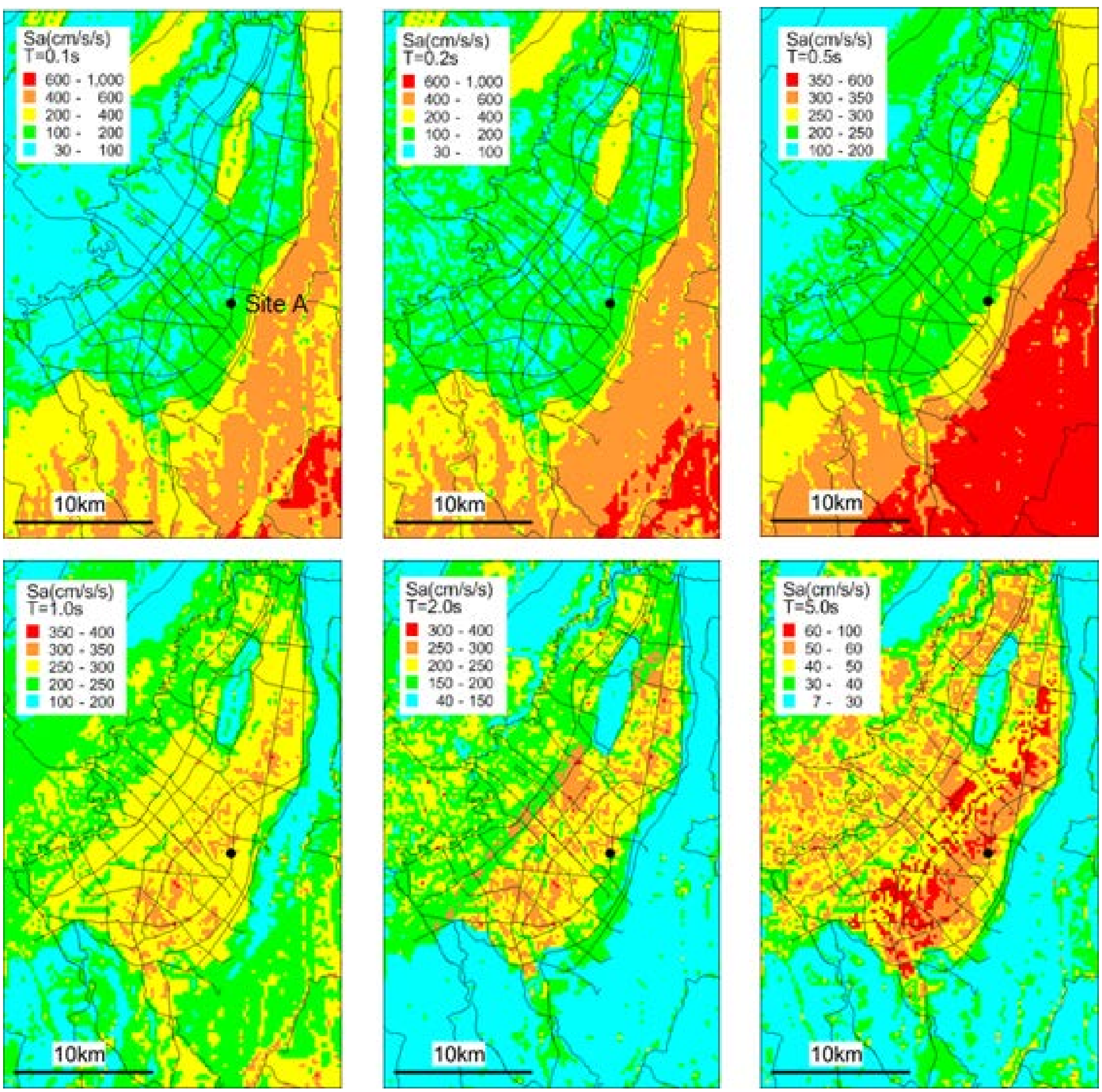

Fig. 10 Distribution of accelerartion response spectra for typical periods

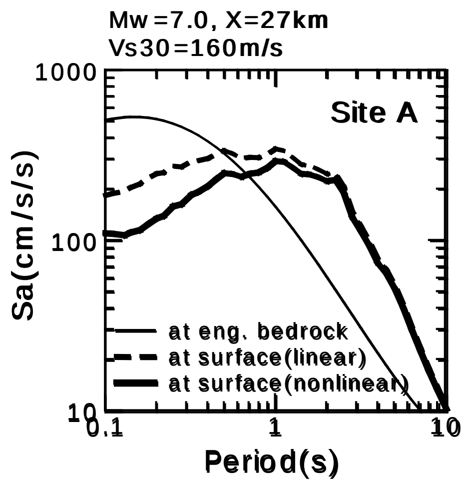

Fig. 11 Computed response spectra at Site A in Fig. 10

The PGV computed from the attenuation relation by Si and Midorikawa [15] is used. In the YM14 model, the response spectra is reduced especially in shorter period range if the estimated effective strain is larger than $3.0\text{x}10^{-4}$. The applicability of the model to Bogota would need to be discussed by applying nonlinear or equivalent linear response analysis of ground to the available soil profiles.

Figure 10 shows the distribution of the acceleration response at each period computed by the attenuation relation, the proposed site amplification model and the nonlinear site effect model. In the shorter period range, the responses in stiff soil sites such as the south-eastern area are larger than those in soft soil sites such as the central Bogota. On the other hand, in the longer period range, the responses in Bogota area become much larger than those in the stiff soil sites. The difference of the response mainly comes from the Vs30 values at the sites, meaning that the spectral characteristics are dramatically changed depending on the Vs30 values. These results suggest that the evaluation of the site condition is highly important for seismic hazard analysis in Bogota. Figure 11 shows an example of the computed acceleration response spectrum at Site A in Fig. 10. Compared to the spectrum on the engineering bedrock, the spectrum at surface is remarkably reduced in the shorter period especially under considering the nonlinear effect and the spectrum is strongly amplified in the longer period.

5. Concluding Remarks

In order to develop the GMPEs applicable to Bogota, Colombia, the existing attenuation relation developed in Japan is applied to evaluate the ground motion at rock sites observed in the 2008 Quetame earthquake. The Vs30-based site amplification model is developed from the spectral ratio of the observed response spectra at soil sites to the computed response spectra on the engineering bedrock. We confirmed that the spectral ratio almost represents the theoretical site amplification with respect to the engineering bedrock. The Vs30 map in Bogota is created based on the relationship between the topographic Vs30 and the measured Vs30. The scenario ground motion map in Bogota due to an M_W7.0 scenario earthquake is estimated by applying the attenuation relation, the site amplification model and the existing nonlinear soil effect model. The result shows that the spectral characteristics are dramatically changed depending on the Vs30 values at the sites.

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