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The new accelerograph network for Santa Fe De Bogota, Colombia and implications for microzonation

Anibal Ojeda[a,b,*], Samuel Martinez[b], Maria Bermudez[b], Kuvvet Atakan[a]

[a]*Institute of Solid Earth Physics, University of Bergen, Allégaten 41, N-5007 Bergen, Norway*

[b]*Instituto de Investigación e Información Geocientífica, Minero-Ambiental y Nuclear, INGEOMINAS, Diagonal 53 # 34-53 Santafé de Bogotá, Colombia*

Abstract

The new accelerographic network of Santa Fe de Bogotá is composed of 29 three-component stations with sensors at the surface and three additional six-component borehole stations with three sensors at the surface and three at depth (115, 126 and 184 m). In total, 32 stations have been operative in the metropolitan area of Bogotá since 1999. During this period of time, a significant number of weak motion are recorded and used for a preliminary analysis of local site effects. Using the SH-wave response spectra we verify the behavior of the different seismic zones proposed by the previous microzonation study of the city. A comparison between normalized SH-wave response spectra and the normalized design spectra for each zone clearly depicts that parts of the design spectra should be revised, as well as the boundaries between different zones may require some changes. The spectral amplification levels reach up to a factor of 5. The predominant periods obtained by the amplification spectra in different stations in the city, show variability from 0.3 to 3.0 s. A comparison is also made between the predominant periods obtained using *H*/*V* spectral ratios of microtremors and those using weak motion. In general, microtremors tend to predict slightly lower values of dominant periods than those calculated by the weak motion spectra. However, there is a general correlation between the two data sets. Using the data recorded by one of the borehole station, an equivalent linear seismic response analysis was conducted. The modeled and recorded response spectra show similarities in period peaks, however, the modeled soil amplification is underestimated for periods less than 0.8 s. Since the available record is weak motion which represents mostly the linear response of the soils, further analysis is required.

Keywords: Accelerographic Network; Borehole accelerometers; Soil response modeling; Microtremors; Bogotá; Colombia

1. Introduction

In general seismic risk analysis for Santa Fe de Bogotá city, capital of Colombia, with 7 million inhabitants is a very sensitive issue. Most of the industrial and governmental establishments are concentrated in Santa Fe de Bogotá, which increase the vulnerability of the city in an earthquake disaster. In the past, the city has been seriously affected during the last three centuries, where three earthquakes in 1785, 1827 and 1917 have produced strong damage [1]. Given these circumstances, la Unidad de Prevención y Atención de Emergencias de Santa Fe de Bogotá—UPES, la Dirección Nacional para la Prevención y Atención de Desastres—DNPAD and INGEOMINAS, from 1994 to 1997, developed a study of microzonation for the city [2]. The final results conclude a maximum horizontal acceleration of 0.20 g for a return period of 475 years for a rock site in the city. Another equally important result is the seismic zonation map, which divide the city in six zones with typical design spectra (Figs. 1 and 2), based on soil type and modeling of the seismic soil response with 1D and 2D models for different sites uniformly distributed in the area. Zone I corresponds to places where the soil condition are rock or stiff soil. Zone II are places which type soil is colluvium. Zones III and IV correspond to places with lacustrine sediments and Zones V and Va to terraces and alluvial aprons, where Zone Va are soils which are potentially liquefiable [2]. This zonation map and the results of the seismic hazard assessment provide the basis for the seismic building construction code and land development in the city. However, one of the most important weakness of this microzonation study is the lack of empirical earthquake data that can be used to calibrate the results previously obtained. Therefore the INGEOMINAS with the support of the UPES since 1997, started a project of establishing and maintaining a digital accelerographic network for the city. In this paper the new accelerograph network for Santa Fe de Bogotá is presented.

* Corresponding author. Address: Institute of Solid Earth Physics, University of Bergen, Allégaten 41, N-5007 Bergen, Norway.

E-mail address: anibal@ifjf.uib.no (A. Ojeda).

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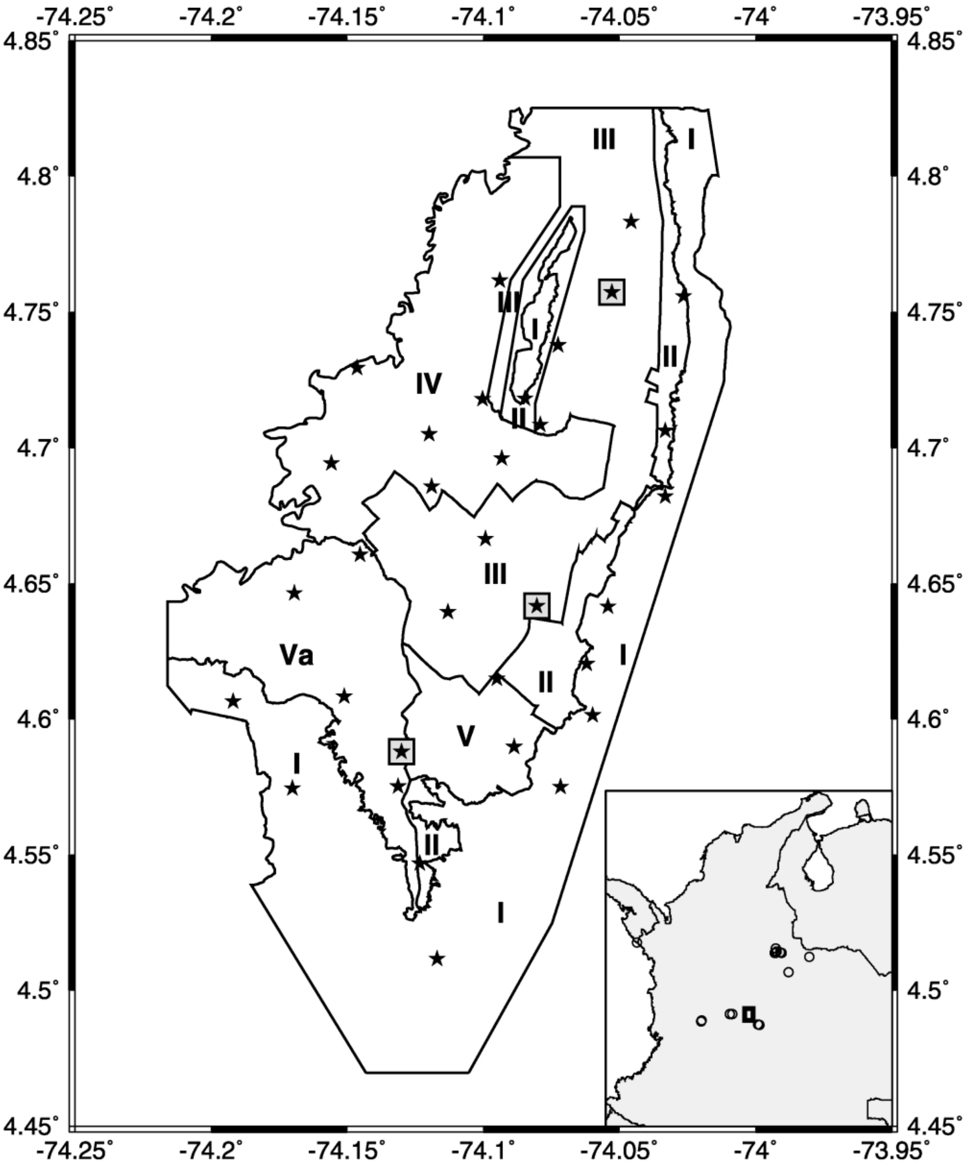

Fig. 1. Location of the accelerograph network in Santa Fe de Bogotá, stars represent station at the surface, square represent borehole stations. The seismic zones resulting from the microzonation project of Santa Fe de Bogotá are indicated by I, II, III, IV, V and Va [2]. Note the uniform distribution of stations in the city. Figure inset is the location map of Santa Fe de Bogotá, circles represent the earthquakes recorded at the accelerographic network.

Furthermore, a preliminary analysis of the earthquake data recorded is included. That is complemented with a microtremor analysis and a 1D linear seismic soil response modeling.

2. Accelerographic network and earthquake data

The new accelerograph network has been operating since January 1999 and is composed of 32 stations (Fig. 1, Table 1). There are basically two types of equipments, where 29 stations have ETNA accelerographs by KINEMETRICS and the remaining three stations have K2 accelerograph by KINEMETRICS with accelerometers at the surface and borehole accelerometers. The stations CGRAL, CUAGR and CBOG1 have boreholes at 115, 126 and 184 m depths, respectively. The location of stations within the city were chosen following the zonation map, which resulted from the microzonation project of Santa Fe de Bogotá [2]. Since January 1999, the network has recorded 15 seismic events with ML magnitudes between 4.4 and 6.5 and epicentral distances ranging from 55 to 510 km (Table 2). All this data corresponds to weak motion with accelerations less than 10 cm/s^2. Using the recorded earthquake data we performed spectral analysis. For each record the linear response spectra with 5% damping were computed for the SH waves. The SH waves were taken from the group velocity windows between 4.3 and 3.5 km/s in the transverse component. Then the response spectra were

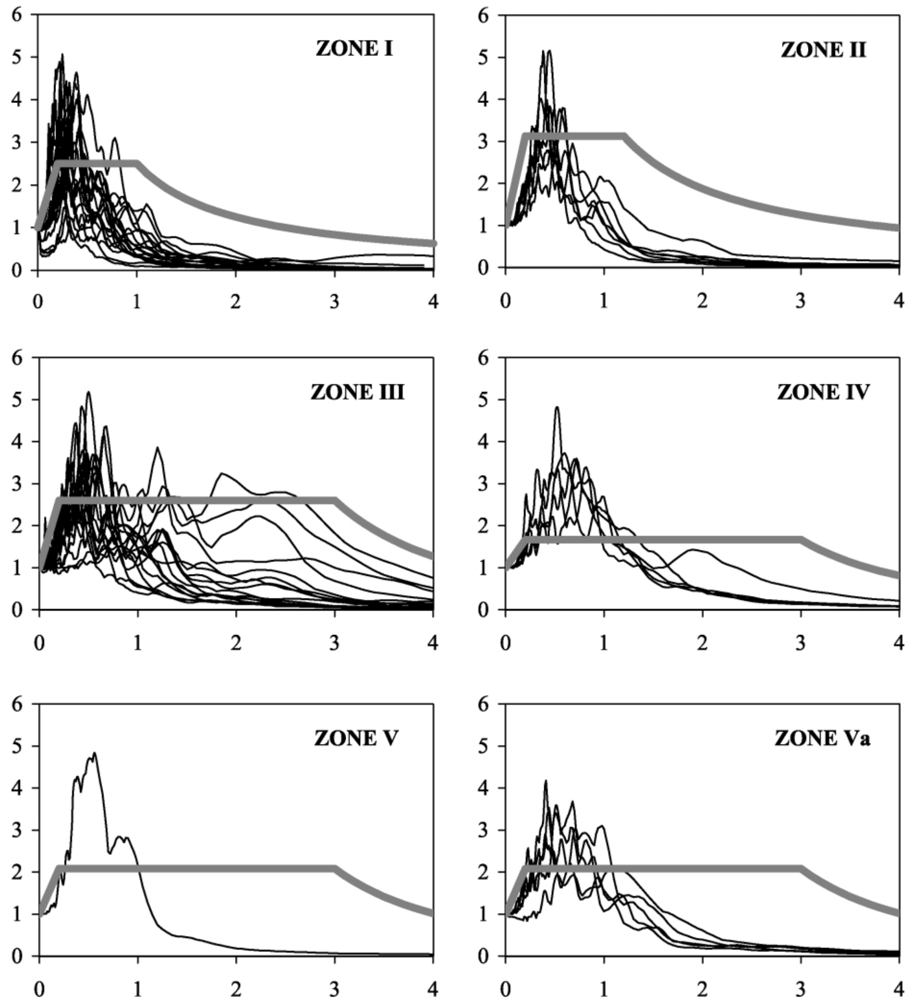

Fig. 2. Earthquakes elastic response spectra for 5% damping. Each response spectrum is normalized to the peak ground acceleration. *X*-axis is period in seconds. The thick gray curves represent the design spectra for each zone in the city, as was previously defined by the microzonation project of the city.

normalized to the peak ground acceleration. Fig. 2 shows a summary of the normalized spectra grouped with respect to the seismic zones, as well as a comparison with the recommended design spectra. The relative spectral amplifications of the peak ground acceleration reach values of up to a factor of 5. The design spectra for seismic zones I, II, III and IV seem to correlate well with the computed spectra. However, the amplification factor for zone IV appears to be low. For zones V and Va the design spectra cover long periods (>2 s), which are not present in the recorded earthquakes. However, the amplification factors appear to be reasonable. Zones I and III present high variability between dominant periods, that may indicate that those zones are associated with sites which have different dynamic behavior and could belong to a different seismic zone. Fig. 3 shows a contour map of dominant period obtained for the computed response spectra at each station. The eastern, southern and central-northern part of the map show a general tendency of low periods (<0.6 s), which correspond to the seismic zones I and II, where the local conditions are dominated by the presence of rocks (zone I) and colluvium (zone II). On the other hand, the central and western part present relatively longer periods (>0.8 s), which correspond to seismic zones III and IV, where the soil is mainly composed of soft lacustrine sediments.

3. Microtremors

In order to evaluate the potential use of microtremors in future investigations and as well as a tool for estimation of soil dynamic behavior, measurements and analysis of microtremors in each station of the accelerograph network was performed. Microtremors were recorded in time windows of 60 s at different times of the day. For each station a minimum of four records were taken. Then each record was processed using Nakamura technique [3]. Nakumura technique proposes that the soil transfer function (the response of the soil) could be estimated by the spectral

Table 1
Accelerograph network of Santa Fe de Bogotá

Station code	Seismic zone	Latitude (°)	Longitude (°)	Instrument type	*T* (s) from earthquakes	*T* (s) from microtremors
CBOSA	1	4.6066	−74.1920	ETNA		0.80
CESCA	1	4.6822	−74.0332	ETNA		0.32
CTVCA	1	4.7181	−74.0848	ETNA	0.32	0.29
CBART	1	4.6205	−74.0620	ETNA	0.23	0.30
CUNMA	1	4.6415	−74.0543	ETNA		0.22
CMARI	1	4.5117	−74.1171	ETNA		0.29
CSMOR	1	4.5746	−74.1701	ETNA		0.27
CVITE	1	4.5750	−74.0716	ETNA	0.31	0.43
CBOG2	1	4.6014	−74.0599	ETNA	0.24	0.28
CUSAL	2	4.7559	−74.0264	ETNA	0.46	0.40
CPSUB	2	4.7379	−74.0726	ETNA	0.43	0.33
CUSAQ	2	4.7064	−74.0332	ETNA	0.43	0.35
CARTI	2	4.5468	−74.1234	ETNA	0.44	0.38
CEING	3	4.7833	−74.0458	ETNA	0.64	1.18
CUAGR	3	4.7573	−74.0527	K2	0.52	0.47
CBANC	3	4.7085	−74.0791	ETNA		0.42
CJABO	3	4.6665	−74.0993	ETNA		0.93
CCITE	3	4.6395	−74.1131	ETNA		0.86
CBOG1	3	4.6418	−74.0803	K2	1.25	1.22
CCORP	4	4.7617	−74.0940	ETNA	0.79	0.80
CFLOD	4	4.7295	−74.1464	ETNA	1.04	1.05
CAVIA	4	4.6858	−74.1190	ETNA	0.91	0.82
CNIÑO	4	4.6962	−74.0932	ETNA		0.90
CTIEM	4	4.6943	−74.1558	ETNA		1.11
CLAGO	4	4.7180	−74.1003	ETNA		1.07
CDIOS	5	4.5899	−74.0888	ETNA	0.52	0.64
CTEJE	5	4.6149	−74.0951	ETNA		0.68
CFONT	5a	4.6607	−74.1454	ETNA	0.83	0.82
CTIMI	5a	4.6084	−74.1511	ETNA		0.83
CTUNA	5a	4.5753	−74.1313	ETNA	0.55	0.69
CGRAL	5a	4.5881	−74.1301	K2	0.54	0.81
CRADI	5a	4.6465	−74.1694	ETNA	1.18	1.05

Table 2
Recorded earthquakes for the accelerograph network

Date	Description	ML	Depth (km)	Latitude (°)	Longitude (°)	Station recorded
25/01/99a	Córdoba	6.2	0	4.44	−75.71	CBART, CBOG1, CBOG2
25/01/99b	Córdoba	5.4	0	4.41	−75.73	CBART
14/04/99	Nido de Buc.	6.1	170	6.82	−73.14	CBART, CBOG1
15/05/99	Pulí	4.8	19	4.67	−74.75	CBOG1
01/06/99	Guayabetal	5.2	0	4.29	−73.73	CEING, CBART, CBOG1, CBOG2
10/06/99	Quetame	4.6	0	4.31	−73.79	CBART
17/07/99	Sativasur	5.6	0	6.10	−72.74	CEING, CUSAL, CCORP, CPSUB, CAVIA, CBART, CBOG1
08/11/99	Betulia	6.5	160	6.92	−73.18	CEING, CUSAL, CCORP, CPSUB, CAVIA, CBART, CBOG1, CUAGR, CTVCA, CFLOD, CFONT, CDIOS, CTUNA, CARTI, CVITE, CGRAL, CRADI, CBOG2
17/01/00	Fortul	5.9	0	6.64	−72.02	CBOG1
05/02/00	Nido de Buc.	6.0	160	6.77	−73.21	CUAGR, CTVCA, CBOG1
24/05/00	Pulí	4.4	0	4.76	−74.67	CBOG1
12/09/00	Nido de Buc.	5.9	160	6.76	−73.18	CUAGR, CBART, CBOG1
08/11/00	Juradó	6.3	0	7.13	−77.94	CUAGR, CFLOD, CBOG1
24/11/00	Nido de Buc.	5.7	160	6.79	−73.02	CUAGR, CTVCA
17/12/00	Nido de Buc.	5.8	155	6.77	−72.97	CEING, CUAGR, CPSUB, CUSAQ, CTVCA, CBOG1

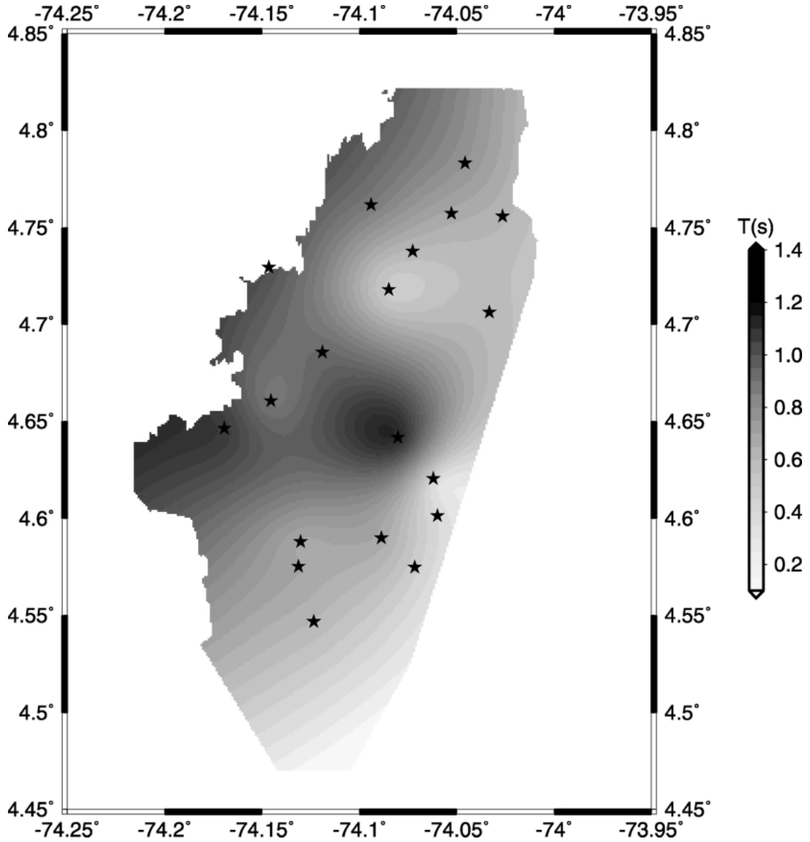

Fig. 3. Contour map of predominant periods evaluated from the response spectrum for earthquakes. Stars represent the locations of the stations used.

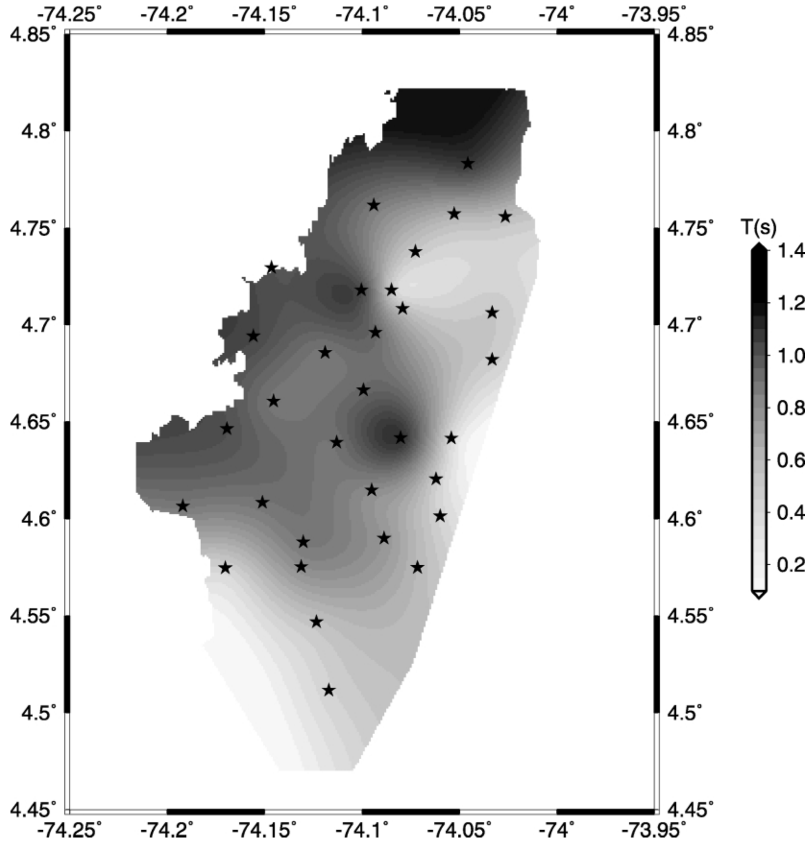

Fig. 4. Contour map of predominant periods evaluated from the microtremors. Stars represent the locations of the stations used.

Table 3
Soil profile at CBOG1 station used for the equivalent linear seismic response analysis

Layer	Soil type	Thickness (m)	Maximum shear modulus G_{max} (ksf)	Density (ksf)
1	3	5.0	750	0.109
2	5	2.0	152	0.093
3	7	3.0	367	0.087
4	6	2.0	220	0.087
5	8	1.8	760	0.075
6	4	1.4	719	0.087
7	7	1.8	490	0.081
8	4	2.0	604	0.093
9	7	4.0	370	0.087
10	9	8.0	1021	0.106
11	2	14.0	822	0.100
12	5	14.0	429	0.087
13	9	10.0	850	0.100
14	1	84.0	1414	0.112
15	4	7.0	1520	0.087
16	1	17.0	2009	0.112
17	Rock			

ratio between the horizontal to that of the vertical component of microtremors recorded at the surface. Table 1 shows the resulting predominant periods in each station. In general dominant periods determined using microtremors and weak motion data are comparable. Fig. 4 shows a contour map of the predominant periods, which shows a good correlation between the predominant periods and the soil types. Stiff soils composed of rocks and colluvium (seismic zones I and II) present low periods (<0.6 s). On the other hand, soft lacustrine sediments have long periods (>0.8 s). Terraces and alluvial aprons (zones V and Va) have intermediate periods from 0.6 to 0.8 s.

4. 1D soil response

The new accelerograph network has three stations with borehole and surface accelerometers. The boreholes are at 115, 126 and 184 m depths in CGRAL, CUAGR and CBOG1 stations, respectively, (Table 1, Fig. 1). Those stations were installed in order to have records of the same earthquake in both the bed rock layer and at the surface, which will then allow the soil dynamic behavior to be measured directly.

Using the recorded earthquake of June 1, 1999 at CBOG1 station, an equivalent 1D linear seismic response analysis was conducted. The analysis was preformed using the computer program SHAKE91 [4]. The input in the modeling are the recorded accelerogram at the bed rock layer (recorded signal in the borehole) and the dynamic soil properties which include soil type, thickness, maximum shear modulus, density, modulus reduction curve and damping curve for each layer of soil ([5]: Table 3 and Fig. 5). The results of the modeling are shown in Fig. 6 as linear response spectra

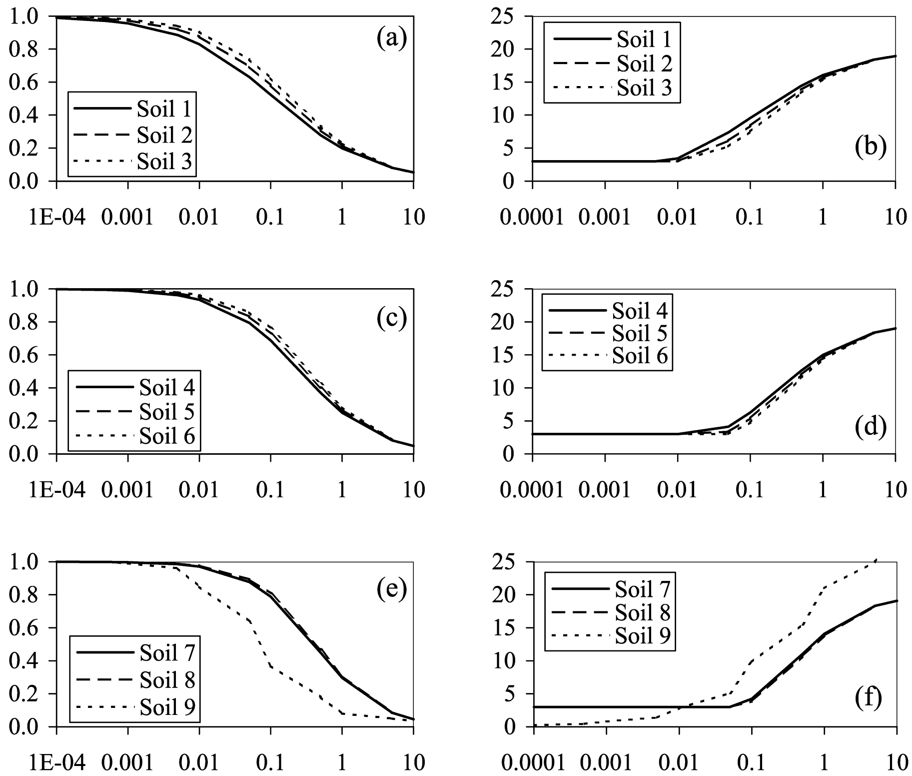

Fig. 5. Shear strain reduction curves for different soil types, (a), (c) and (e) *X*-axis represents strain values in percent. *Y*-axis represents the modulus reduction G/G_{max}. (b), (d) and (f) are the damping curves for different soil types. *X*-axis represents strain values in percent. *Y*-axis represents damping in percent.

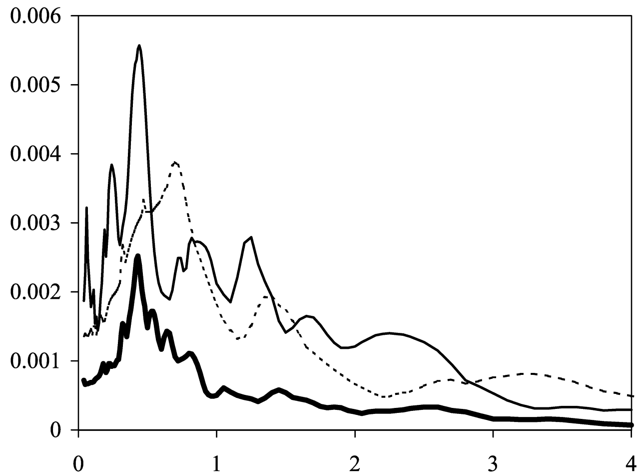

Fig. 6. Elastic response spectra with 5% damping. *X*-axis is the period in second. *Y*-axis is the spectral acceleration in *g*. The continuous thick line represents the response spectrum for the record at the borehole at 184 m depth. The continuous thin line represents the response spectrum for the record at the surface. The dotted line represents the modeled response spectrum at the surface resulting from the equivalent linear seismic response analysis.

for a damping of 5%. In general it is seen that for periods longer than 0.8 s the modeled and the recorded response spectra show moderate agreement in amplitude. For short periods (<0.8 s) there is not a clear correlation between the modeled and recorded amplitudes in the response spectra. However, there is a reasonable correlation of the predominant periods in the response spectra for the modeled and the recorded.

5. Conclusions

This paper highlights the new accelerograph network for Santa Fe de Bogotá and show that new data of a desirable quality are now available for detailed research into soil dynamics and earthquake engineering. The results of the preliminary analysis of the data recorded during the first 2 years of operation on the network are the following:

- Santa Fe de Bogotá has now a fully operational and well-calibrated accelerograph network that can provide good data for assessing a realistic seismic risk. The effectiveness in dealing with the correct estimates of seismic hazard and vulnerability and the implementation of the results will be the future challenges in the fight against earthquake disaster in Santa Fe de Bogotá.
- The analysis of the recorded earthquake data indicates that the proposed design spectra in the microzonation project need to revise. Significant differences in amplitudes and spectral shapes have been found in some zones for the city.
- The good correlation between soil types, weak motion periods, and microtremors indicates that microtremors could be a useful tool for refining a future map of isoperiods in the city.

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