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COMPREHENSIVE SITE EFFECTS EVALUATION APPROACH FOR CITIES AND ITS APPLICATION IN BOGOTÁ

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ABSTRACT

We present a methodology for assessing site effects for microzonation purposes, which is based on the geometry of the geological formations that give origin to the soft soil deposits of the city under analysis. This methodology allows calculating the dynamic response at any point within the city, and consequently it allows to calculate seismic hazard at surface level and to harmonize hazard with the national construction regulations. The methodology is applied to the city of Bogotá, capital of Colombia, and the results are discussed in comparison to the current building construction requirements in the city.

INTRODUCTION

For more than a decade, the city of Bogota has developed studies related to the understanding of the conditions of seismic response of soils. In this regard, it led, together with other cities of Colombia, the development of methodologies for the assessment of seismic hazard, dynamic response of soft soils, topographic effects, structural vulnerability, disaster risk and risk management at national level. In 1997, the Universidad de los Andes, the National Geological Survey of Colombia and the Colombian Association for Earthquake Engineering, published the final report of the seismic microzonation study of the city, which marked the beginning of a series of activities related to direct applications of seismic risk management in Bogotá.

From the results of the seismic microzonation study, local construction regulations were issued by the mayoralty of the city, particularly decrees 074 of 2001 and 193 of 2006, by which the city adopted as regulatory design spectra resulting from the study. After several years of implementation of these decrees, and given the existence of more and better information for the characterization of the dynamic response of the soil deposits within the city, the DPAE financed a new seismic microzonation study, which was executed by the Universidad de los Andes, Colombian Geotechnical Society and the Colombian Association for Earthquake Engineering. The results were harmonized with the national construction regulation (NSR10). In December 2010, was signed in Bogota the decree 523 by which the city administration adopts the results of this new study.

In the present study, we developed a methodology for assessing site effects in Bogota, which is based on the geometry of geological formations that gave origin to the soft soil deposits of the city. This methodology allows calculating the dynamic response at any point within the city, and

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consequently it allows to calculate seismic hazard at surface level and to harmonize hazard with the national construction regulation.

METHODOLOGY FOR ASSESSING SITE EFFECTS

The steps for the correct application of the proposed methodology are:

1. Seismic hazard assessment at bedrock level: The seismic hazard is calculated in terms of spectral acceleration. In the evaluation of the hazard, it is desirable to use calibrated attenuation functions for the specific tectonic environment and with formulations that are based on the radiated Fourier amplitude spectrum, so as to allow the direct incorporation of site effects into strong motion attenuation.
2. Definition of geometry of geological contacts: Based on the available geological and geophysical information, the topography of the geological contacts is defined. It is possible then to construct a three-dimensional geometric model to set the total depth of the deposits in each point within the city, as well as the depth of the geological contacts, which mark variations of soil materials.
3. Definition of geometry of the boundary conditions: As boundary conditions are understood topography and water table depth. Topography marks the upper limit of the geometric model. The water table is necessary to establish at each location saturation conditions and soil confinement.
4. Geotechnical information: It is important to collect geotechnical data through a campaign of field studies, including a series of perforations in different locations of the territory under analysis. Geotechnical studies should be detailed enough so that they provide sufficient information to characterize the index (i.e. Atterberg limits), static and dynamic soil properties.
5. Defining soil types of analysis: From the geotechnical information, soil types are defined for each geological formation, so that this soil type is the typical material associated with it. These soil type profiles establish the change on geotechnical properties depending on the depth.
6. Selecting seismic signals: In order to establish the behavior of soils within the nonlinear range, seismic signals are selected for different levels of PGA.
7. Calculation grid: the grid must be contained by the extent of geologic information layers. In each node of the grid a synthetic stratigraphy is constructed based on the geometry of the geological and geotechnical information of the entire city.
8. Dynamic response: For each synthetic stratigraphy at each node of the grid, nonlinear one-dimensional response is calculated for each of the selected signals. Transfer functions of the Fourier spectrum a are then obtained at each grid node, along with time histories at surface level and the associated response spectra.
9. Transfer functions averaging: For each grid node, Fourier spectrum transfer functions are averaged for different levels of PGA at bedrock.
10. Attenuation functions: For each grid node, an attenuation function that incorporates site effects is calculated using a methodology based on the theoretical formulation of the Fourier amplitude spectrum radiated by a seismic source. The Fourier spectrum is altered by the transfer functions. The latter spectrum is modified by the transfer functions of oscillators of one degree of freedom, so that, using random vibration theory, it is possible to obtain the moments of probability of strong motion at surface level for several structural vibration periods.
11. Calculation of seismic hazard at each site: Uniform hazard spectrum at each grid node is calculated, using the site-specific attenuation functions, for 475 years return period.
12. Harmonized spectra: From uniform hazard spectra, design spectra consistent with the national construction regulations (NSR-10) are defined. These design spectra are given in terms of the parameters associated soil parameters, Fa and Fv, for each grid node. This results in a spatial representation of the parameters that control the final shape of the design spectra for new structures.

The following sections detail the information, procedures and assumptions taken into account in each of the steps outlined above.

SEISMIC HAZARD ASSESSMENT AT BEDROCK

We evaluated the seismic hazard at bedrock level for the city of Bogotá, using the seismic source model from the General Seismic Hazards Study of Colombia (AIS 2009) and the attenuation model developed by Bernal et. al (2012). This attenuation model is based on theoretical formulations of the Fourier amplitude spectrum of strong motion radiated from a seismic source, and therefore allows the incorporation of non-linear soil transfer functions. Figure 1 presents a map of the geographic distribution PGA at bedrock level for 475 years return period. Hazard calculations were done using the software CRISIS2007 V7.6.

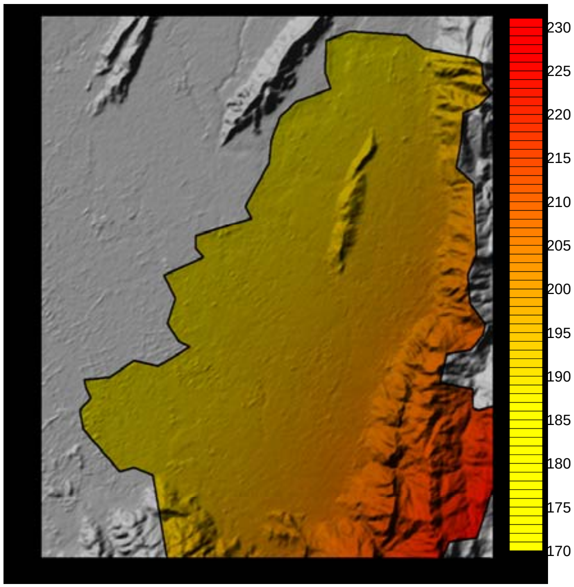


Figure 1. Map of uniform seismic hazard in terms of PGA (cm/s^2). 475 years return period.

DEFINITION OF THE GEOMETRY OF GEOLOGICAL CONTACTS

Bogotá soft soils come from alluvial and lagoon deposits. The main geological formations are the Subachoque formation, and Sabana formation. According to Helmens and Van der Hammen (1995), the Subachoque formation consists mainly of this fine material alternating with clayey sands and gravels. The Sabana formation, which is lacustrine deposits that outcrop throughout the entire savannah of Bogotá.is mainly composed of clays.

The geometry of the contacts of formations Subachoque and Sabana are defined in the Geotechnical Model of Bogotá, developed by the Colombian Geotechnical Society (SCG, 2006). Figure 2 shows the geometry of the total thickness of the soft deposit and the geometry of geological contact Subachoque-Sabana.

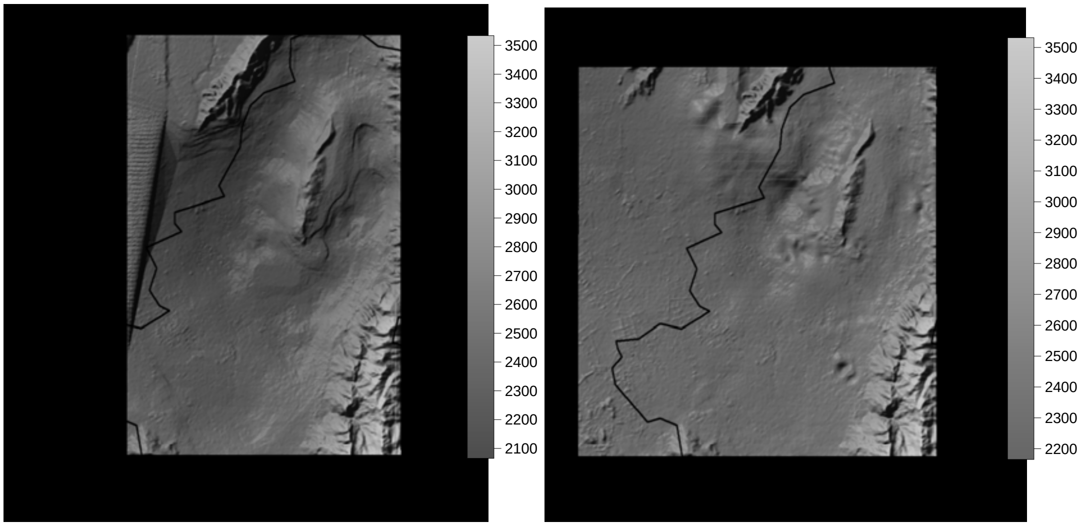


Figure 2. Geometry of the bedrock (left) and of the of the Subachoque-Sabana contact (right). Scale is given in meters above the sea level.

BOUNDARY CONDITIONS

The boundary conditions, as understood in this method correspond to the surface of the soil deposit (i.e. topography), and water table. The topography employed in this study has a spatial resolution of 90 m. For the case of the geometry of the water table, an average value of 3 meters was set citywide. This assumption is adopted for simplicity because of the difficulty in defining the spatial variation of this parameter. However, further efforts are intended to improve the definition of this layer.

GEOTECHNICAL INFORMATION

There are detailed geotechnical studies for several locations within the city, resulting from information gathering campaigns associated with seismic microzonation studies, metro and local response studies. This information is centralized by the DPAE in what is known as the Geotechnical Database of Bogotá. Of the 200 surveys existing in the city, 84 were selected because of the quality of the information. For these 84 surveys, it was possible to establish a depth profile of index properties, Atterberg limits, specific weight and shear wave speed.

SOIL TYPES DEFINITION

From the geotechnical information available, we performed a statistical analysis on the data associated with each geological formation, to obtain profiles of the variation in depth of the main geotechnical properties. These properties are defined by an expected value, variance, and minimum and maximum limits for each depth.

We defined two soil types, characteristic of Subachoque and Sabana formations respectively. These soil types constitute the set of geotechnical properties that define the characteristics of the materials. The soil type 1 is a clayey soil, associated with the Sabana formation. Figure 3 shows the variation in depth of the main geotechnical properties (expected value plus and minus one standard deviation).

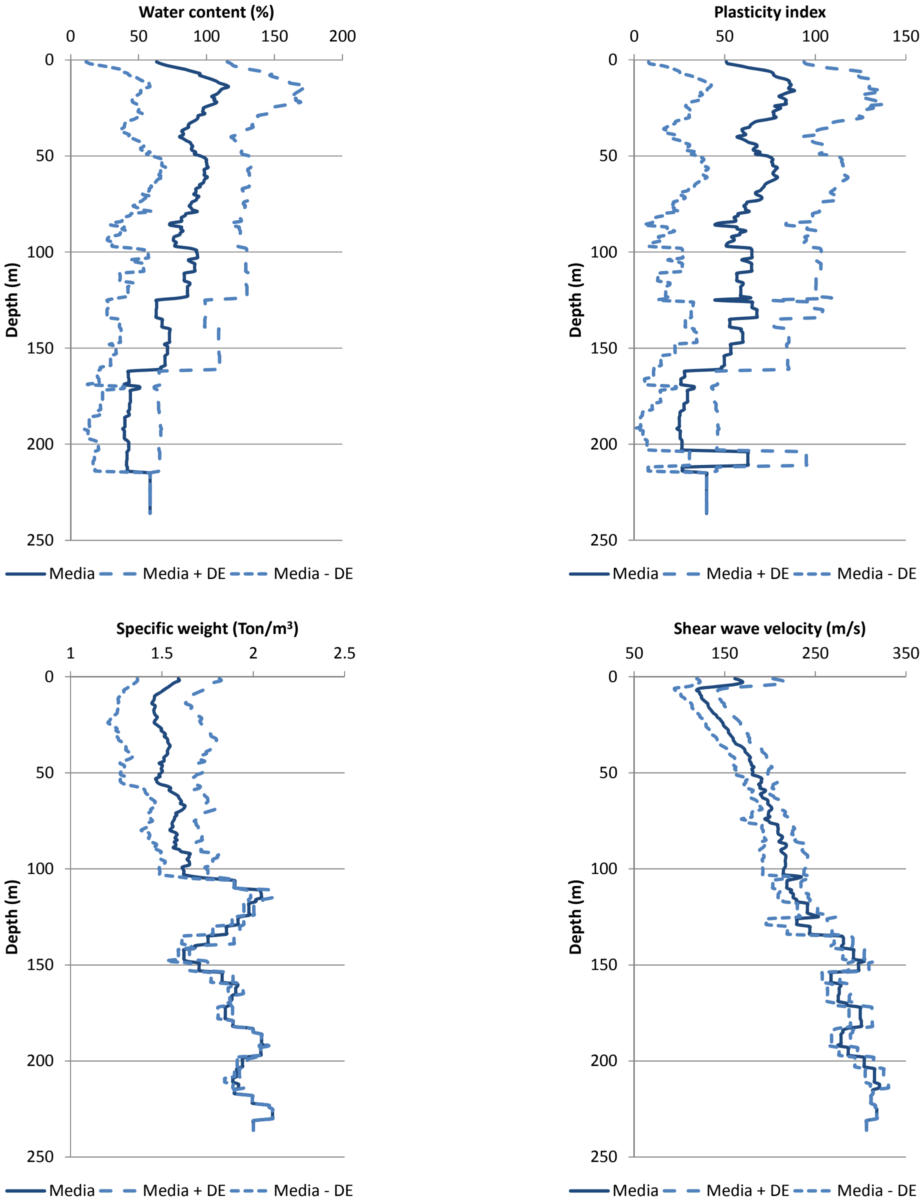


Figure 3. Depth profiles of selected geotechnical properties of soil 1.

Soil type 2 is soil with high contents of coarse material, sand mainly, associated with the Subachoque formation. Figure 4 shows the depth profile of variation of the main geotechnical properties.

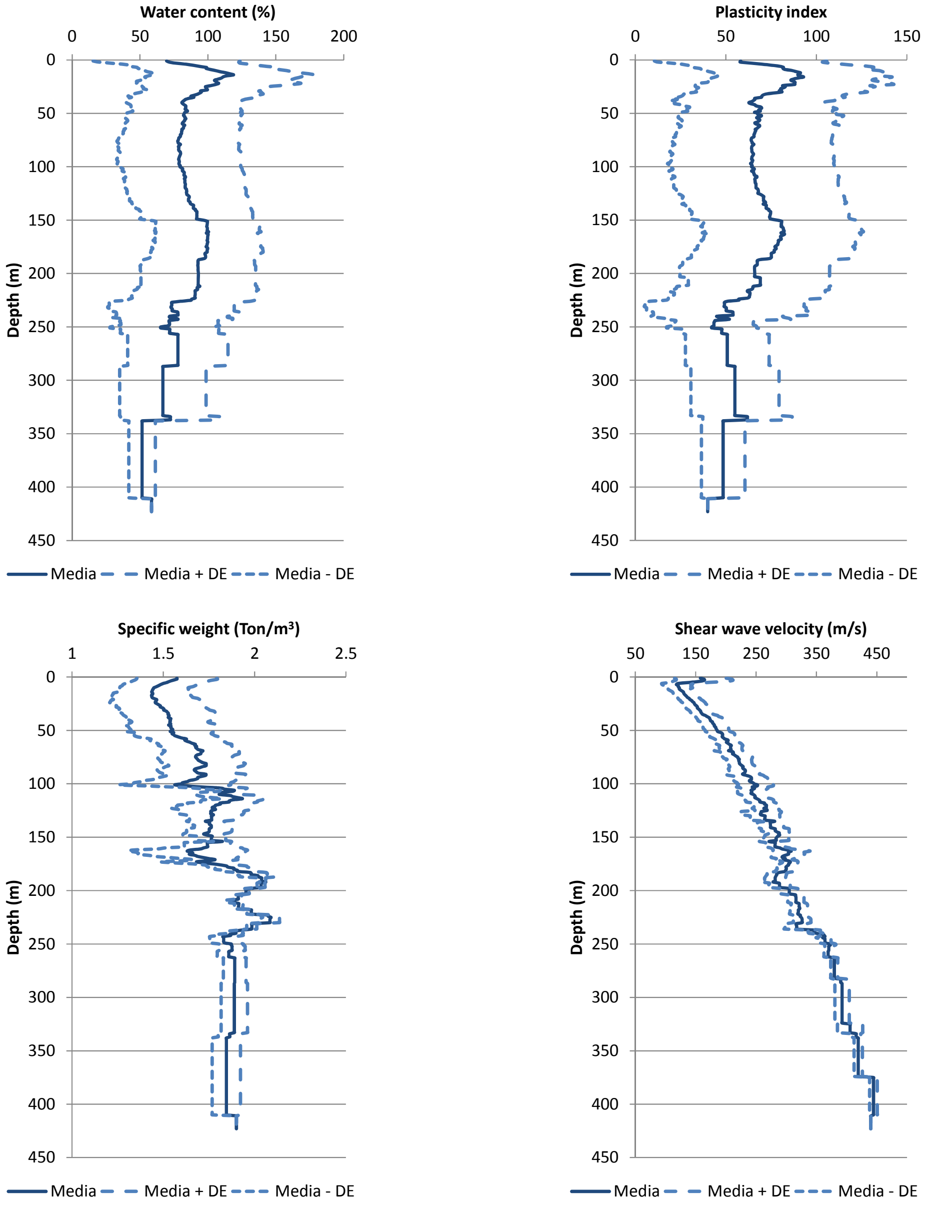


Figure 4. Depth profiles of selected geotechnical properties of soil 2.

SEISMIC SIGNALS FOR THE CALCULATION OF TRANSFER FUNCTIONS

The transfer functions are calculated for different intensity levels (i.e. PGA) of strong motion at the base of the soil deposit. In this research, we selected the following levels PGA: 0.05 g, 0.10 g, 0.20 g, 0.40 g. Tables 1 and 2 present the main characteristics of the seismic signals used, such as identification, date of event, magnitude, epicentral distance, duration and maximum acceleration. Signals were selected depending of the tectonic setting: 12 for intraplate earthquakes (active source), and 10 for subduction earthquakes (subduction source).

Table 1. Intraplate earthquake signals

ID	Name	Country	Date	Magnitude	Distance (km)	Duration (seg)	PGA (g)	PGA used (g)
A01	Chalfant Valley	U.S.A	21/07/1986	6.2	50	39.81	0.051	0.05
A02	Georgia		15/06/1991	6.2	52	38.17	0.046	0.05
A03	Palm Springs	U.S.A	08/07/1986	6	63	24	0.053	0.05
A04	Anza	U.S.A	08/07/1986	6	26	24	0.113	0.1
A05	Armenia - Bocatoma	Colombia	19/01/1999	6.2	42	31.92	0.084	0.1
A06	Imperial Valley	U.S.A.	15/10/1979	6.5	36	28.28	0.109	0.1
A07	Irpinia	Italy	23/11/1980	6.5	33	36.34	0.199	0.2
A08	WhittierNarrows	U.S.A	10/01/1987	6	10	29.96	0.199	0.2
A09	San Fernando	U.S.A	09/02/1971	6.6	27	29.66	0.212	0.2
A10	Coalinga	U.S.A.	22/07/1983	5.7	12	21.3	0.375	0.4
A11	Northridge	U.S.A.	17/01/1994	6.7	35	30.33	0.493	0.4
A12	Park Field	U.S.A.	28/06/1966	6.1	10	30.33	0.356	0.4

Table 2. Subduction earthquake signals

ID	Name	Country	Date	Magnitude	Distance	Duration	PGA	PGA used
S01	Nuxco	Mexico	15/07/1996	6.5	45	83	0.049	0.05
S02	Ocotito	Mexico	14/09/1995	7.2		61	0.059	0.05
S03	Zihuantejo	Mexico	10/12/1994	6.6		34.05	0.053	0.05
S04	Paraíso	Mexico	25/09/1984	6.5		36.67	0.102	0.1
S05	Red Smart	Taiwan	12/06/1985	6.5		27.15	0.142	0.1
S06	La Unión	Mexico	10/12/1994	6.6		54.98	0.092	0.1
S07	Caleta	Mexico	09/08/2000	6.7		42.21	0.194	0.2
S08	Ocotito	Mexico	25/04/1989	6.5		53.16	0.195	0.2
S09	Copala	Mexico	24/10/1993	6.2		58.94	0.292	0.4
S10	Las Vigas	Mexico	25/04/1989	6.5		34.43	0.345	0.4

CALCULATION GRID

The calculation grid is presented in Figure 5. It was defined by 25x25 nodes in each direction, for a total of 625 calculation sites. The red box indicates the extent of the analysis.

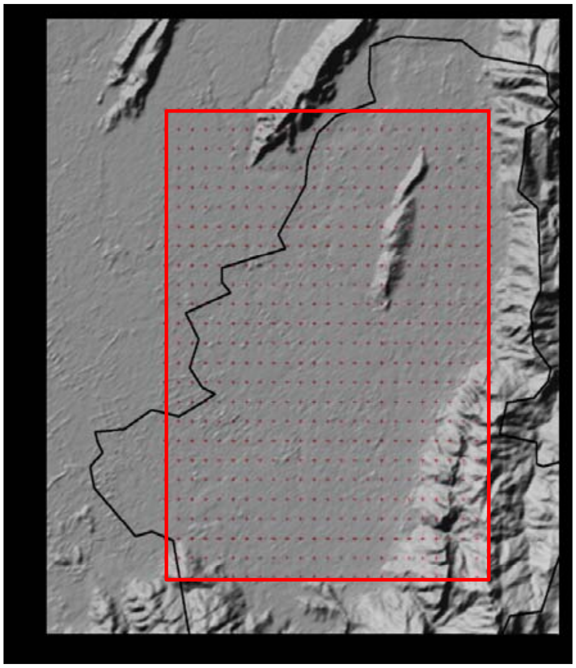


Figure 5. Calculation grid.

DYNAMIC RESPONSE

At each grid node, a synthetic stratigraphy with uniform soil layers 3 meters thick is constructed. For each synthetic stratigraphy, one-dimensional dynamic response is calculated using a nonlinear behavior model (linear equivalent) to each of the selected signals. The dynamic response is calculated using the equivalent linear analysis method, first proposed by Idriss and Seed (1968). The linear response calculations were done using the propagator matrix method of Thompson- Haskell (Thompson 1950 Haskell 1953).

TRANSFER FUNCTIONS

Following the procedure outlined above, transfer functions of the Fourier spectrum are calculated at each grid node, for different PGA at the base of the soft deposit. Figure 6 shows the transfer functions for active and subduction source, for two sites selected within the grid.

Site 226 **Location WGS84: -74.1326, 4.5872 | Depth: 66 m**	**Site 429** **Location WGS84: -74.0797, 4.6157 | Depth: 12 m**

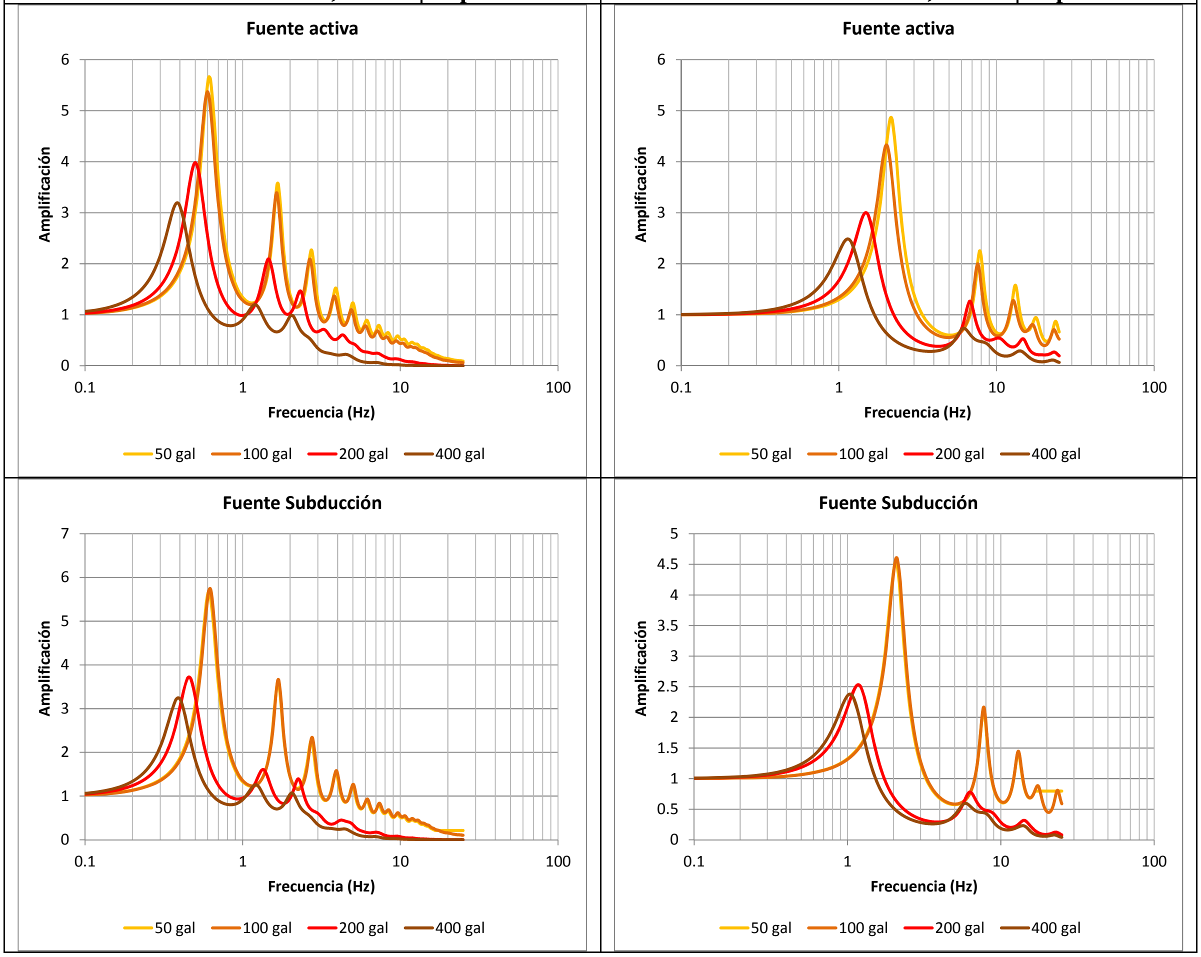
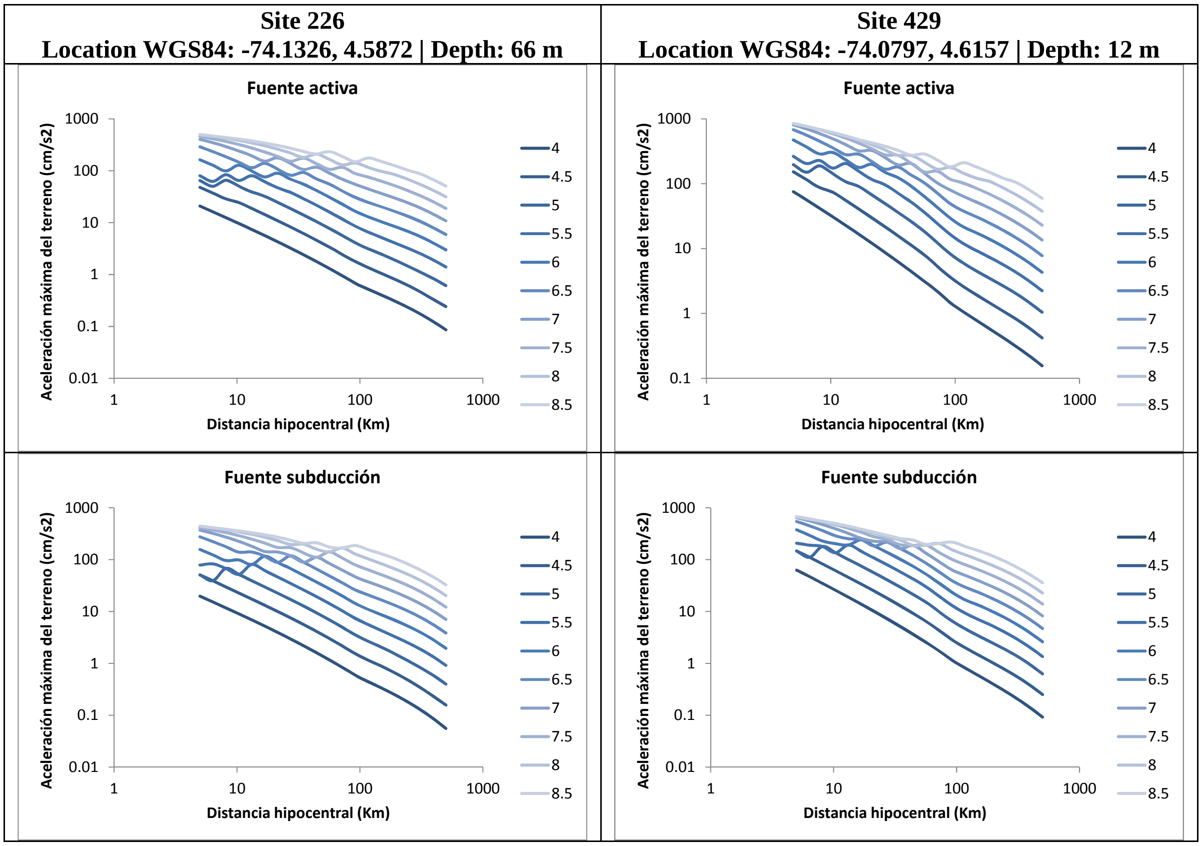


Figure 6. Transfer functions for selected sites.

ATTENUATION FUNCTIONS

The attenuation model proposed by Bernal et.al (2012) is modified to include the particular transfer function of each site. Figure 7 shows the attenuation functions for the same two sites.

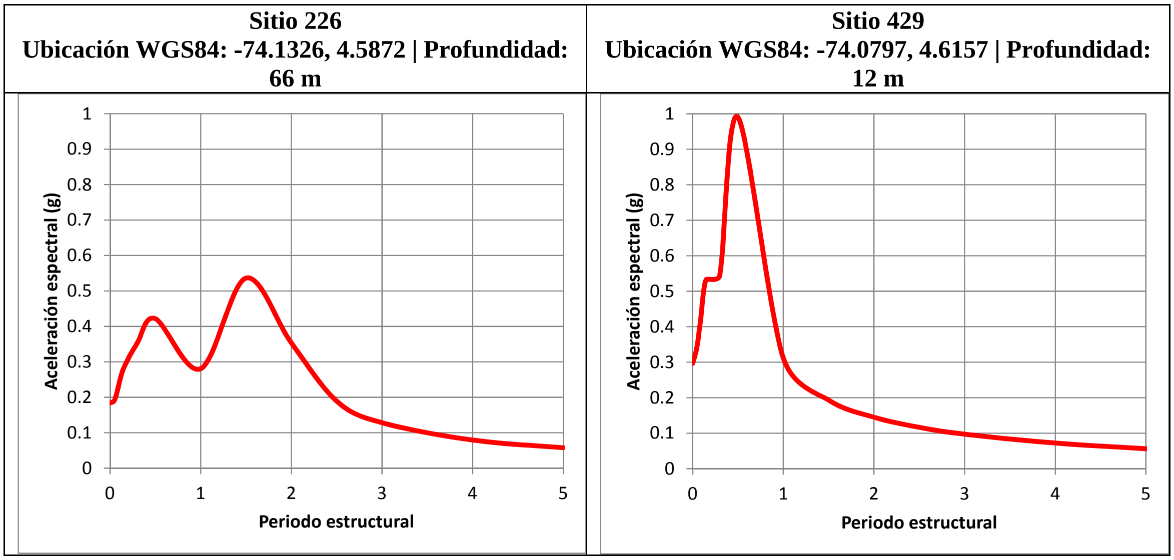

Site 226
Location WGS84: -74.1326, 4.5872 | Depth: 66 m

Site 429
Location WGS84: -74.0797, 4.6157 | Depth: 12 m

Figure 7. Attenuation functions for selected sites.

SEISMIC HAZARD AT SURFACE LEVEL

Using the calculated attenuation functions, a particular seismic hazard analysis in each grid node is performed, using the same seismic hazard model that for evaluating hazard at bedrock. Figure 8 presents the uniform hazard spectra for 475 year return period for the same locations.


Sitio 226
Ubicación WGS84: -74.1326, 4.5872 | Profundidad: 66 m

Sitio 429
Ubicación WGS84: -74.0797, 4.6157 | Profundidad: 12 m

Figure 8. Uniform hazard spectra for selected sites. 475 years return period.

Figures 9 and 10 show the spatial distribution maps of spectral acceleration for structural periods of 0, 0.3, 1 and 3 seconds.

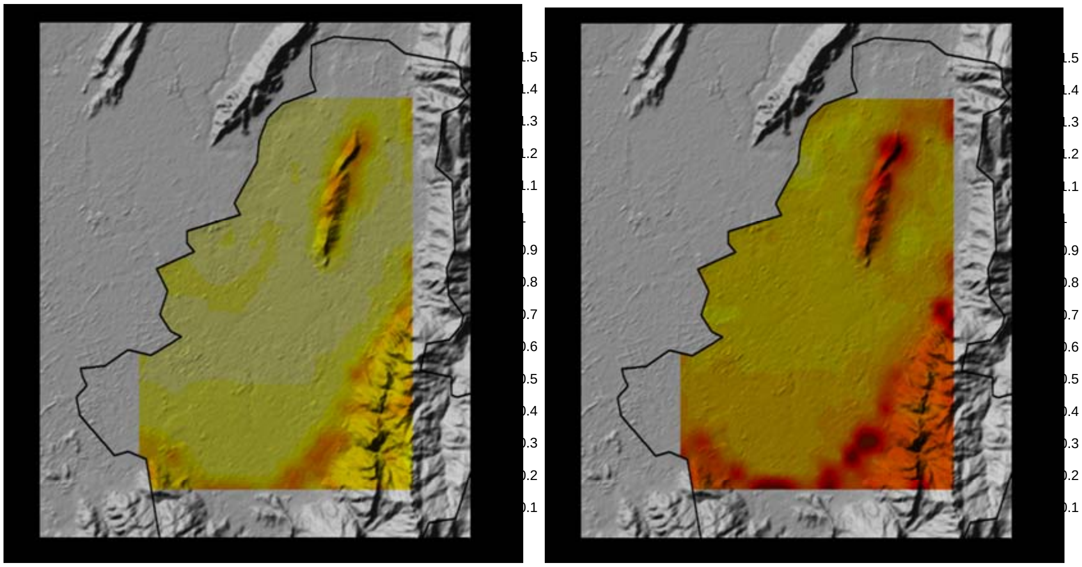


Figure 9. Uniform hazard map of PGA (left) and spectral acceleration for 0.3 sec. (right). 475 years return period. Color scale is in g.

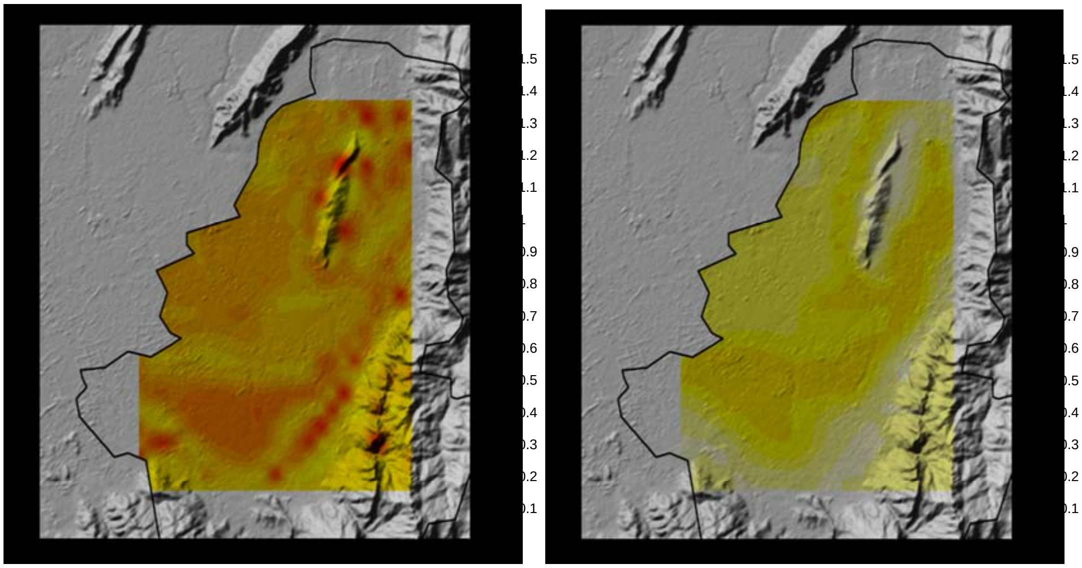


Figure 10. Uniform hazard map of spectral acceleration for 1.0 (left) and spectral acceleration for 3.0 sec. (right). 475 years return period. Color scale is in g.

HARMONIZED DESIGN SPECTRA

Uniform hazard spectra obtained in the previous analysis are used as the basis for the final shapes of the design spectra. These spectra are defined in a harmonized manner as specified in the NSR- 10. The harmonization of spectral shapes is done by means of a computational procedure by which the spectral shape is adjusted to the uniform hazard spectrum calculated at each site. To ensure a good fit, we minimize three different characteristics:

- The difference of the area under the uniform hazard and design spectra.

- The maximum difference in spectral acceleration for any structural period.
- The average spectral acceleration differences for all structural periods.

Design spectra are calculated using the definition of five parameters: Aa, Av, I, Fa and Fv. The first two parameters are associated with the hazard at bedrock, the third is related to the level of importance and the remaining 2 to site effects. Aa and Av are set to the value given by the national construction regulation Aa = 0.15g and Av = 0.2g. The importance factor is set to I=1. Fa and Fv are adjusted by means of a genetic algorithm.

The obtained Fa and Fv parameters are shown spatially in Figure 11. It is possible then, for any location within the city, to define a design spectrum specific for each location.

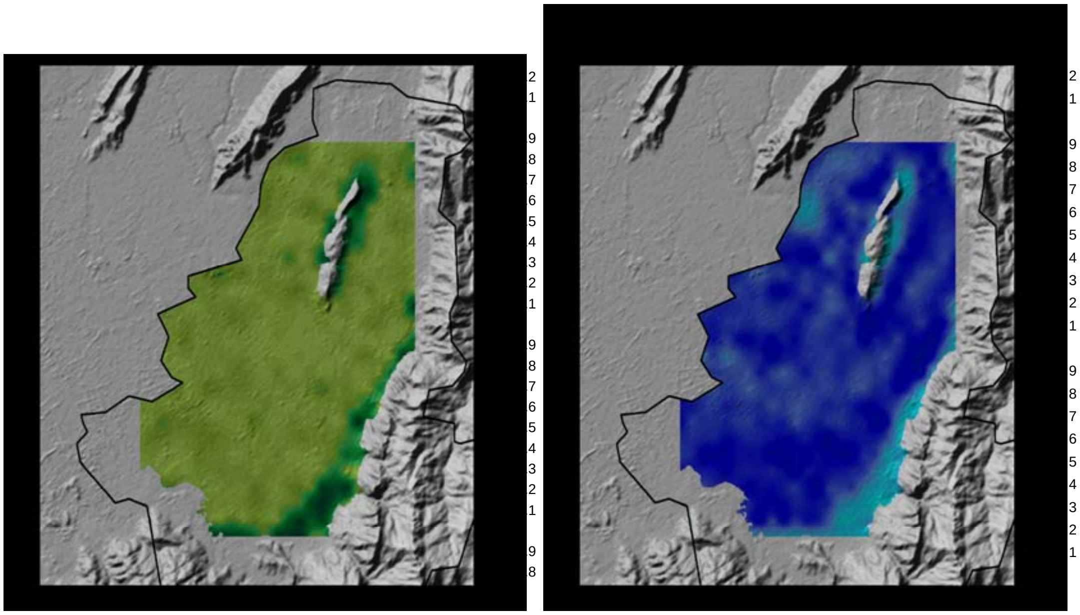


Figure 11. Map of the distribution of Fa (left) and Fv (right)

CONCLUSIONS

The methodology presented in this article is a novel approach for the analysis of the seismic response of soft soil deposits. Although the results presented are susceptible of improvement and refinement, is the first time a city in the world is subjected to seismic response analysis of these features and the first that seismic design parameters are defined at the resolution used.

The work presented is a starting point in the search for new ways to address the problem of site effects in cities, to cover all aspects relevant to the problem, from the assessment of seismic hazard at bedrock, going through the geometry of geological formations, soil characteristics, seismic signals and the response of soft deposits, to the evaluation of seismic hazard level ground at surface and its harmonization with the applicable regulations.

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