PROBABILISTIC SEISMIC SOIL RESPONSE MODEL FOR BOGOTÁ

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ABSTRACT

A dynamic response model for soft soils has been developed for Bogotá through the application of a modern methodology which is based on the geometry of the geologic formations. A tridimensional geometric model of the city's sub-soil is constructed based on the geologic interpretation of the formations present, defining the elevation (above sea level) of the geological contacts. Available geotechnical information is used to assign types of soil to the geometric model. The static and dynamic properties of the soils are defined as random variables and their probability moments are calculated through statistics performed over the available geotechnical data. A grid of calculation sites is defined for the city, and for each point a set of synthetic stratigraphies are obtained, characterized by geotechnical parameters assigned following their probability distributions. The dynamic response is calculated for each point in the grid and for each stratigraphic simulation via a one-dimensional non-linear analysis (equivalent linear analysis) using a set of Fourier amplitude spectra (FAS) generated at rock level through a source-spectrum model for different combinations of magnitude and distance. This allows for the definition of strong motion attenuation functions, which include the uncertainty associated with the site response, specific for each grid point. Seismic hazard is calculated at ground level and uniform hazard spectra are obtained for a return period of 475 years. Design spectra are adjusted to the uniform hazard spectra accordingly with the Colombian building code NSR-10 through an optimization algorithm to find the best fitting Fa and Fv soil parameters. This soil response model was also employed in a seismic risk evaluation performed for Bogotá, as well as in the construction of the automatic post-earthquake damage evaluation system for Bogotá, LISA.

Keywords: Seismic microzonation; Soil dynamic response; Site response uncertainty.

1. INTRODUCTION AND METHODOLOGY

The seismic microzonation studies conducted in recent years, determine zones with an expected similar soil response and for each zone define an elastic spectrum for buildings design. To determine the response on a territory, first the dynamic response on selected sites is calculated and then it is interpolated for the remaining territory. The methodology used for this model in Bogotá determines the soil dynamic response in any location without the need of interpolations. In addition, this methodology allows the use of the model in three aspects associated with seismic risk management: i) probabilistic risk assessment, ii) automatic post-earthquake damage assessment systems, in which it is required to know the strong motion intensity distribution on the entire city (shakemap); and iii) to develop seismic microzonation studies that regulate the seismic resistant building design. The methodology is summarized in Figure1.

2. DEFINITION OF THE TRIDIMENSIONAL SUBSOIL MODEL

2.1 Seismic hazard assessment on hard-rock level for Bogotá

The seismic hazard at bed-rock level was assessed for Bogotá using the updated sources and seismicity model at national level correspondent to the update of the Colombian Seismic Resistant Construction Code of 2010 (NSR-10) and the Bernal (2014) attenuation model. Figure 2 shows the map of PGA for 475 years return period in Bogotá. For the city the maximum ground acceleration varies from 145 cm/s² to 180 cm/s² where major accelerations are presented toward the southeast and lower accelerations towards the northwest.

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1. **Seismic hazard assessment on rock**: set up a tectonic, local sources and seismicity model. The national building code NSR-10, and the Bernal (2014) attenuation were used. This is the basis on which local site effects are added.

2. **Geological contacts’ geometry definition**: identify existing geological formations and define the limits’ topography to establish the depth of each deposit to the rock, resulting in a 3D soil model.

3. **Limits’ geometric definition**: the topography sets the superior limit of the soil geometric model and the water table is necessary to determine at each point the saturation and containment soil conditions.

4. **Geotechnical information collection**: collect field studies detailed enough to count with information regarding the index, static and dynamic soil properties.

5. **Soil type definition**: a soil type is defined for each formation. The geotechnical properties are treated as random variables.

6. **Definition of the calculation grid**: define a grid or calculation point list within the area of study. Each point is a site were all calculations will be performed.

7. **Construction of synthetic stratigraphies**: using the 3D geometry and the defined soil types a set of synthetic stratigraphies is built for each site. Each one has a sequence of values of each geotechnical property randomly generated following each’s probability distribution and depth correlation.

8. **Dynamic response assessment**: the equivalent linear methodology for FAS on rock signals is applied to each stratigraphy to assess the unidimensional non-linear dynamic response. The results are the Fourier amplitude spectra at terrain surface level for each calculation point.

9. **Computation of transfer functions**: functions that specify the amplification factor that the soil at one site generates to the intensities present at bedrock for the complete range of structural periods. It is calculated as the relation between the response spectra on the surface and on rock.

10. **Computation of attenuation functions**: using the Fourier amplitude spectra, the transfer function of a one-degree-of-freedom-oscillator and the random vibrations theory attenuation functions are generated that include the amplification characteristics in terms of the response spectrum for each computation site.

11. **Probabilistic seismic hazard assessment**: perform a PSHA using the same model of sources and seismicity from step 1, and the attenuation functions from step 9. The intensity on the surface associated to any return period and for different vibration periods is obtained.

12. **Design spectra harmonization**: define design spectra compatible with the NSR-10. A genetic algorithm is applied where the parameters that give shape to the design spectra are optimized.

**Figure 1. Summary of the followed methodology**

![Figure 1](image1)

**Figure 2. Map of uniform hazard on rock in terms of PGA (cm/s²) for a return period of 475 years**

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2.2 Definition of the geologic contact geometry and border conditions

The geological formations present on the savanna of Bogotá date from the Lower Cretaceous period to the Quaternary period and vary in soil type from hard rock to extremely soft soils. On the flat area of the savanna of Bogotá are the Quaternary formations which are soft soils deposits (Consorcio PCAI-OYO, 2001). These soils belong to two geological formations whose origin and material type are clearly distinguishable and are the Subachoque Formation and Sabana Formation. Subachoque comes from a fluvio-glacial deposit altered by fluvial and lacustrine processes and consists of layers of fine material, sandy clays, organics and shale-lignites which alternate with sands and gravels and is the deepest layer of soft soil. The Sabana Formation is the superficial layer and consists of fine soft materials with high plasticity (mainly clays) of lacustrine origin (SCG, 2007; Helmes & Van der Hammen, 1995).

It is required to study the geometry of the present geological formations both in plan and depth, for which is necessary the topography for each geological contact. This model uses the inputs provided by the IDIGER (Instituto Distrital para la Gestión del Riesgo y Cambio Climático): (1) topography on hard rock, (2) topography of the Subachoque Formation (its upper limit and lower limit of the Sabana Formation), and (3) terrain topography which represents the upper limit of the Sabana Formation. A 3D model of Bogotá’s subsoil is presented on Figure 3 where bed rock, the contact between the two formations and the topography can be observed.

Figure 3. 3D model of Bogotá’s geologic contacts

2.3 Recollection of geotechnical information

A Geotechnical Data Base for Bogotá has been assembled from previous studies for the Seismic Microzonation of the city, as well as studies for the construction of the Metro. This database is managed by IDIGER (formerly DPAE) and gathers all the geotechnical studies performed on exploration campaigns (around 200). In this model 84 boreholes from the existing 200 were selected because of their quality. For the 84 boreholes it was possible to build a depth profile including all the relevant geotechnical properties such as index properties, Atterberg limits, specific weight and shear wave speed. Only a few of the boreholes have high depths (in most of the city the depth of explorations does not exceed 40m) which result in many cases to not reaching rock (in most parts of the city the explored percentage for soft deposits does not exceed 30%). On this basis, incomplete boreholes were completed until rock using assumed geotechnical properties or values from nearby boreholes of higher depth following these two methods:

1. In those cases where there are no nearby boreholes with a higher depth (for example N51 on El Dorado Airport with coordinates -74.141213, 4.697736 is the deepest of all boreholes with a depth of 246m where rock is at a depth of 430m) basic properties such as soil moisture, specific weight and plasticity index were extrapolated as a constant until reaching rock whereas dynamic properties such as shear wave speed and shear modulus were determined by the methodology suggested by Sociedad Colombiana de Geotecnia (SCG, 2006).

2. In those cases where there are nearby boreholes with a higher depth (for example PA1 on Calle 68 and Carrera 110 with coordinates -74.132083, 4.707792 and a depth of 100m where rock is at 430m) the properties of such borehole where emulated until rock (the mentioned PA1 borehole was completed using data from the N51 borehole already extrapolated until rock).
As an example, Figure 4 shows the profiles for specific weight and shear wave speed for borehole N51 which were completed using the first method discussed before. On this figure the red dot represents the end of the data obtained on field and the dotted lined shows the result of the extrapolation. This figure shows that a constant extrapolation for the specific weight implies an almost linear extrapolation for the shear wave speed. In like manner, Figure 5 shows the profiles for borehole PA1 which were completed using the second method discussed. On this figure it is visible that the data was completed duplicating the profiles of borehole N51.

2.4 Definition of analysis soil types

As the soil profiles are completed the following step consists on performing a statistic analysis of the data for each geological formation thus obtaining the main statistical moments of the profiles for the geotechnical properties for each formation. The properties for each formation are defined by an expected value, a variance, a minimum and maximum limit for each depth. A summary of the results for each soil type is presented below:

**Soil type 1 (Sabana Formation):** This soil is associated with the Sabana Formation and has clayey characteristics. Figure 6 shows the profile in depth for the specific weight along with degradation curves of the shear modulus and the corresponding damping (Ishibashi and Zhang, 1993 modified by SCG, 2006).
Soil type 2 (Subachoque Formation): This soil is associated with the Subachoque Formation and has a high content of coarse material, mainly sands. Figure 7 shows the profile in depth for the specific weight along with degradation curves of the shear modulus and damping from the average sand model proposed by Seed and Idriss (1970).

Figure 6. Geotechnical properties for Soil 1

Figure 7. Geotechnical properties for Soil 2
3. RESULTS OF THE MODEL

3.1. Dynamic response assessment

A grid with nodes every 0.00045° (approximately 50m) was defined resulting in a grid with 550 nodes on the widest part of the city and 880 nodes on the longest part of the city for a total of 259,400 computation sites constrained within the perimeter of the city of Bogotá. At each node of the computation grid synthetic stratigraphies were generated for which the geotechnical properties were treated as random variables and for each one its expected value, variance, minimum limit, and maximum limit as a function of depth were determined (using borehole data). With these parameters a truncated normal probability distribution was defined for every property thus allowing the simulation of stratigraphies at each site as follows: for each property, values that follow the same distribution are randomly assigned using the parameters of the distribution from each layer that conforms the stratigraphy. Given that the properties are correlated in depth, the sequence of generated values was multiplied by the triangular matrix resulting from applying the Cholesky decomposition to the correlation matrix. This is necessary because although the soft soil deposit was modelled as a stratified mean, the soils are part of the same geological formation and do not present defined layers but soft variations on the value of their properties along their depth. Following this procedure, a set of various stratigraphies’ simulations was generated at each computation site to determine the uncertainty associated with the soil’s dynamic response. Figure 8 shows as an example the results of ten simulations on the site 2240 (Coordinates: -74.0365, 4.7993), Depth: 48m, Period: 1.35s, average Vs: 142.5 m/s).

After performing synthetic stratigraphies at each of the 484,000 computation sites, a set of real accelerograms is taken (preferably recorded on rock or hard soil) and each of the signals is transformed to the FAS and run through each stratigraphy using the equivalent linear analysis method from Idriss and Seed (1968) and Seed and Idriss (1970) to obtain the dynamic response at each site. The selected signals were obtained from strong ground motion databases such as the database from the Pacific Earthquake Engineering Research Center (PEER) affiliated with the University of California, Berkeley and the database from the Engineering Institute of UNAM. These signals must be differentiated according to the event mechanism because properties of subduction earthquakes are different from cortical sources earthquakes. The signals have been escalated to four acceleration levels (0.05g, 0.1g, 0.2g, 0.4g) to later obtain transfer functions for these intensity levels and therefore lastly obtain uniform hazard spectra (UHS) that consider the hysteretic behavior of the soils that constitute the stratigraphic column.

Figure 8. Profiles in depth with ten simulations and the average value on site 2240

The equivalent linear analysis method is currently the most used for the calculation of the dynamic response on the non-linear soil range. The method consists in assessing the soil’s stratum linear response and then by means of successive iterations adjusting the properties for shear stiffness and damping
according to non-linear soil behavior constitutive models: the stiffness degradation and damping curves. To calculate the elastic response the propagating matrix method of Thompson-Haskell (Thompson, 1950; Haskell, 1953) was used. It consists in calculating Fourier spectrum linear transfer functions for a stratified mean which provides a computationally efficient solution on the frequency domain. The result is the FAS at terrain surface level along with the transfer function for the soil column, \( H_s(f) \). This way, the seismic response is obtained at each synthetic stratigraphy defined on the model. Figure 9 shows an example of signal A05 (1999 Quindio’s earthquake) before and after performing the dynamic analysis on one of the simulations at computation site 1648 (Coordinates: -74.0725, 4.7273; Depth: 18m; Period: 0.58s; average Vs: 127.09 m/s).

![Figure 9. Comparison of accelerogram and FAS on surface and on rock for an active signal at site 1648](image)

Additionally, the assessment of the uncertainty on the soft soils dynamic response is a subject that has been a matter of study for several years and has not yet been fully resolved. For this model in Bogotá the approach proposed by Bazurro and Cornell (2004) and the modification by Stewart and Goulet (2006) were used. It defines the standard deviation of the surface spectral acceleration logarithm, \( \sigma_{lnSa} \) (where \( T \) is the structural vibration period) as:

\[
\sigma_{lnSa} = \sqrt{\sigma_{lnSa(T)}^2 + \sigma_{lnAF(T)}^2 + 2\rho \sigma_{lnSa(T)} \sigma_{lnAF(T)}} \tag{Eq. 1}
\]

where \( \sigma_{lnSa(T)} \) is the standard deviation of the spectral acceleration on rock (given by the attenuation function), \( \sigma_{lnAF(T)} \) is the standard deviation associated to the uncertainty on the site’s dynamic response (determined using multiple simulations and therefore the multiple \( AF(T) \) on the computation sites) and \( \rho \) is the correlation coefficient between the two terms. This way it is possible to introduce the uncertainty associated with the dynamic response of the soil in the attenuation function specific for each site.

3.2. Generation of Shakemaps

The results on the dynamic soil response allow to determine the spatial distribution of the strong ground motion at a surface level. This intensity distribution resulting maps are commonly named *shakemaps* and these are a very important part of automated post-earthquake damage assessment systems, such as the LISA system implemented on Bogotá (Bernal et al., 2017a). To generate a *shakemap* related to a real event, this model is used along with an accelerogram at bedrock (which can be assumed uniform on all the city) and the resulting accelerogram and response spectrum on surface are obtained at each of the 259,400 defined computation sites. To view an application, refer to the work of Bernal et al., (2017a).

3.3. Generation of transfer functions

Transfer functions show the amplification factor that a soil generates to the intensities present at bedrock at a specific location for the complete range of structural periods. To determine the transfer functions
the relation between the response spectra at surface level and at bedrock is calculated for different levels of PGA at the base, different structural periods and a damping coefficient of 5%. These functions are required for a probabilistic seismic hazard assessment because this is how the site effects are included in this methodology (see Bernal et al., 2017).

Given that for the same level of maximum acceleration several signals are available and that there are as well several acceleration levels, to obtain one transfer function for each intensity level the average of the transfer functions from the signals belonging to the same group is computed. One response spectra transfer function will be available for every intensity level and for every stratigraphy at each computation site. Since there are multiple simulations (several stratigraphy at each point) at the end the transfer functions for each simulation are averaged to obtain just one function for each intensity level and for each computation site. As an example, Figure 10 shows the amplification functions for 10 simulations on site 1648 (18m thickness of soft deposit) along with the average value.

![Figure 10. Amplification functions of the spectral acceleration on the site 1648](image)

### 3.4 Design spectra harmonization

To create design spectra, like on a traditional seismic microzonation, first the uniform hazard spectra (UHS) must be obtained. To do so, a probabilistic seismic hazard assessment (PSHA) must be performed using the same source and seismicity model used on section 2.1, and specific attenuation functions for each site. To generate these functions the methodology proposed by Bernal (2014) was followed in which it is possible to generate attenuation functions that include the amplification characteristics specific for each site in terms of the acceleration response spectra for each computation site using the FAS and the uncertainty associated with the dynamic response obtained from the previous step and modifying them with the transfer function from a one-degree-of-freedom oscillator and applying the random vibration theory. Additionally, for every structural period considered in the attenuation function the standard deviation value is computed using Equation 1. These attenuation functions are defined in terms of the spectral accelerations for multiple structural periods and one must be obtained for each main focal mechanism on the analysis area, as seen on Figure 11.

![Figure 11. Surface attenuation’s tables for site 1538](image)
After the attenuation tables are computed, a probabilistic seismic hazard assessment is performed on each computation site. The result is a set of uniform hazard spectra for each computation site which relate the expected intensity (acceleration, for instance) at each site for the complete range of structural periods and for different return periods. Figure 12 presents the uniform hazard spectra for the same sites.

![Uniform hazard spectra for sites 1538 and 622](image)

Figure 12. Uniform hazard spectra for sites 1538 and 622

Once the UHS are obtained it is possible to define design spectra compatible with the applicable seismic resistant construction code. To do so, a genetic algorithm is applied to optimize the parameters that shape the design spectra to be able to minimize the values of these three characteristics: (1) the difference on the area under the uniform hazard and design curves, (2) the maximum difference (between the two curves) of spectral acceleration for any structural period, and (3) the average of the differences (between the two curves) of spectral acceleration for every structural period. According to the NSR-10 the parameters that shape the design spectra are five: $A_a$, $A_v$, $F_a$, $F_v$ and $I$. Given that parameters $A_a$ and $A_v$ belong to a hard rock condition, they result as constant values for the city of Bogotá disregarding the site effects model to be implemented and on a same manner, parameter $I$ can also be considered a constant value equal to 1 since it is a factor that can be assigned later according to the building type being designed. For these reasons the only free design parameters left to define and that do depend on the site effects model used are $F_a$ and $F_v$.

Given that it is a non-linear problem it is not possible to use classic statistic methods to adjust the optimum value of the free design parameters, hence, the procedure followed with this methodology consists of iterations over the values following a genetic algorithm with the purpose of ensuring the convergence of the solution. The procedure is summarized as follows (for more details refer to Bernal (2014)): i) “individuals” are defined which correspond to the different $F_a$ and $F_v$ pairs (this is the genotype); ii) an initial population is generated, and it is composed by $n$ individuals with a randomly generated genotype; iii) crossing the individuals from this first generation and applying a mutation breeds a second generation of individuals; iv) on the new generation, the fitness of all individuals is evaluated, which means the bias for each individual from the control value, and the fittest individual is determined; v) this individual is named “champion” and is crossed with all the individual from its generation breeding the new generation (this is called forced evolution); vi) this process is repeated the desired number of times until a fitness level good is obtained or until the maximum number of generations is reached and the champion of the last generation defines the optimum values for parameters $F_a$ and $F_v$.

By applying this procedure, the values of the designed parameters associated with the soil for each node of the computation grid are defined. This results on a spatial representation of the parameters that control the final shape of the design spectra for new buildings. Figure 13 shows the design spectra adjusted from the uniform hazard spectra for sites 1337 (Coordinates: -74.0905, 4.7183; Depth: 3m; Period: 0.07s; average Vs: 167.7m/s) and 1576 (Coordinates: -74.077, 4.7543; Depth: 6m; Period: 0.16s; average Vs: 153m/s) while the spatial distribution of parameters $F_a$ and $F_v$ is presented on Figure 14.
6. CONCLUSIONS

With this methodology it is possible to obtain the seismic movements for designing for new buildings for the extent of the city which is the final objective on a seismic microzonation study. The built model constitutes a key point in the investigation of new ways to address the problem of site effects on the cities since it embraces all the relevant characteristics on the problematic from the seismic hazard assessment on rock, to the geometry of the geological formations, the characteristics of the soils and the response of soft deposits until the seismic hazard assessment at terrain surface level and its harmonization with the applicable code. Besides, this methodology constitutes an innovation in the sense that it allows to determine the dynamic response of the soil at any location on the city without the need of interpolations making it possible to create a grid as dense as desired where the dynamic response on each site will be assessed. Lastly, this methodology allows the use of the model on several aspects related to seismic risk management (Shakemaps for emergency response, transfer functions for risk assessment and generation of a seismic microzonation) given its complete flexibility and compatibility with these applications.
7. REFERENCES


