# Dynamic characterization of alluvial deposits by geophysics and specialized tests in Floridablanca, Santander, Colombia.

*Carlos Buenahora*[1], *Daniel Galvis*[2], *Laura Ortiz*[3], *Antonio Martínez Graña*[4], *Nelson Amaya*[5] and *Mario Silva*[6]

[1]*Floridablanca, Santander, director@ingeotecnia.com.co, Colombia*
[2]*Socorro, Santander, danieljave15@gmail.com, Colombia*
[3] *Floridablanca, Santander, lortiz.ingeotecnia@gmail.com, Colombia*
[4]*USAL, Salamanca, amgranna@usal.es, España*
[5]*Floridablanca, Santander, namaya@ingeotecnia.com.co, Colombia*
[6]*Floridablanca, Santander, marioalfredosilvac@gmail.com, Colombia*

## ABSTRACT

The Metropolitan Area of Bucaramanga is located within one of the three seismic nests in the world and therefore presents a high seismic and geotechnical threat (INGEOMINAS, 2001), therefore certain zones, especially those with alluvial and colluvial deposits, have limitations for the development of infrastructure projects, unless a threat assessment is carried out that indicates otherwise or, in its absence, it is reduced to low levels with stabilization works. The thicknesses of these deposits vary from a few meters to two hundred meters and their definition and dynamic behavior (damping coefficient and terrain degradation curves), would allow analysis with special non-linear constitutive models to better understand their response to a possible earthquake and to ensure the stability of the structures and even an optimization based on a possible lower spectrum. A new two-tower housing project of up to 36 stories high is a perfect scenario to carry out a local seismic response study and perhaps transform the way future projects are designed. It should be noted that, given the acceptable stiffness and granular composition of the soils, it is difficult to take unaltered samples and the Colombian NSR-10 standard does not require local behavior studies and therefore its study has not been properly established. It is sought through geophysical tests and laboratory tests such as triaxial, resonant column and bender element to perform such characterization and to perform soil modeling that allows the calculation engineer to have the appropriate inputs for their analysis.

**Keywords:** Dynamic characterization; spectrum; bender element; down hole; seismic; cyclic triaxial; bender element; seismic.

## 1. Introduction

The municipality of Floridablanca is located in one of the three seismic nests in the world and has a high seismic hazard level according to the Colombian seismic resistant standard (NSR-10). This indicates the importance of carrying out a dynamic characterization of the alluvial soils present, in order to know their behavior and response to seismic events, vehicular traffic, microseismic events caused by vibrating equipment, among others.

For the elaboration of this article, a new project in Floridablanca will be taken as a case study, consisting of two apartment towers of 19 and 36 floors, which will be developed in an area of approximately 4910m². As important inputs for soil characterization, geophysical and laboratory tests will be carried out, such as: seismic refraction test, MASW test, down-hole, cyclic triaxial, resonant column, and Bender element test.

Through the integration of the aforementioned inputs it is possible to construct the degradation and damping curves, which are used to demonstrate the dynamic behavior of surface soil due to seismic wave propagation in dense alluvial soils in the city of Floridablanca. The above, by means of a wave amplification analysis, zoning and obtaining seismic surface design movements as established by the NSR-10 from several analysis methods.

The results of the analysis showed that the behavior of the profile of the area of interest is more rigid than expected, i.e., it does not behave as a type C soil profile according to NSR-10, but its behavior is more in line with a type B response spectrum as a minimum to better reflect the real seismic hazard. The analysis of the dynamic behavior at the surface allows the optimization of seismic designs.

## 2. Study area

The area of interest of the research was a project located in the municipality of Floridablanca, in the department of Santander-Colombia. In the lot next to Fosunab located at 158th Street, Cañaveral neighborhood, as shown in Figure 1.

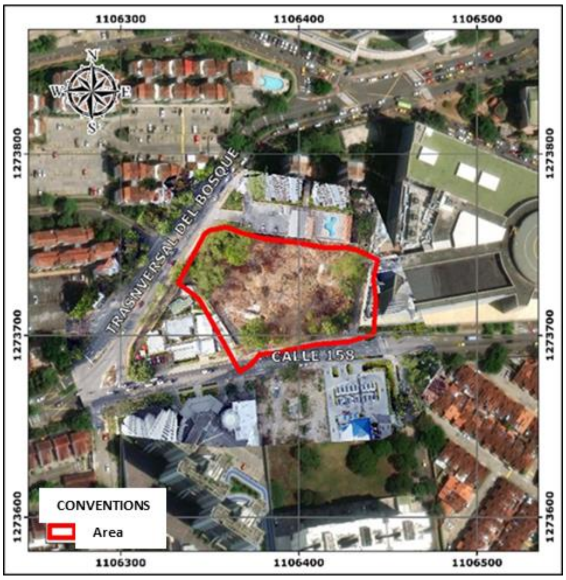


**Figure 1.** Location of the study area.

## 2.1. Geology

### 2.1.1. Regional geology

Taking into account the information available from the Colombian Geological Service (SGC), in its geological sheets (see Figure 2), the study area includes alluvial soils composed of fine and coarse sands with the presence of gravels and rock fragments, predominantly sandstone, as shown in Figure 2. Lithologically, the sector presents alluvial soils of the Órganos member of the Bucaramanga formation (Qbo) and residual soils of the Girón formation (Jg); the latter formation is affected by the Bucaramanga, Ruitoque and Florida faults.

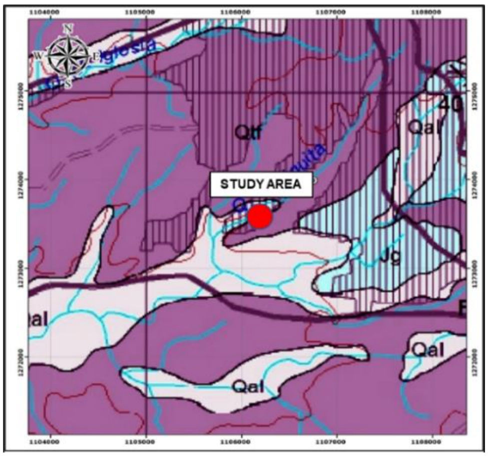


**Figure 2.** Regional geologic map, Taken and modified from (SGC, 2015a).

### 2.1.2. Local geology

In the area were found and recognized mainly fill soils and disturbed soils. It is underlain by alluvial soils mainly characterized by abundant rounded pebbles in a clastic-supported and sandy-supported matrix, and some lenses of finer material with varied colorations of variable extension and thickness corresponding to the Organ Member of the Bucaramanga Formation (Qbo).

Additionally, at greater depths, there was evidence of residual soils of the Girón formation (Jg) composed of clayey sands with gravels, pebbles and thin levels and intercalations of sandstones, quartz sandstones and conglomeratic sandstones with different degrees of weathering.

## 3. Methodology

In order to estimate the characteristic values of the dynamic parameters of the materials that make up the study area, it was necessary to carry out the following activities:

### 3.1. Geotechnical characterization

For the geotechnical characterization of the soils present, percussion and rotation geotechnical soundings, apiques, seismic lines, down hole and electrical tomography were carried out, distributed throughout the study area, as shown in Figure 3:

#### 3.1.1. Direct exploration

Five geotechnical rotary borings were made, with variable depths between 3.0 and 41.0 meters and five geotechnical percussion borings, with variable depths between 1.5 and 4.0 with standard penetration tests every 0.5 meters, for the recovery of samples and determination of the geomechanical characteristics of the existing materials in the study area. Additionally, 3.0 apiques were executed at 3.0 meters depth, for the extraction of unaltered samples for specialized laboratory tests (see Figure 3). Table 1 shows a brief summary of the description of the materials found in the deepest borings.

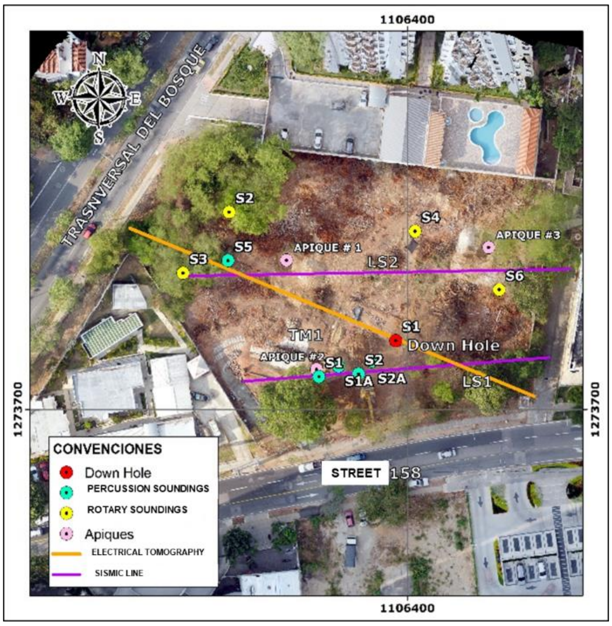


**Figure 3.** Geotechnical exploration.

**Table 1.** Drilling summary at greater depth.

| Drill holes | Depth From (m) | Depth To (m) | Description |
|---|---|---|---|
| | 0.0 | 5.0 | Member organs Bucaramanga Formation (Qbo): Fine sands with some fine and coarse gravels of quartz and igneous rocks. |
| **SRT1** | 5.0 | 28.0 | Member organs Bucaramanga Formation (Qbo): Clayey and clayey-gravelly sands, Resistant sandstone and meta-sandstone boulders and blocks within a sandy-clayey matrix with heterometric gravels. |
| | 28.0 | 41.0 | Residual soils of the Girón formation (Jg): Gravelly and clayey sands with levels and intercalations of quartz sandstones. |

### 3.1.2. Indirect exploration

**Seismic Refraction and MASW**

Its fundamental principle is based on the measurement of the travel times of seismic waves generated by an impulsive source at the subsurface surface (or close to it) and refracted at the interfaces between media (refractors) with different physical properties. The analysis of these travel times allows in principle to obtain a depth profile of the geometrical distribution of the different refractors, with the corresponding velocities at which the seismic wave propagates through them (Redpath, 1973).

On the other hand, the MASW test is a method that consists of the interpretation of surface waves, where as in the refraction test, the waves are generated by an impulsive source along an axis on the ground surface. This test allows to obtain a dispersion curve that associates the velocity with the frequency and the wavelength, which shows the variation of the stiffness in depth. In other words, the MASW method allows identifying soft and stiff strata. Figure 4 shows the results of one of the seismic lines executed, showing the different stratigraphic zones and their respective descriptions.

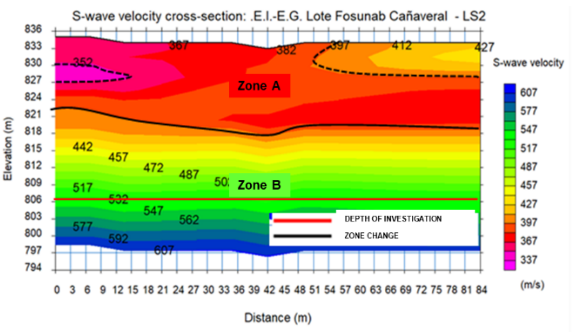



**Figure 4.** MASW/2D LS2 Surface Wave Testing.

Zone A has shear velocities (Vs) between 360 and 390 m/sg (Profile type C) and compressional wave velocity (Vp) between 441 and 735 m/sg. This layer has a thickness of 6.0 to 15.0 meters and is associated with alluvial soils of dense to very dense consistency composed of sands with gravels and fine to very fine sands.

The dotted lines represent at the beginning of the seismic line the presence of a material with slightly lower velocities but very close to the average velocity of the layer, so the consistency of the material in this zone is a little looser. Likewise, superficially there is a zone with higher velocities associated with the presence of gravels or blocks.

Zone B presents shear velocities (Vs) higher than 400 m/sg and compressional wave velocity (Vp) higher than 900 m/sg. This layer is associated with alluvial soils of greater rigidity and very dense consistency and towards the northern part of the lot, direct exploration showed that after 21.0 m there is a rigid residual soil layer of the Girón formation (Jg).

**Down Hole**

This method consists of seismic wave propagation used for in situ shear wave profile measurements for the analysis of the seismic response of a terrain (Correia, 2015). To perform the test, surface waves are generated by tapping on a plate at a distance x from the borehole, where a geophone is located in charge of recording the travel times of compressional and shear waves. Figure 5 shows the results obtained from the test.

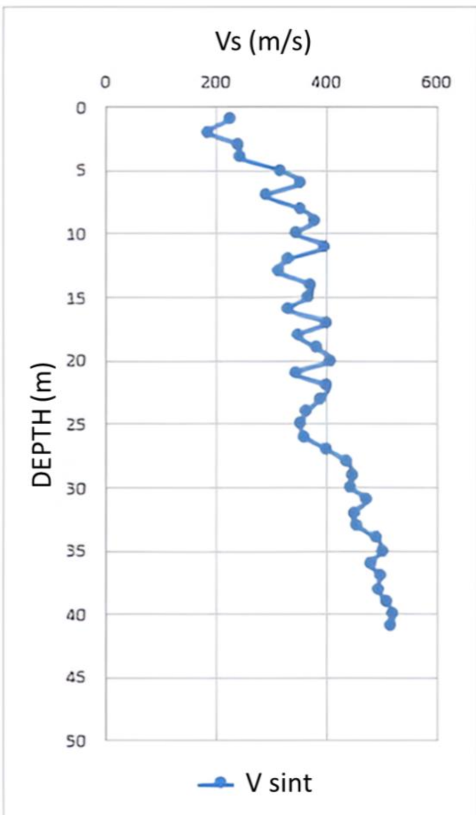



**Figure 5.** Vs intervalic: Down Hole Test

#### Electrical tomography

The electrical tomography or "Electrical Imaging" test is one of the most traditional prospecting methods in geophysics (Arias, 2011). Its main principle is based on the measurement of currents and voltages of currents and voltages generated by a current injection initially at the surface and subsequently into the ground. With the acquired measurements, a two-dimensional (2D) section is constructed that shows a first approximation of the changes in the subsurface. Subsequently, an inversion algorithm is applied to obtain the real distribution of resistivities or electrical image that will give information about the physical characteristics of the subsoil (see figure 7).

### 3.1.3. Laboratory Tests

#### Triaxial cyclic test

The triaxial test is designed to investigate soil response in terms of deformation and changes in mechanical properties, particularly shear modulus (*Glab*) and damping ratio (D), rather than focusing only on shear strength as required by ASTM D5311 (2011). For the execution of the test, electromechanical equipment was used which, since it has an electric piston, the loading cycles are much more accurate. Table 2 and Figure 6 show the results obtained from one of the cyclic triaxial tests performed.

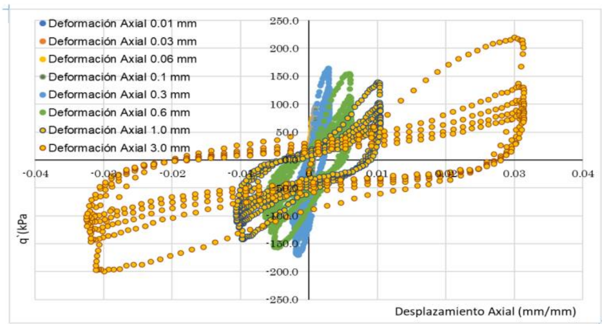



**Figure 6.** Cyclic triaxial test (400 kPa)

#### Bender Element Test

This method consists of applying a voltage to a piezoceramic element, which transmits a shearing motion over one end of the cylindrical soil sample. This disturbance travels along the specimen to the other end where another similar element receives the mechanical disturbance and generates a voltage (Dyvik and Madshus, 1985).

In this test the time difference between the emitted and received signals is measured and these signals allow to calculate the shear wave velocity and the initial shear modulus G0. The following equations taken from SAGGEP 2021 are used to calculate the above mentioned:

**Table 2.** Triaxial cyclical results (400 kPa).

| Triaxial cyclical **(400 kPa)** | | |
|---|---|---|
| **γ** | **Glab** | **D** |
| **%** | **MPa** | **%** |
| 0.007 | 108.32 | 1 |
| 0.02 | 81.82 | 5 |
| 0.041 | 58.3 | 9.1 |
| 0.068 | 46.51 | 12.5 |
| 0.203 | 23.37 | 17.8 |
| 0.406 | 9.41 | 19 |
| 0.677 | 4.74 | 19.8 |
| 2.031 | 1.01 | 20.3 |

$$Vs_{lab} = \frac{L}{ts} \quad (1)$$

Where $Vs_{lab}$ is the shear wave velocity, L is the distance between the bender elements, and ts is the transit time of the shear wave.

Additionally, an important aspect to be performed is the correction for confinement, an equation used empirically is the following:

$$Vs_{labc} = Vs_{lab} * (1 + k * \sigma')^{1/4} \quad (2)$$

Where $Vs_{lab}$ is the wave velocity corrected for confinement, σ^' is the effective confinement, and k is a coefficient depending on the type of soil, which for granular materials is 0.05. The results are shown in Table 4.

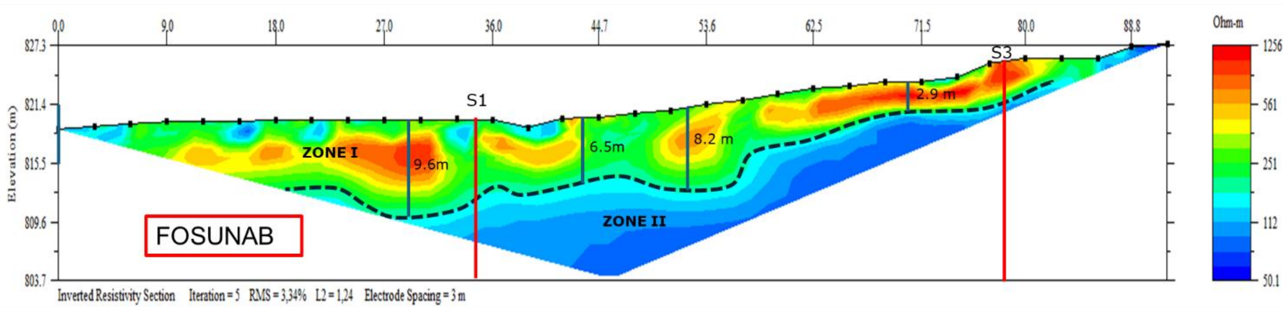
#### Resonant Column Test

The resonant column test is the most widely used laboratory method to measure dynamic properties of soil at small deformations. For the execution of the test, a soil sample is subjected to a harmonic load, where the amplitude and frequency of the load are controlled while a motion transducer measures the vibration level of the resultant allowing to obtain the stiffness of the soil at small deformations (Camacho et al, 2013), as well as the damping modulus and the shear wave velocity Vs. Table 3 shows the results obtained for one of the resonant columns:

**Table 3.** Resonant column 1 (150 kPa).

| **Fr** | **γ** | **Glab** | **D** |
|---|---|---|---|
| **Hz** | **%** | **MPa** | **%** |
| 112 | 0.0013 | 86.7 | 0.5 |
| 110 | 0.0021 | 84.6 | 0.75 |
| 107 | 0.0036 | 81.0 | 1.1 |
| 104 | 0.0063 | 74.2 | 1.64 |

ELECTRICAL TOMOGRAPHY No.1




La **ZONE I** is composed of rock fragments embedded in a sandy-clay matrix with heterometric gravels, low moisture content. In some sectors with resistivity values (180-280 Ohm-m), materials of smaller granulometry, fine and medium sands, predominate. This zone belongs to the organ member of the Bucaramanga formation.

La **ZONA II** shows a decrease in resistivity values, possibly due to the presence of high moisture content in the subsoil. The zone is composed of granular materials comprising intercalations between clayey sandy soils and sandstone rock fragments embedded between clayey sands.

**Figure 7.** Electrical tomography

**Table 4.** Bender Element Results

| Apique | Initial specimen height | Bender instrument length (1)) | Bender instrument length (1) | Average Wave Travel Travel Time | Measured shear wave velocity (Vs) | Confining stress | Corrected shear wave velocity (Vsc) | Unit weight | Maximum laboratory shear modulus ($Go_{lab}$) |
|---|---|---|---|---|---|---|---|---|---|
| | **mm** | **mm** | **mm** | **s** | **m/s** | **kPa** | **m/s** | **kN/m3** | **MPa** |
| Apique 1 | 98.7 | 4.72 | 5.19 | 0.00075 | 118 | 400 | 254 | 19.0 | 124 |
| Apique 2 | 99.2 | 4.72 | 5.19 | 0.00076 | 117 | 150 | 201 | 19.5 | 80 |
| Apique 3 | 101.2 | 4.72 | 5.19 | 0.00184 | 50 | 150 | 85 | 22.5 | 16 |

## 3.2. Compilation and analysis of results

Soils exhibit a spectrum of behaviors under dynamic loading, each with specific characteristics and deformation ranges. The Bender Element and resonant column tests determine the maximum shear modulus in the laboratory and evaluate degradation at small deformations. On the other hand, triaxial tests contemplate the analysis providing critical data on shear modulus degradation at larger deformations.

### 3.2.1. Integration and extrapolation of data

All tests must agree in terms of strain, these provide a consistent point of comparison between the $G_{labmax}$ obtained with Bender Element and resonant column. Through careful extrapolations of the shear modulus in magnitude, degradation curves are constructed for confining pressures of 400 kPa and 150 kPa. In addition, intermediate values are presented for 300 kPa confinement, representatively located between the extreme data (see Figure 8).

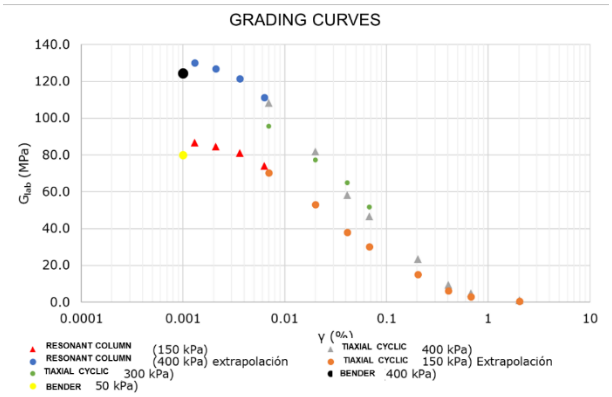



**Figure 8.** Compilation of results: gradation curves Compilation of results: gradation curves

According to the previous results, normalized curves are determined (see Figure 9), which can be adjusted in stress depending on the stiffness of the in situ material, which in general is measured in detail through geophysics, in this case, by MASW and Down Hole.

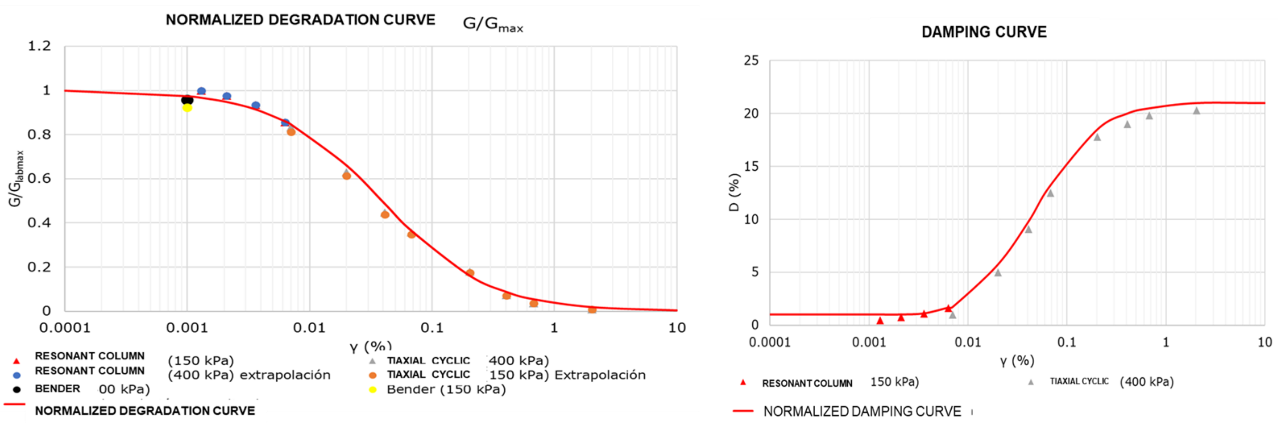



**Figure 9.** Normalized degradation curves and damping curves.

## 3.3. Inputs to determine the local seismic response.

For this it is necessary to define the record of accelerations representative of the seismic environment of the site. For the municipality of Floridablanca, according to Law 400 of 1997, for a 10% probability of exceedance over a 50-year period, i.e., a return period of 475 years and without taking into account local responses, the acceleration values Aa and Av have a magnitude of 0.25.

A detailed comparison between the Uniform Hazard Spectrum (UHS) proposed by Gallego and the one provided by the Colombian Geological Survey (SGC) is presented in Figure 10. Historically, Gallego's UAE has been widely referenced in the field of earthquake engineering. However, after rigorous analysis and review of various publications, it has been identified that the attenuation equation tends to overestimate the seismic hazard over longer time periods, which is attributed to the use of seismic records affected by site effects. This overestimation is a significant concern, as it can lead to excessive conservative design and inefficient allocation of resources in seismic hazard mitigation. Given this context and based on the available technical evidence, the decision has been made to adopt the UAE provided by the SGC. This choice is based on the search for a more accurate and adjusted representation of the seismic hazard for the region. For this reason, resolution D-080 of February 25, 2020 has been used, which is aligned with the latest findings and recommendations in seismic risk assessment.

Based on this disaggregation and the uniform hazard spectrum for 475 years presented by the SGC (2020), a search was performed in the PEER database of real earthquakes representative of different seismographic sources (see Table 5). two (2) seismic events were selected for each seismogenic source in each of its components.

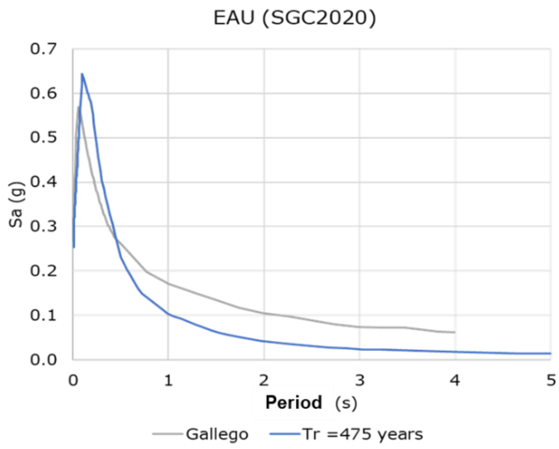



**Figure 10.** Spectrum of Gallego vs. spectrum of SGC.

From this search, two (2) seismic events were selected for each seismogenic source in each of its components. Figure 11 shows the scaled response spectra, together with the target spectrum (UAE city of Bucaramanga) with which the signals were searched in the PEER database. Likewise, the average spectrum of the selected earthquakes is included (red dashed line), which was obtained as the arithmetic mean of the signals taking into account the range of representativeness of each one of them and guaranteeing that between 0.5 and 2.0 times the period of the structure (more than 30 stories) the condition that the average of the signals in its period of applicability is higher than 90% of the target spectrum is fulfilled.

**Table 5.** Selected earthquakes.

| **Scalar factor** | 1 | 1.5 | 1.4 | 1.5 | 2.2 | 2.1 |
|---|---|---|---|---|---|---|
| | **Nearby Source** | | **Intermediate source** | | **distant source** | |
| **EAU SGC475** | RSN 72 | RSN 8110 | RSN 81 | RSN 1626 | RSN 3079 | RSN 5911 |
| | 72 | 8110 | 81 | 1626 | 3079 | 5911 |

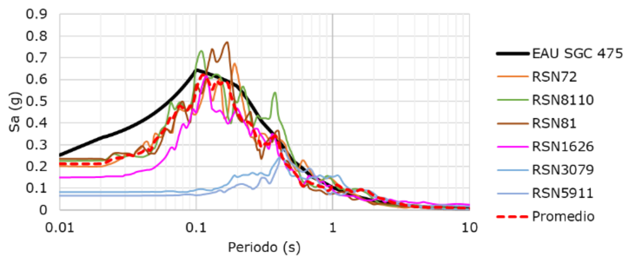



**Figure 11.** Average spectrum of selected earthquakes vs. the uniform hazard spectrum of the city of Bucaramanga.

Another necessary input to obtain a local response spectrum is the geotechnical geological profile, based on the results of the exploration, for the modeling performed a thickness of 40.0 m of alluvial deposit was considered, because after that there is material with a Vs of more than 760 m/sg in which, properly speaking, it would not generate wave amplification.

### 3.4. Dynamic response analysis by means of vertical or two-dimensional propagation.

Next, the nonlinear analyses in the finite element software show that the profile taken corresponds to dense alluvial soil, which increases its stiffness and resistance in depth (see Figure 12).

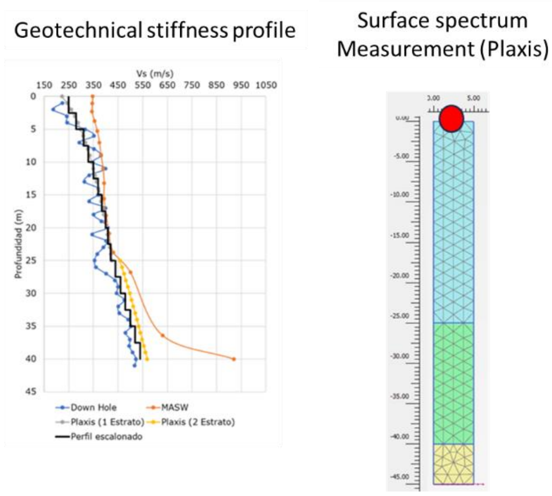



**Figure 12.** Geotechnical low strain stiffness profile and plaxis surface response modeling.

### 3.5. Local response

#### 3.5.1. Deepsoil Modeling

One-dimensional response analysis was performed with the Deepsoil V7.0 program (Developed by Hashash, Y, Musgrove, M. in 2011). This program performs a one-dimensional horizontal shear wave propagation analysis taking into account the variations of the damping ratio and shear modulus with deformation in the profile soils. This model implemented a finite difference equivalent line geometry.

In this case, the degradation and damping curve defined through laboratory tests was fixed, and an example layer with its approximation mentioned above is also shown. Accordingly, Figure 13 presents the spectral accelerations obtained at the surface for the two horizontal components of the six earthquakes selected in the analysis.

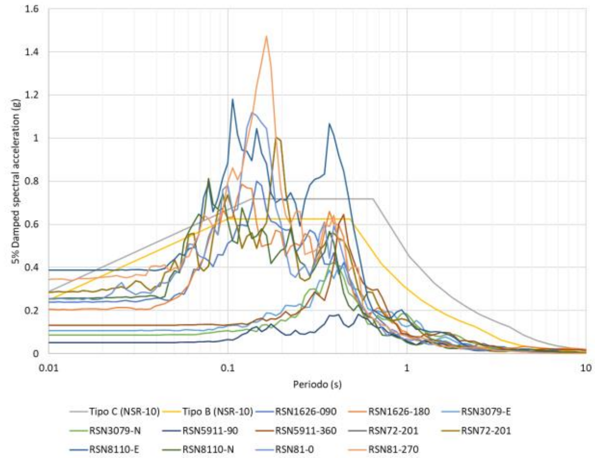



**Figure 13.** Spectral accelerations obtained at the surface.

#### 3.5.2. Plaxis modeling.

In order to verify the surface behavior with a nonlinear model, a plaxis modeling was performed with finite element geometry with dynamic analysis with viscous and hysteretic damping, with the HS small model, which allows having degradation and damping curves associated to the material, depending on the depth stiffness and strength of the material with Mohr Coulomb criteria (see Figure 12 and Table 6).

#### 3.5.3. Comparison of Deepsoil vs. Plaxis response spectra

According to the detailed analysis, it is identified that the equivalent linear result of Deepsoil is almost the same in response as plaxis, when considering similar thickness of soils and when considering similar stiffness parameters in the models. This indicates that the local response analysis of the chosen signals is consistent and has a good starting point for further detailed studies (see Figure 14).

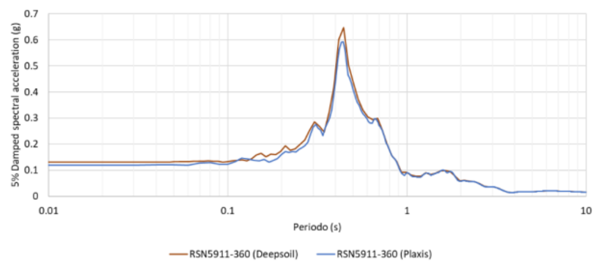



**Figure 14.** Surface response spectrum Deepsoil-plaxis signal RSN5911-360.

## 4. Conclusion and discussion

Through the integration of geotechnical field and laboratory tests, a geo-mechanical profile of the site including stiffness, strength, damping and deformation-dependent stiffness was defined with high accuracy.

Thanks to the application of highly sophisticated and controlled methods of extraction of unmolded soil samples, given their high hardness and granular composition, it has been possible to preserve the integrity of the behavior of the material, even in very thick samples. This care in the handling has been crucial to ensure the validity of the measurements and observations, since in most cases it turns out to be unfeasible to perform them or their results do not reflect the reality of their behavior.

The investigation has revealed that, in the case study exposed, the soil profile of the area, by exhibiting a stiffer than expected behavior, does not properly conform to the type C response spectrum defined in the NSR-10 standard. This inherent stiffness results in an overestimation of the amplification of seismic movements over long periods. Therefore, it is recommended to consider a type B response spectrum as a minimum to better reflect the actual seismic hazard. This normative reevaluation leads to anticipate a lower spectral acceleration for taller structures, which has significant implications on seismic design and thus on costs.

The present study also provides preliminary indications on the differentiation of seismic hazard in the Floridablanca area, laying the groundwork for future more detailed investigations in seismology and advanced geotechnical engineering. In addition, it provides valuable and verified data for the community.

**Table 6.** Modeling parameters in Plaxis.

| T | γ (kN/m3) | E50ref (kPa) | Eoderef (kPa) | Eurref (kPa) | Goref (kPa) | γ0.7 | φ (°) | c' (kPa) | m | pref (kPa) | ξ1 (%) | ξ2 (%) | f1 (Hz) | f2 (Hz) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 19 | 12000 | 12000 | 36000 | 250000 | 1.50E-04 | 35 | 15 | 0.5 | 100 | 1 | 1 | 1 | 10 |
| 2 | 19 | 10560 | 10560 | 31680 | 220000 | | | | | | | | | |

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