Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Determination of rock foundation levels for the expansion of the Cañaveral - Colombia shopping center, based on geophysical tests and their correlation with direct exploration.

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ABSTRACT

The Cañaveral shopping center is located on a low slope formed by recent alluvial deposits of low consistency, supported on sedimentary rock of the Girón formation, which is found at depths that change abruptly between one and twelve meters in short distances, influenced by the presence of a geological fault line and processes of erosion and weathering by subway water currents. Considering that the loads on the foundation are of great magnitude, it is necessary to build about 100 deep caisson foundations to reach the rock. However, performing a borehole on each one of them represented a very high cost and long execution times that would generate discomfort in the operation of the warehouse. Therefore, an alternative was proposed to determine the depth levels of the rock through different geophysical tests of seismic lines and electrical tomography and try to calibrate the results through the correlation of some boreholes. During the execution and data processing phase of the geophysical tests, difficulties were encountered due to the level of environmental noise and the obtaining of the wave records, given the variability of the rock levels and even the effect that in some sectors of the study area the rock is very sub-surface. In conclusion, it was possible to identify the strengths and weaknesses of each of the exploration methods and generate a 3D map of the depths of the rock levels that served as input for the design and budget of the foundations, which were verified by constant supervision during construction and thus be able to determine the error percentages, as well as to present recommendations for future works where it is intended to use this type of techniques.

Keywords: Geophysics; Geotechnical Exploration; MASW 2D, Refraction, Foundations, Rock.

1. Introduction

Since ancient times, the understanding of soil properties has been fundamental for the success of numerous construction and engineering projects. For this reason, throughout history, the characterization of the soil together with the determination of the stratigraphic profile has been a constant objective of study in the geotechnical field, and geophysics has emerged as an essential tool for this task since it allows the exploration of the soil in depth with little impact on the environment.

Usually when a geotechnical exploration is performed, the aim is to obtain as much information as possible. However, many times obtaining this information can be costly and even unfeasible as, for example, in the case of a large structure with high loads in each of its supports. Although it could be considered to borehole for each support, from the economic point of view it would be too costly, in addition to increasing the execution time of the works. These activities could even affect or disturb third parties due to the dust and noise generated by borehole, especially in urban environments. A similar case was presented in the Cañaveral shopping center, where the expansion of its facilities through the construction of a new module. However, the sector where the construction was planned was characterized by being in a highly urbanized area with a diversity of commercial premises.

The foundation soil was made up of recent alluvial deposits of low consistency, which could generate a great inconvenience in the future considering the high loads that shopping centers normally present, which is why it was required to lay foundations at a greater depth until reaching a competent rock stratum.

The moderately competent soil was normally found at a depth of more than 6.0 meters deep, so the use of a shallow foundation was unfeasible, so a deep foundation was proposed through the construction of caissons supported on the sedimentary rock of the Giron formation. However, because the sedimentary rock formations such as Giron and others, have different types of inclinations and folds due to tectonics, the thicknesses where the rock outcrops vary in depth, making it difficult to identify accurately by conventional direct exploration techniques such as borehole, therefore, it was decided to complement the results obtained with geophysical tests to determine the depth of the rock throughout the entire sector of interest generating the least possible impact.

2. Study area

The research had as area of interest a specific sector of the Cañaveral shopping center, which is located in the municipality of Floridablanca in the department of Santander-Colombia (see Figure 1). Regionally this area is in the limits of the geological regions of the Santander Massif and the tectonic depression of Bucaramanga, and therefore in the zone of influence of the Bucaramanga - Santa Marta fault system, the Suarez, and Rio de Oro Fault system. Its geographic location is very close to the Bucaramanga seismic nest, locating this area with seismic influence and possible development of natural phenomena related to events of this type. Deposits of alluvial-torrential and gravitational alluvium origin rest on these rock formations, mainly from the denudation of the altered materials that make up the Santander Massif, which are transported along the watercourses that originate in it.

This article focuses on the construction project of the foundation for the expansion of the Cañaveral shopping center, a sector characterized by being ecologically located in the tropical dry forest with transition to the pre-mountain humid cool. The thermal floor on which the municipality of Floridablanca is located is temperate with significant temperature variations, which range between 23.7ºC in the northern part of the terrace and 24.3ºC in the southern part closer to Girón. The average annual rainfall is 1220 mm. The area has a mostly flat topography.

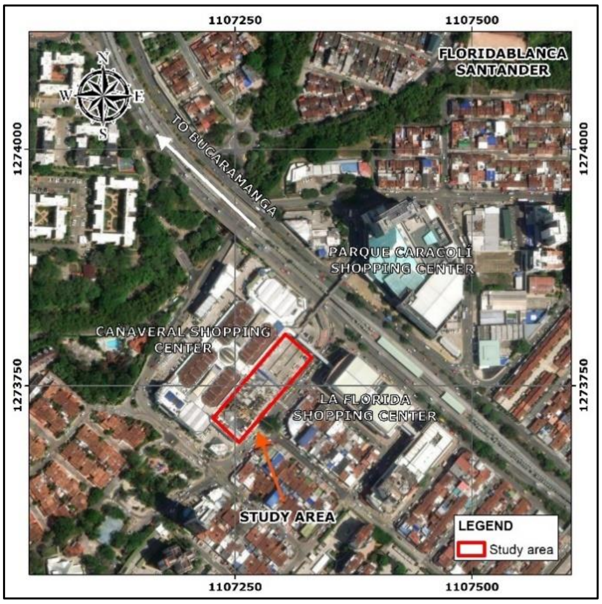

Figure 1. Cañaveral Shopping Center, Floridablanca, Santander-Colombia.

3. Theoretical framework

3.1. Seismic refraction

Refraction seismic is one of the most traditional surveying methods in geophysics. Its fundamental principle is based on the measurement of travel times of seismic waves generated by an impulsive source at (or near) the subsurface surface and refracted at interfaces between media (refractors) with different physical properties (i.e. acoustic impedances) (see Figure 2). The analysis of such travel times, under certain defined hypotheses and following the laws of wave propagation, allows in principle to obtain an in-depth profile of the geometrical distribution of the different refractors, with the corresponding velocities at which the seismic wave propagates through them (Redpath, 1973).

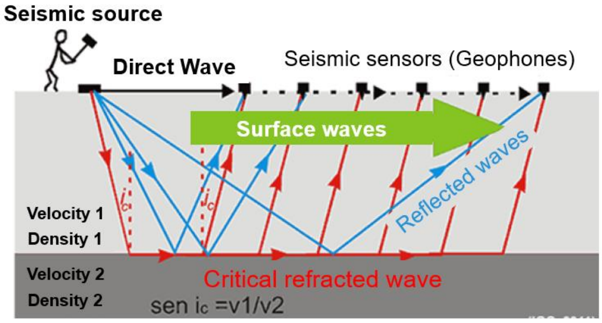

Figure 2. Diagram of waves generated by means of an active source.

It is important to note that one of the limitations of the seismic refraction method is its inability to model velocity inversions in the subsurface (intercalations of softer strata below harder strata), since the presence of such a feature negates the possibility of critical angle refraction (parallel to the interface between the two media), which is essential for the wave to be detected again at the surface (Redpath, 1973). Therefore, one of the conditions for the application of seismic refraction is that there is an increase in velocity with depth in the subsurface.

3.2. MASW surface wave testing

Surface waves are known as energy traveling along or near the earth's surface which decreases rapidly with depth. They are characterized by their relatively low velocity, low frequencies, and high amplitude. These waves are easily generated by active sources (hammer) and passive sources such as ambient noise, micro-earthquakes. Surface waves appear as vertical elliptical motions on the surface, where the direction of the waves varies from one side of the ellipse to the other.

The fundamental principle of surface wave analysis is based on the fact that Rayleigh waves travel at a speed independent of their wavelength in uniform and homogeneous soils. For example, for the same stratum the Rayleigh wave speed is 0.919 Vs, which could be assumed equal to speed Vs for practical purposes. For this reason, MASW analysis is a very frequently used technique to define the in-situ shear wave velocity.

3.3. Electrical Tomography Test

The electrical tomography or "Electrical Imaging" test is one of the most traditional geophysical prospecting methods (Arias, 2011). Its main principle is based on the measurement of currents and voltages generated by a current injection initially at the surface and subsequently into the ground. From a geometric factor generated by the array or device used, added to the measured current and voltage values, the apparent resistivity values at depth and laterally of the line can be established.

With the acquired measurements, a two-dimensional (2D) section is constructed to show a first approximation of the changes in the subsurface. Subsequently, an inversion algorithm is applied to obtain the real resistivity distribution or electrical image. This image will be an interpretable result from a physical and geological point of view, and will give information about the physical characteristics of the subsoil.

It is characterized by being a multi-electrodic resistivity technique, whose geometric arrangement varies depending on the object of study (see Figure 3).

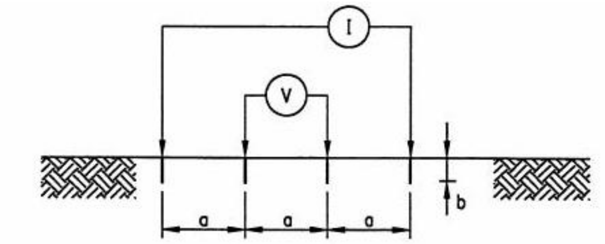

Figure 3. Typical assembly or Wenner-type electrostatic configuration taken from (EPM, 2008).

It is important to note that one of the limitations of the electrical method is the presence of highly resistive layers on the ground surface, which makes it impossible for the method to work properly, making it necessary to use other techniques, in this case electromagnetic ones, which do not require physical contact with the soil (Arias, 2011).

4. Site Analysis

As part of the research, reference information from the geotechnical study developed in 2021 (Geotecnología, 2021) was used, which contains a series of twelve boreholes with exploration depths between 10.0 and 15.0 meters using SPT equipment (see Figure 4), which allowed the extraction of samples and characterization of the terrain. In addition to the above, and as a complement, four seismic lines of refraction and MASW-2D together with an electrical tomography were carried out (see Figure 5). The different exploration methods allowed determining the geological-geotechnical profile, where it was mainly found that the soils of the sector corresponded to alluvial soil levels (Qab) of medium to low consistency, but at variable depths there is a fractured sandstone type rock level with low RQD and with certain intercalations of weathered rock.

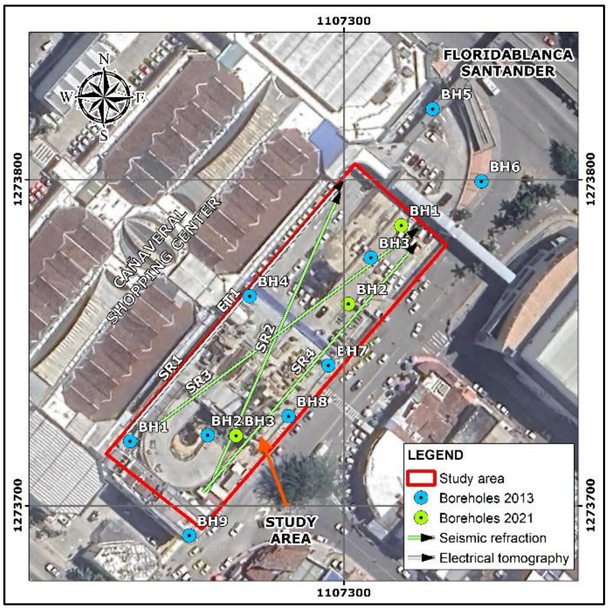

Figure 4. Direct and indirect geotechnical exploration carried out in the study area.

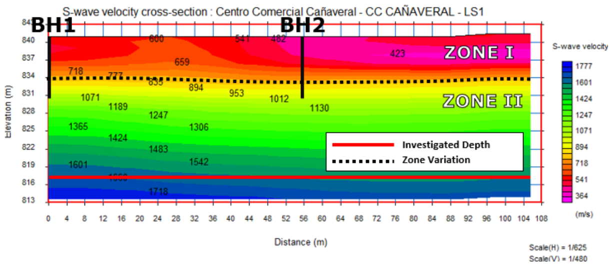

Figure 5. Example of results of geophysical tests performed to characterize the site.

Zone I presents shear wave velocities (Vs) between 364 m/s and 800 m/s and compressional wave velocities (Vp) between 773 and 1800 m/s; it is associated with soils composed of clayey sands, clays and sands with gravels with an approximate thickness of between 6.0 and 10.0 meters, as evidenced in borehole S4.

Zone II has shear (Vs) and compressional (Vp) wave velocities greater than 800 m/s and 1800 m/s respectively, of undetermined thickness and whose stiffness increases at depth. It is associated with rock fragments and sandstone cores of the Girón Formation (Jg), according to what was found in boreholes S1 and S4.

5. Analysis of the information

During the exploration it was found that the materials within the study area correspond to alluvial soils of Abanicos (Qab) composed of clayey sands of medium dense to dense consistency, under this stratum there are intercalations of residual soils composed of clayey sands and very soft sandy clays and rocky levels of the Girón Formation (Jg) associated with fragments of rock (crushed) and sandstone of the Girón Formation (Jg).

It is important to highlight that sedimentary rock formations such as Girón and others present different types of inclinations and folds that make the thicknesses where the rock outcrops vary in depth and are difficult to identify (see Figure 6).

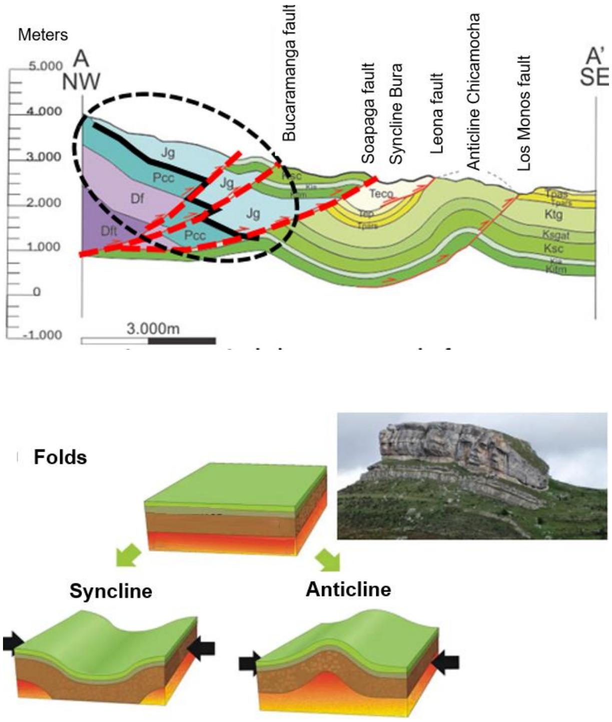

Figure 6. Example of faults or geologic fault lineaments.

On the other hand, this geological formation presents intercalations of softer rocks among other harder rocks, as shown in Figure 7 and as identified in borehole 2 (see Table **1**) where a sequence of loose soil - rock - "crushed" rock - residual soil was observed.

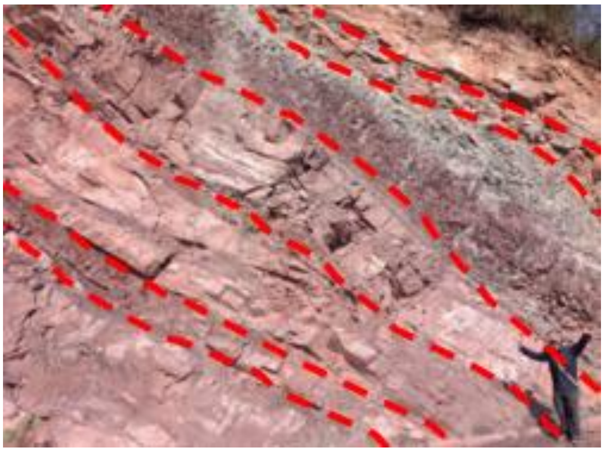

Figure 7. Example of intercalations evidenced in borehole 2.

Table 1. Registration of borehole 2.

Depth m	N	Description	S.U.C.S
0.0 to 5.5	3 to 33	RESIDUAL SOILS composed of clayey sands, non-coherent, medium consistency clayey sands, non-coherent, of medium dense consistency, medium dense, humid, somewhat permeable, without specific odor, reddish yellow, light brown and pinkish color. Girón Formation (Jg).	SC
5.5 to 8.5	RT	ROCK LEVELS of hard consistency, of color pale yellowish orange, very pale green and grayish yellow. grayish yellow. Girón Formation (Jg).	ROCK
8.5 to 10	8 to 37	CRUSHED LEVELS composed of clayey sands, with presence of semi-angular gravels, non-coherent, very dense coherent, of very dense consistency, saturated, somewhat permeable, no specific permeable, without specific odor, light gray, gray and light brown gray and light brownish gray. Girón Formation (Jg).	SC

In addition to the above, a fault line was identified in the electrical tomography (see Figure 8). This is consistent with the tectonic activity that originated the inclinations and folds in the rock. In addition, there are sectors with possible high fracture zones in the rock and with water accumulation.

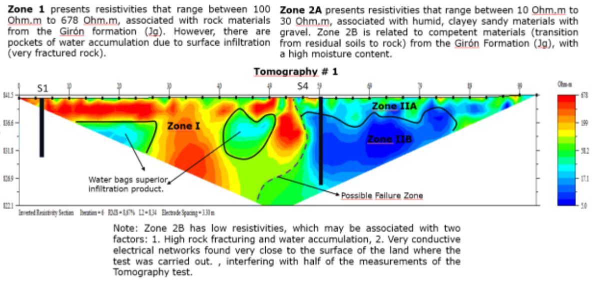

Figure 8. Electrical tomography performed where a possible failure zone and water accumulation can be observed.

The thicknesses of this vary in depth and are difficult to identify accurately, for this reason, geophysical tests consisting of 2D MASW and seismic refraction were used, where compressional wave velocities of 1830 m/s and shear wave velocities of 760 m/s were defined as reference values according to tables 2 and 3 respectively for the sandstone type rock found in the sector.

Table 2. Range of compressional wave velocities in soil and rock taken from (ASTM, 2000).

Natural soil and rock	Velocity (ft/s)	Velocity (m/s)
Weathered surface material	800 to 2000	240 to 610
Gravel or Dry sand	1500 to 3000	460 to 915
Sand (saturated)	4000 to 6000	1220 to 1830
Clay (Saturated)	3000 to 9000	915 to 2750
Water	4700 to 5000	1430 to 1665
Sea Water	4800 to 5000	1460 to 1525
Sandstone	6000 to 13000	1830 to 3960
Shale	9000 to 14000	2750 to 4270
Chalk	6000 to 13000	1830 to 3960
Limestone	7000 to 20000	2134 to 6100
Granite	15000 to 19000	4575 to 5800
Metamorphic rock	10000 to 23000	3050 to 7000

Table 3. Classification according to the range of shear wave velocities in soil and rock taken from (AIS, 2010).

Soil Types	Rock/Soil Description	Average shear wave velocity (V_{s30}) m/s
A	Hard rock	> 1500
B	Rock	760 – 1500
C	Dense soil/soft rock	360 – 760
D	Stiff soil	180 – 360
E	Soft soil	< 180
F	Special soils requiring special evaluation	-

Based on the determined values, a 3D model of the study area was made (see Figure 9Figure 10), which was calibrated through direct exploration and available geophysical tests, resulting in the following rock depth zonation map according to the results of both the 2D MASW test and the refraction test, where shear and compressional wave velocity values were obtained, respectively.

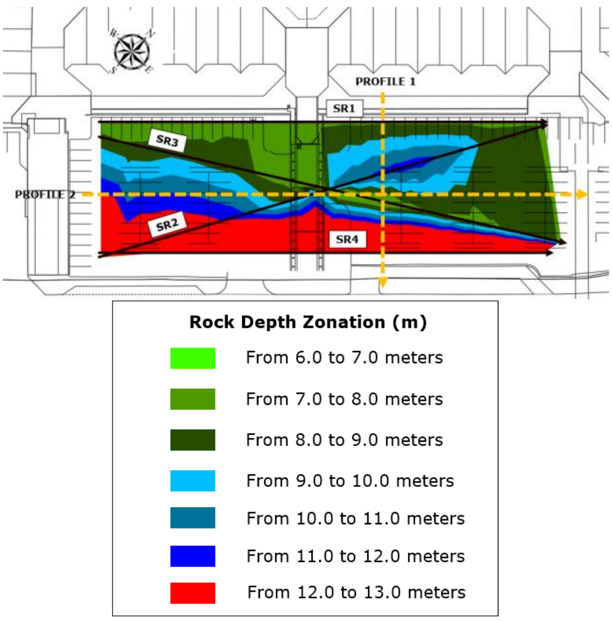

Figure 9. Rock depth zonation according to the test of MASW-2D.

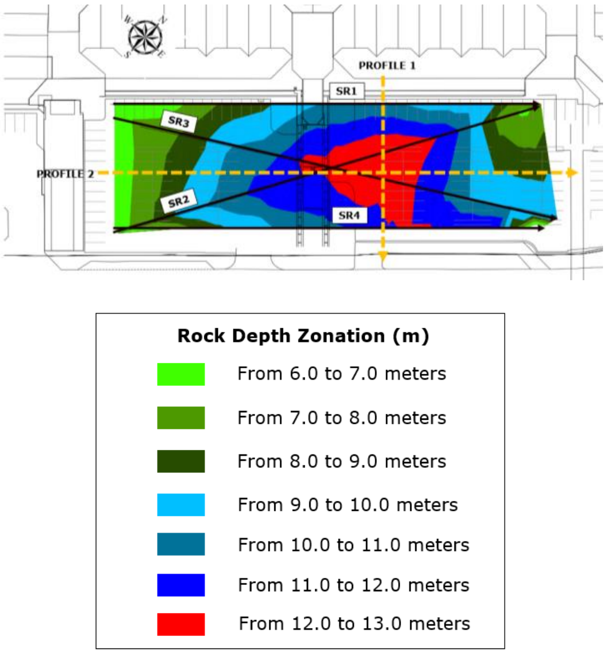

Figure 10. Rock depth zonation according to seismic refraction test.

These values were then compared with the rock depths actually found in the field during the excavation phase of the mall's caissons. It should be noted that during the extraction of the material, an alluvial soil composed mainly of clayey sands and sandy clays with the presence of boulders was identified superficially, and a classification of three types of rock was made according to their resistance (see Figure 11).

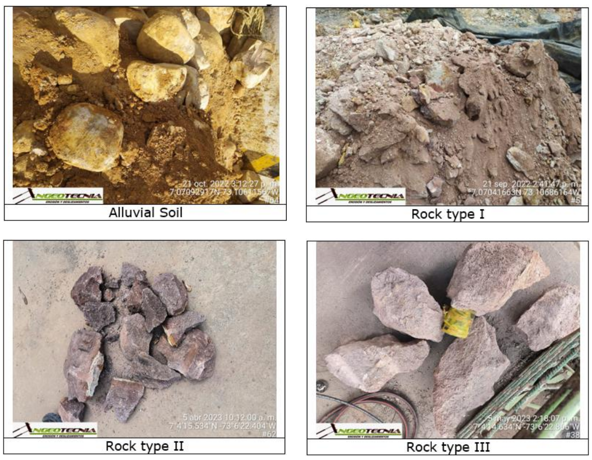

Figure 11. Typology of soils and rocks found in the caisson excavations.

The rock material was classified into three main categories:

- Rock Type I: Soft rock, broken by hand. Not suitable for high load foundations.
- Rock Type II: It is not broken by hand, but it can be broken by impact with the ground or other rocks. Not suitable for high load foundations.
- Rock Type III: Very hard rock, suitable for high loads, it does not break when hit with soil or other rocks and even less with the hand. Suitable for foundations with high loads.

Below is a comparative table showing the differences found in the depth of the rock using the wave speeds Vs and Vp with respect to the rock depth values reported in the field. Note: Figure 12 shows the nomenclature for each of the caissons referenced in Table 4.

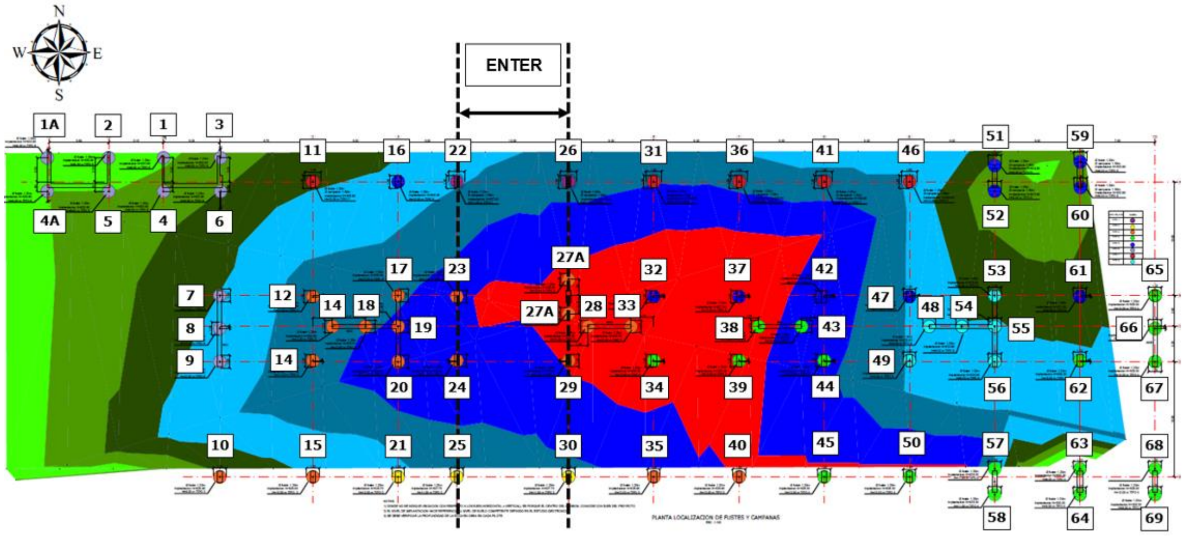

Figure 12. Nomenclature of the caissons executed in the field.

Table 4. Comparison between geophysically finished rock depth and field determined rock depth.

#	Estimated level Vs (m)	Estimated level Vp (m)	Field rock level (m)	Error Vs	Error Vp
1	7.0	6.0	4.1	71%	46%
1A	7.0	6.0	4.1	71%	46%
2	7.0	6.0	4.3	63%	40%
3	7.0	6.0	4.9	43%	22%
4	7.0	6.0	3.8	84%	58%
4A	7.0	6.0	4.1	71%	46%
5	7.0	6.0	3.8	84%	58%
6	7.0	9.0	4.6	52%	96%
7	10.0	9.0	5.9	69%	53%
8	10.0	9.0	5.6	79%	61%
9	11.0	9.0	7.5	47%	20%
10	12.0	8.0	8.0	50%	0%
11	7.0	8.0	4.7	49%	70%
12	9.0	10.0	7.0	29%	43%
13	10.0	10.0	8.3	20%	20%
14	11.0	10.0	10.0	10%	0%
15	12.0	9.0	10.1	19%	11%
16	7.0	9.0	5.1	37%	76%
17	8.0	10.0	10.5	24%	5%
18	9.0	10.0	10.1	11%	1%
19	9.0	11.0	8.5	6%	29%
20	10.0	11.0	9.1	10%	21%
21	12.0	9.0	8.0	50%	13%
22	7.0	9.0	9.6	27%	6%
23	7.0	11.0	9.3	25%	18%
24	10.0	11.0	9.6	4%	15%
25	12.0	10.0	8.0	50%	25%
26	8.0	10.0	6.4	25%	56%
27A	9.0	12.0	9.7	7%	24%
27B	8.0	12.0	9.5	16%	26%
28	7.0	12.0	9.6	27%	25%
29	10.0	12.0	9.2	9%	30%
30	12.0	10.0	8.1	48%	23%
31	8.0	10.0	7.5	7%	33%
32	9.0	12.0	9.5	5%	26%
33	6.0	12.0	10.1	41%	19%
34	9.0	12.0	9.5	5%	26%
35	12.0	11.0	9.4	28%	17%
36	9.0	10.0	8.0	13%	25%
37	9.0	12.0	7.7	17%	56%
38	8.0	12.0	7.7	4%	56%
39	7.0	12.0	7.2	3%	67%
40	12.0	12.0	8.7	38%	38%
41	9.0	10.0	7.0	29%	43%
42	9.0	11.0	7.0	29%	57%
43	8.0	11.0	7.1	13%	55%
44	8.0	11.0	7.1	13%	55%
45	12.0	12.0	8.3	45%	45%
46	8.0	9.0	7.2	11%	25%
47	8.0	9.0	6.7	19%	34%
48	8.0	9.0	6.7	19%	34%
49	7.0	9.0	7.0	0%	29%
50	12.0	12.0	7.8	54%	54%
51	8.0	7.0	7.2	11%	3%
52	8.0	7.0	7.0	14%	0%
53	8.0	8.0	7.1	13%	13%
54	8.0	9.0	7.1	13%	27%
55	8.0	9.0	7.0	14%	29%
56	8.0	9.0	7.0	14%	29%
57	12.0	11.0	11.0	9%	0%
58	12.0	11.0	9.6	25%	15%
59	7.0	7.0	7.1	1%	1%
60	7.0	7.0	7.0	0%	0%
61	8.0	8.0	6.5	23%	23%
62	8.0	9.0	7.9	1%	14%
63	12.0	11.0	10.8	11%	2%
64	12.0	11.0	11.2	7%	2%
65	7.0	8.0	9.6	27%	17%
66	7.0	9.0	9.6	27%	6%
67	7.0	9.0	11.8	41%	24%
68	12.0	10.0	12.0	0%	17%
69	12.0	10.0	12.0	0%	17%

According to the above, it was found that the reported field depths adjust on average with an error percentage between 27 and 29%. It is possible that these errors are due to the large amount of interferences presented in the study area mainly related to environmental noise and the presence of surface moisture in some sectors at the time of the execution of the tests. Although these tests were conducted at night, the sector where the shopping center is located is characterized by being surrounded by busy avenues even at night, so the noise and vibrations of vehicles could have altered in some way the data collection. The stratigraphic profiles determined are presented below (see Figure 13 and Figure *14*).

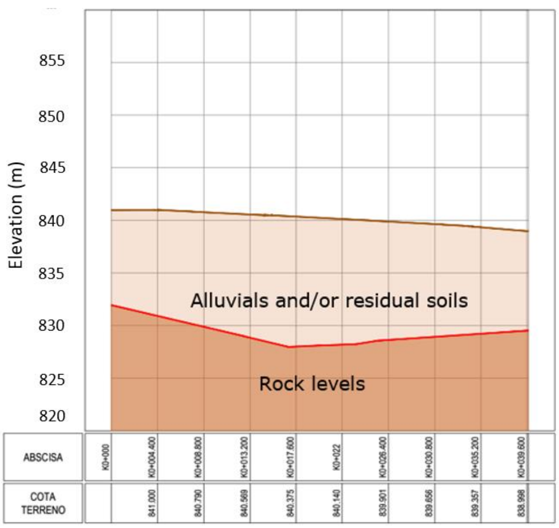

Figure 13. Profile 1 - Depth zoning of the different soil and rock layers.

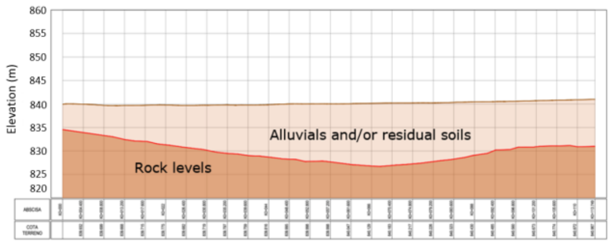

Figure 14. Profile 2 - Depth zoning of the different soil and rock layers.

During the execution of the excavations for the caissons, a complementary study was carried out for another new expansion of the shopping center, this time in the north zone, but taking into account the lags presented in the previous zone (south), possibly due to errors accumulated as old boreholes and whose real location in plan was difficult to determine, which is why some of these boreholes did not coincide with the result of the geophysics. In addition, the use of relatively long seismic lines with a wide separation between geophones generated zones with little information that in an environment with such abrupt variations in the depth of the rock could have induced not so reliable predictions. For this northern zone, it was decided to carry out a new exploration, consisting of four boreholes with exploration depths between 8.0 and 14.5 meters using SPT equipment, which allowed the extraction of samples and characterization of the terrain (see Figure 15). In addition to the above, four seismic lines of refraction and MASW-2D together with an electrical tomography were also carried out.

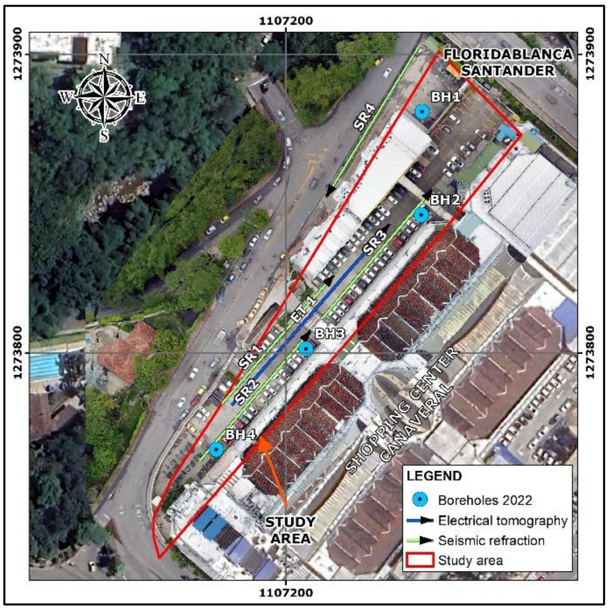

Figure 15. Direct and indirect geotechnical exploration carried out in the northern area.

For this new case, at the time of making the comparison between the borehole and the geophysics, a greater degree of adjustment was found. In this case, both the seismic lines and the borehole were tied and referenced with the existing topography (see Figure 16 and Figure *17*). In addition, the seismic line was shorter with separations between geophones of 2.5 meters and not with the 4.4 meters used in the south zone, it could also influence that in this zone the level of environmental noise (vehicles) was considerably lower compared to the south zone.

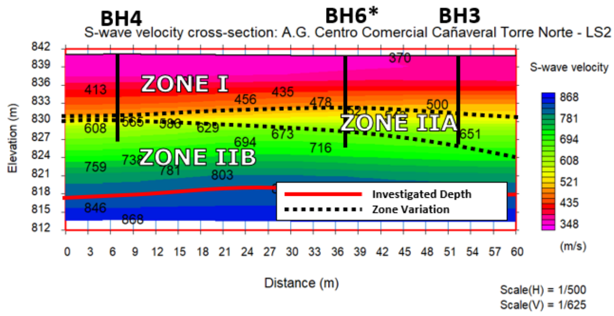

Figure 16. 2D MASW test performed in the northern area for the LS2 seismic line.

Zone I has shear wave velocities (Vs) between 348 and 521 m/s and compressional wave velocities (Vp) between 534 and 1012 m/s; it is associated with soils composed mainly of clayey sands and fragments of sandstone pebbles and blocks with an approximate thickness of between 9.5 and 10.0 meters. Evidenced in boreholes 3 and 4.

Zone IIA has shear wave velocities (Vs) between 521 and 716 m/s and compressional (Vp) between 1012 and 1600 m/s, whose stiffness increases at depth. It is associated with conglomeratic and fine- to medium-grained sandstone levels of the Girón Formation (Jg) with an approximate thickness between 1.5 and 6.0 meters and with an RQD between 7 and 15%.

Zone IIB has shear wave velocities (Vs) greater than 716 m/s and compressional (Vp) greater than 1600 m/s, of undetermined thickness and whose stiffness increases at depth. It is associated with levels of conglomeratic and fine- to medium-grained sandstones of the Girón Formation (Jg) with RQD values greater than 75%.

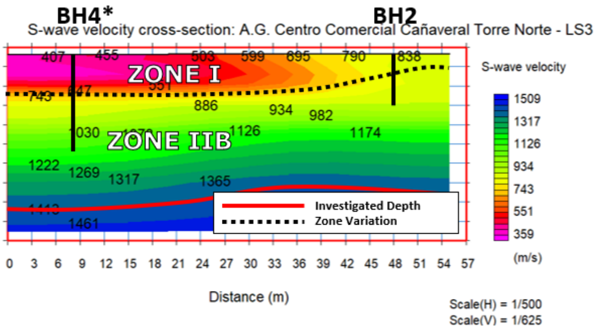

Figure 17. 2D MASW test performed in the northern area for the LS3 seismic line.

Zone I presents shear wave velocities (Vs) between 359 and 647 m/s and compressional wave velocities (Vp) between 386 and 1600 m/s; it is associated with soils composed mainly of clayey sands and fragments of sandstone pebbles and blocks with an approximate thickness of between 2.0 and 6.0 meters. Evidenced in the boreholes 2 and 4 carried out by Ingeotecnia and Geotecnología respectively.

Zone IIB has shear wave velocities (Vs) greater than 647 m/s and compressional (Vp) greater than 1600 m/s, of undetermined thickness and whose stiffness increases at depth. It is associated with levels of conglomeratic and fine- to medium-grained sandstones of the Girón Formation (Jg) with RQD values greater than 75%.

The following is the borehole log of borehole 3, showing the agreement with the 2D MASW test (see Figure 16), which shows the contact with the rock at around 9.5 meters.

Table 5. Registration of borehole 3.

Depth m	N	Description	S.U.C.S
0.0 to 9.5	RT	ALLUVIAL SOILS Alluvial soils composed of fragments of very resistant meta-sandstone cobbles, with high mica content, yellowish gray color within a very dense orange-yellow sandy-clay matrix. (Qab) Fans.reddish yellow, light brown and pinkish. Girón Formation (Jg).	-
9.5 to 14.5	RT	ROCK LEVELS of fine to medium grained sandstones, very resistant, beige, gray, reddish brown, reddish brown clayey-loamy residual soils are evidenced. RQD=7% (Jg) Girón Formation.	ROCk

The following is the zoning performed to determine the depth of the rock (see Figure 18).

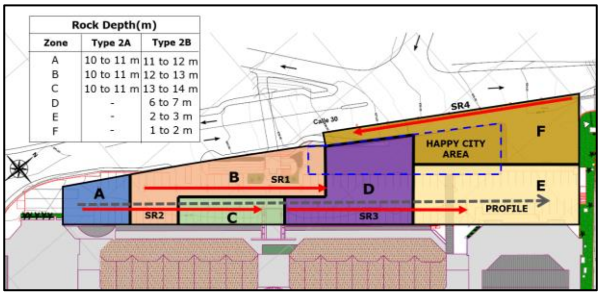

Figure 18. Rock depth zoning for the expansion of the northern part of the commercial center.

It is expected to find a better adjustment in the rock depths, taking into account the realization of short simian lines and specifying the location of the boreholes with topography, however, it will be necessary to wait until the excavation activities are executed.

6. Conclusions and discussion

An approximation of the rock levels present in the expansion area of the Cañaveral shopping center was determined, where, in addition, the presence of alluvial soils composed of clayey sands of medium dense to dense consistency with the presence of boulders was found, under this material residual soils composed of clayey sands and sandy clays were reported. Finally, at depth there is a level associated with rock fragments (crushed) and sandstone of the Girón Formation (Jg). Taking into account the need to lay foundations on the rocky level due to the high loads projected for the building, models and integration of the available "Big Data" information were carried out to generate a 3D map of the depths of the rock levels, which served as input for the design and budget of the foundations, These were verified through constant supervision during construction, where it was possible to determine error percentages of 29% and 27% for the maps generated by the direct exploration complement and the seismic refraction test and the direct exploration complement and the MASW-2D test, respectively. Although this variation does not seem to be considerable between both Vs and Vp models, it is important to highlight that there was a better fit in some areas with Vs and in other areas with Vp, possibly due to greater accumulations of humidity in certain sectors affecting the measurements, especially in the seismic refraction test.

During the execution of the project, it was possible to evidence the presence of intercalations between softer and harder rocks as evidenced in the boreholes carried out. In addition, this confirmed the disposition of the rock in the sector as a rock with inclinations and folds which make it difficult to identify the depths of the rock for the foundation. The geophysics allowed a better estimation of these depths and even determined an existing fault line in the site which is consistent with the variability of the rock levels found.

The discrepancies found with respect to the real values reported in the field may be due to different factors, among which is mainly the level of noise found in the sector at the time of carrying out the tests. In addition to the above, we have the presence of intercalations of soft rocks to hard rocks and vice versa. A clear example of this was the report from borehole 2 where a sequence of loose soil - rock - "crushed" rock - residual soil and again rock was observed. Another important factor to take into account was the high variability of the rock with abrupt changes in its depths, which by using a relatively high separation between geophones (4.4 m) could leave considerable sections without information in which the information missing was interpolated by discarding some natural ridges and folds in the rock (see Figure 19). Furthermore, the presence of high humidity in the terrain evidenced in the electrical tomography performed could interfere with data collection by reducing the resistivity values.

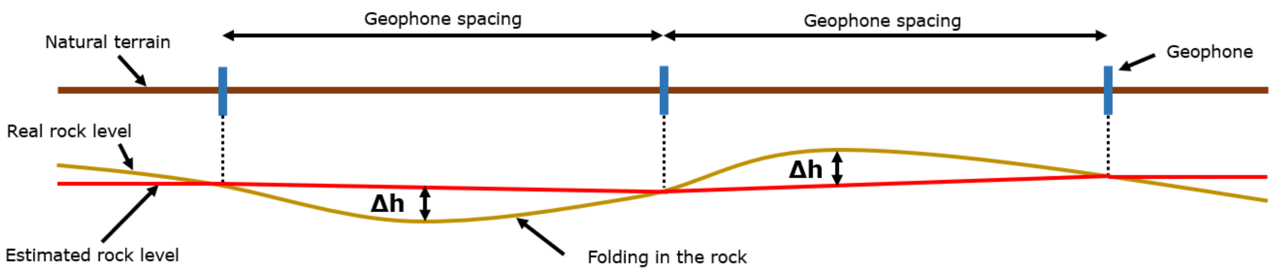

Figure 19. Variability in rock levels vs geophone spacing.

In future projects where these techniques are applied to determine the depth of rock levels, it is recommended to use short seismic lines with geophone separations of less than 2.5 meters, in order to reduce uncertainty in sites where rock folds and inclinations occur. In addition, it is also recommended to carry out the tests at a time when the least amount of environmental noise is present since this can considerably affect the results. It is not recommended to apply these methods in industrial or process areas that contain high levels of vibrations and external noise. In addition, it is important to highlight the need to tie the exploration that is carried out to a topographic survey, in order to ensure that the location of all the tests is correct and that at the time of generating the 2D models, they are better adjusted to the real conditions of the area.

Finally, as a complement to this article, the recommendations raised above were applied in a new exploration for the second phase of expansion of the shopping center, located on the north side. It is expected to find a better adjustment in the rock depths, considering the creation of short seismic lines and specifying the location of the surveys with topography. However, one must wait for the excavation activities to be carried out.

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