Foundations and basements construction of a shopping mall on the soft soils of Bogotá – PAPER #849 PanAm-CGS 2011

Luis F. Orozco, MSc &, Marcela Salcedo, MSc
LFO Ingenieros de Suelos, Bogotá,DC, Colombia

2011 Pan-Am CGS
Geotechnical Conference

ABSTRACT
The lacustrine soft soils of Bogotá imply great geotechnical challenges for the foundations of tall buildings as well as for the excavations of more than two underground levels. This paper presents the foundations and excavation system of a large shopping mall with three basements and four stories high. The TITAN Commercial Center is being constructed at the intersection of Calle 80 and Avenida Boyacá, north east corner. There is a description of the geotechnical characteristics of the highly plastic soft clays. There is also a description of the mat and pile foundation and construction systems, which include open pit excavation to 4.5 m depth, then the construction of piles, retaining walls, belt and strut slabs, and then open pit excavation to 9m depth in stages. Also the excavation to 11.5 m under the structure is described. The paper includes conclusions and instrumentation results.

RESUMEN
Los suelos blandos del depósito lacustre de la sabana de Bogotá implican grandes retos geotécnicos, tanto para la cimentación de edificios de gran altura como para la ejecución de más de dos sótanos. En este artículo se presenta la cimentación y sistema de excavación de un centro comercial de grandes dimensiones con tres sótanos y cuatro pisos de altura que se encuentra localizado en la esquina nor-oriental del cruce de la Calle 80 con Avenida Boyacá, en la ciudad de Bogotá. Aparecen aquí las características de los suelos arcillosos muy blandos y de alta plasticidad, se describe la cimentación con placa y pilotes y el sistema de construcción que incluye una primera excavación a 4.5 m de profundidad, muros de contención tipo pantalla y pilotes, placas puntal y placas cinturón y luego la excavación por etapas a cielo abierto hasta 9 m de profundidad y también se presenta la excavación de 9 a 11.5 m bajo la estructura. Se incluyen igualmente los resultados de instrumentación y las conclusiones respectivas.

1. INTRODUCTION

Bogota's soft soils imply very important geotechnical challenges. It is a quaternary lacustrine clay deposit over 200 m thick, formed by highly plastic soft clays with a low over-consolidation ratio. The foundation of buildings, with 2 to 5 underground levels, usually includes a mat foundation to avoid bottom failure and support water pressures, as well as piles needed to carry a substantial portion of the load, work in tension for low weight portions of the building and support the loads during construction with an up-down construction method.

This paper deals with the problems, due to the very soft soils, for the construction of a large shopping mall (230 x 130 m) with three underground levels and in most of the area only three to four stories above ground level. The TITAN Commercial Center is being constructed at the intersection of Calle 80 and Avenida Boyacá, north east corner. The description of the geotechnical properties to a depth of 50 m is presented, followed by the account of the foundation and construction methods.

The foundation includes a mat foundation supporting an upward pressure of 6 T/m² or 59 KPa (bottom failure as well as water pressures) and cast in place friction piles with a length of 23-28 m. The construction method includes first a large excavation to 4.5 m depth, covering the foot print area, then the construction of piles and slurry walls. The piles are constructed to -11.5 m elevation (foundation grade level), except for those necessary to support peripheral wale slabs and two slabs as struts across the area, all of which work to support the large horizontal pressures on the retaining walls.

The excavation proceeds as an open pit in the three central areas to a depth of 9.0 m. From this depth the construction includes caissons to reach the head of the piles, columns and the upper structure, as well as the excavation under the structure to 11.5 m depth (up-down construction).

There is a description of the geotechnical instrumentation program; which is a priority in this type of job. Also there is a description of some of the problems that had to be solved during excavation. Among the main conclusions are the importance to build to be able to excavate, or load to unload, and the need for careful planning of each stage of excavation. Also important are detailed geotechnical instrumentation and a close relation with the soils engineers as the construction of underground structure proceeds.

2. SOIL PROFILE

At the site the soft highly plastic clays of the Sabana Formation go down to a depth of at least 200 m, and there are no inter-bedded layers of sand above 80 m depth. The micro-zoning map for the city published in 2010 by DPAE (Dirección para Prevención y Atención de Emergencias, of the Secretary of Government Office of Bogotá) shows the depth of the deposit and defines the seismic acceleration spectra for the structural design. Figure 2.1 shows the map and figure 2.2 shows the average soil profile as assumed for the soils and foundations report and designs.

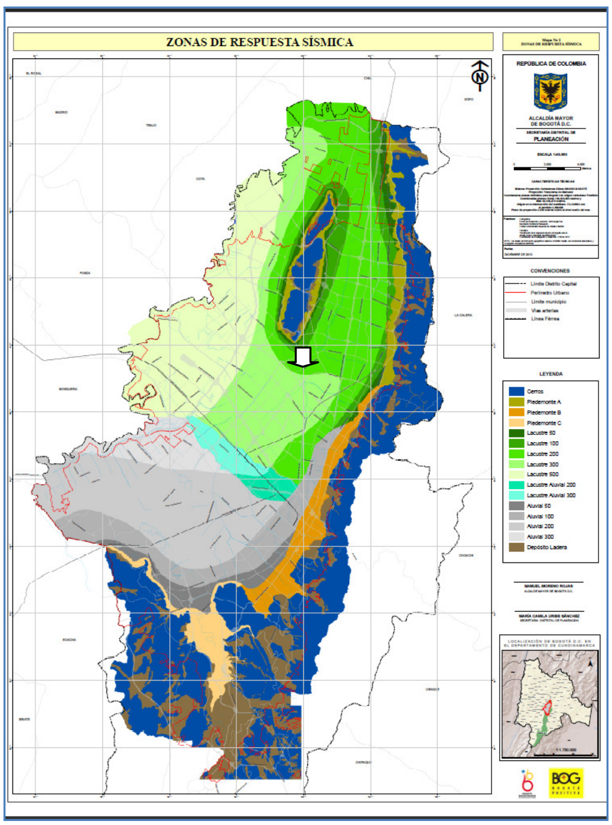


Figure 2.1 Micro-zoning map for Bogotá published in 2010 by DPAE (1)

The profile includes man-made fills with a varying thickness of 1 to 3 m. These are followed by brown silty clays and highly plastic gray clays, 2 to 3 m thick, which form a crust of over-consolidated materials due to cycles of drying and wetting during the age of the deposit.

Bellow the crust, the soft, highly plastic gray clay and clayey silt is found to very large depths. It is also known as the Bogotá Clay which belongs to the Sabana Formation. This clay deposit acquired its normal consolidation as it was being formed due to the low rate of sedimentation, around 0.2 mm per year as established by studies of the age of the deposit from pollen samples(2). It also became slightly over-consolidated due to secondary consolidation or creep over the last 200,000 years, estimated time of sedimentation for the upper 40m. Its over-consolidation ratio, as established by very careful odometer tests performed, is between 1.1 and 1.3.

Figure 2.2aAverage resistance parameters and shear velocity for mean boring (3)

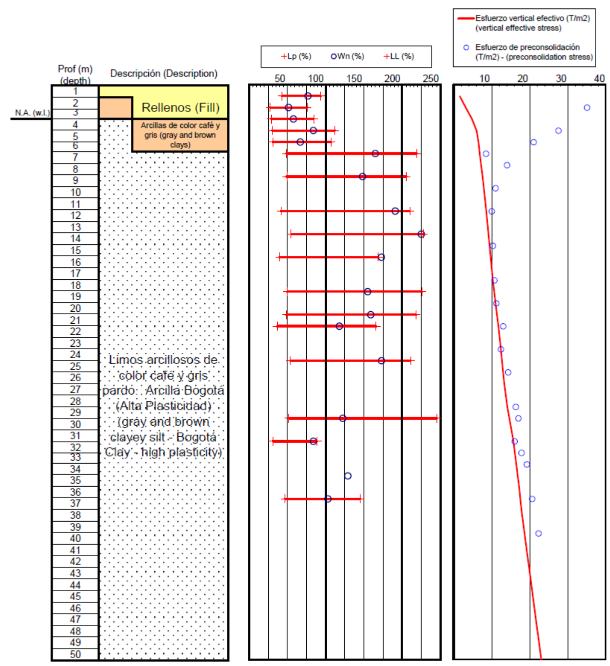
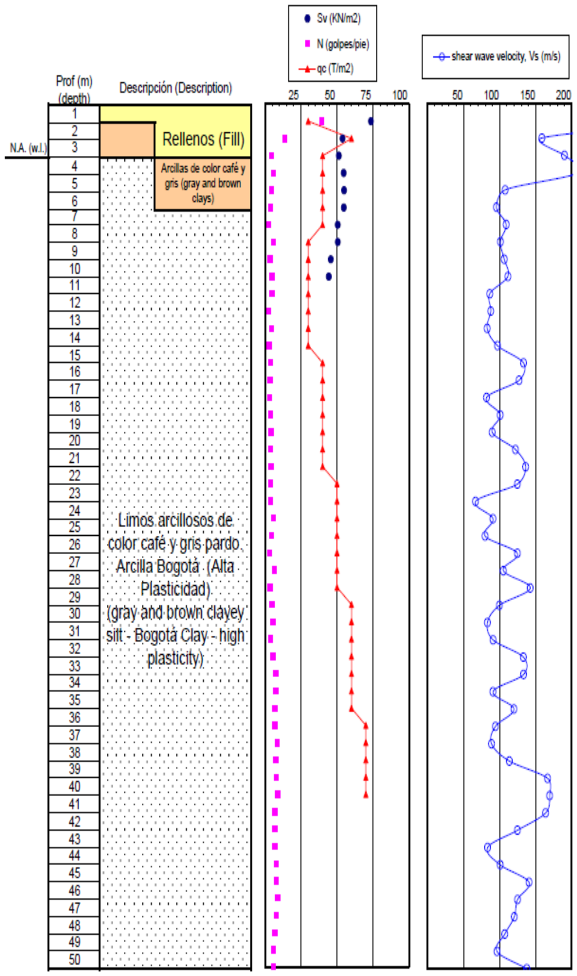


Figure 2.2b Average Atterberg limits and vertical stress – Mean boring (3)



The most important index and mechanical properties in the upper 50m are:

Table 2.1.Characteristics of Tested Soils (3).

Depth. (m)	Y (T/m³)	e	qu (T/m²)	Cc	Cr	Cs
5 – 10	1.30–1.40	4.5	0.21–0.35	2	0.44	0.31
10 – 20	1.25-1.35	5.3–3.4	0.19–0.51	2.29–1.72	0.79–0.20	0.32
20 – 30	1.38–1.54	3.4–2.1	0.40–0.50	1.72	0.20	0.27
30 - 40	1.56	2.1	0.40–0.70	1.1	0.07	0.20

- $C_v \approx 1 \times 10^{-4}$ cm/sec 10 to 30 m depth
- Depth of static water table – 3 to - 6 m.

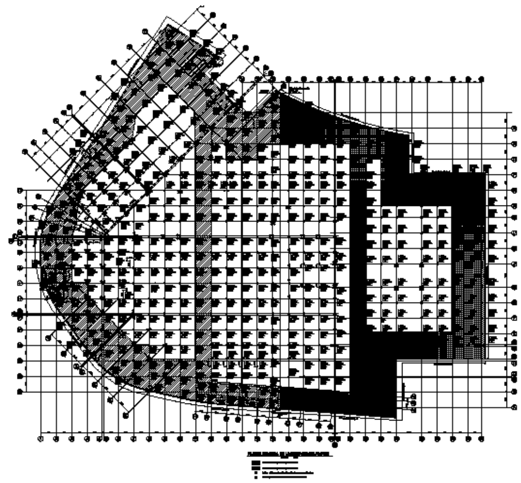
3. SHOPPING MALL AND OFFICE BUILDING PROJECT

Fig 3.1 Mall panoramic, Scale model (Tamayo Montilla Arquitectos)

The TITAN Commercial Center is being constructed at the intersection of Calle 80 and Avenida Boyacá, north east corner.

The shopping mall, with two basements and first floor partially underground plus three stories, covers an area of 30,000 m^2 (300,000 ft^2) of irregular shape, with a largest dimension of 230m and an average width of 130m, figures 3.2a and 3.2b plan view and section. The peripheral ground level (street sidewalks),as well as the ground level within the site, vary within elevations 2551.5 m above sea level and 2547.7 m. The second basement has two floor levels at elevations 2540.3 on the southeast half of the footprint area and 2539.0m on the northwest half. These levels imply that the height of excavation, including a 0.20 m high foundation mat and 0.3 m gravel bed, vary between 11.7 m and 9.1 m. Towards the southwest, covering a footprint area of 2500 m2 (25000 ft2), the project includes an eight stories high building above the commercial floors.

The typical vertical static loads for columns on a regular grid of 8.0 by 8.0 m are 416 metric tons (4080 KN). The highest static load under the taller office building goes up to 900 tons (8820 KN). These loads correspond to a distributed load of 6.5 T/m2 (63.7KPa) in the commercial area, which goes up 10.1 T/m^2 (99KPa) in certain areas. There is also a higher distributed load for the office building with a value of 14 T/m^2 (137KPa).



Figures 3.2a plan view showing belt and strut slabs (4)

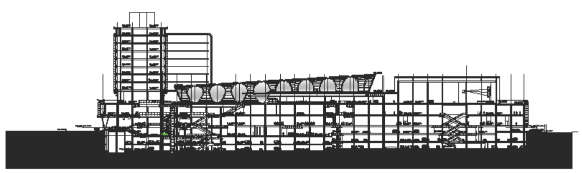


Figure 3.2b west-east section (4)

4. GEOTECHNICAL CHALLENGES

The main geotechnical challenges include: the foundation, its proper functioning during excavations and partial loading as well as in the long run; the excavation program, to around 11.4m depth, of a large area in the very soft soils; large earth pressures to be supported as excavation proceeds; and large hydrostatic pressures on the walls as well as on the bottom of the excavation. In addition, besides being cost efficient, the excavation and construction procedures had to meet tight schedules for a 250,000m^2 (2.5x10^6 ft^2) construction area, 2 years, considering that around 90,000m^2 had to be built underground, with very difficult conditions.

The excavation to an average depth of 11.7m of saturated clay soils, and some man-made fills, with an average unit weight of 1.45 T/m^3 (14.2KN/m^3) means an effective pressure relief of 17.1 T/m^2 (167.5KPa), or around 510,000 tons, 5x10^6 KN (of soil to be removed. The largest part of the building weighs between 6.0 and 7.0 T/m^2 (59 to 68KPa) which means that the soil swells elastically as it is being excavated and plastically in the long run, as the pore pressures tend to recuperate. This fact differentiates the project from those of office buildings with three to five underground floors and more than sixteen stories above ground, which our group described in a paper for the Geo-frontiers conference in Dallas, earlier this year (5).

Figure 4.1 Aerial view from the east showing belt and strut slabs at first floor level.

5. SOLUTIONS – FOUNDATION AND CONSTRUCTION

The foundation is a combined system of long friction or floating piles and a mat covering the footprint area of the project, this is the area of the second basement. The retaining walls, which complement the system, were built as slurry walls from -4.5m bellow the ground original level to a depth of 20m to 21 m., around 9 m bellow the depth of excavation, for vertical support of its own weight. The piles were designed with lengths between 23 m. and 27 m. for the commercial areas and close to 38m for the area with the office building (figure 5.1 schematic section of the foundation). It should be noted that the architects and structural engineers divided the building into six separate structures, with different weights or to avoid very long slabs, separated of course by construction joints.

The combination of a mat and piles is needed in this type of soil to facilitate construction and to avoid large differential settlement values. The construction procedure called for an initial excavation, covering the project area, with no retaining walls and 45^o sloping sides, to a depth of 4.5 m. It was excavated to allow elastic unrestricted heave of the soil mass. It may be noted that this is a pressure relief of 6.7 T/m^2 (66KPa) or around 39% of the total pressure relief. The initial heave is beneficial since it does not affect the piles, and reduces future elastic expansion which might affect the structure. The amount of elastic heave was not measured at this stage with the projected extensometers to avoid interference with the massive excavation procedure.

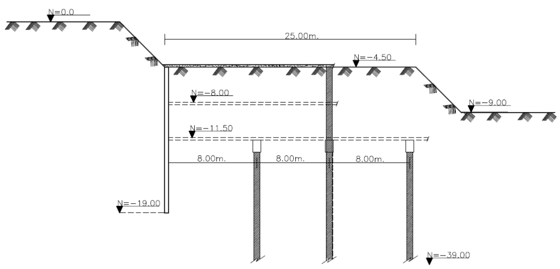


Figure 5.1 Schematic section of the foundation and open pit excavation to -9.0 m

From this depth the piles and walls were constructed to partially reinforce the soil and minimize additional heave as well as to have the support needed for the columns since the construction of the structure was advanced before conclusion of the excavation to -11.5m and construction of the mat.

Piles were designed to support a theoretical value equal to 50% of the load of the column, with a bearing capacity factor of safety of two and reinforced according to the building code so they were also able to support substantial tension loads. Friction pile capacities were designed according to the beta method (7) (figure 5.2) and checked with values obtained from the Dutch cone penetrometer, but were later adjusted upwards, a small percentage, based on a load test of a pile ϕ 60 cm with its tip at a depth of 45 m which had been isolated in the upper 7.5 m to simulate the future excavation for the underground floors. It resulted in failure at 305 tons.

Table 5.1 Pile Bearing Capacities in Compression. Tons

		DIAMETER (m)		
Z (m)	L(m)	0,6	0,7	0,8
36	24	93	108	123
37	25	98	114	129
38	26	103	120	136
39	27	108	125	143
40	28	113	131	149
49	37	164	190	216
50	38	170	197	225

Figure 5.2 Load Test (8)

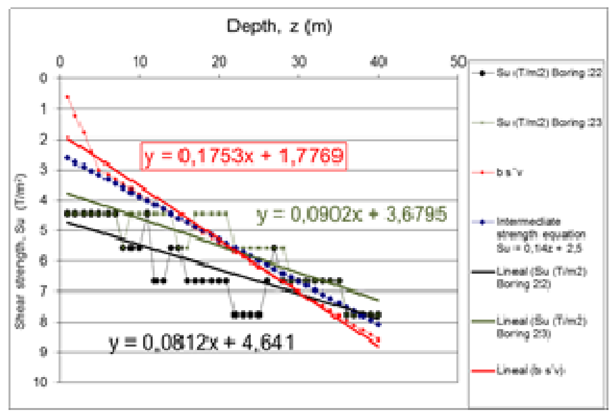


Figure 5.3 shear resistance (Friction pile capacities were designed according to the beta method). (3)

The complementary mat foundation was designed to support 6.0 T/m^2 (59KPa) of the weight of the building, which is almost its total weight in the commercial area, and it was designed also to support 7.6 t/m^2 (74KPa)of the total weight in the footprint area of the office building. The mat works to distribute the load evenly, for each of the six separate structures. It is needed to avoid bottom failure due to the weight of the soil around the building as well as to support a pore pressure of 6.0 T/m^2 (59KPa) which will develop at foundation level with time after construction is finished. This also means that the water table will be lowered at the site from a depth of 5.0 m or somewhat lower, according to vibrating wire piezometer levels at the beginning of construction, to a depth around 6.0 m. (Fig 5.4)

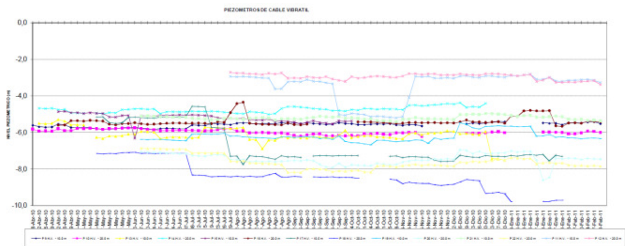


Figure 5.4 Pore pressures around the site according to vibrating wire piezometers (10)

After piles and walls had been built, the belt (wale)and strut slabs, as shown in figure 3.2a were constructed at a level coincident with the first floor or semi- basement level, this is at -3.1 m and -4.4 m (-3.7 and – 5.0 grade level). These slabs are supported vertically by the slurry walls and by construction piles; which are piles built to support the belts and struts only during construction, and might become part of a column at a later stage or be demolished as needed. As shown in the figure 3.2 a, the project has been divided into three main areas for excavation to -9.0 m and construction of the underground structures. Also, the area in the middle was divided into two smaller areas to avoid excessive elastic heave.

The next stage was the excavation to -9.0m as an open pit excavation in each of the separate areas. This was done with a 25 m wide berm or shoulder surrounding the site and supporting the slurry walls at -4.5m level. The berm complements the belt and strut slabs; it has sloping sides at 45^{o} with the horizontal (figure 5.1). The shoulders are needed to support the walls and the exterior soil which otherwise would move into the excavation as a bottom failure, like a liquid with high viscosity.

Then, from level -9.0 m, within each of the excavated areas, the excavation of large cylindrical pits, named locally as caissons de aproximación, was advanced down to foundation level, where the heads of the piles were found, each pile cap was built and the corresponding column constructed up to the first floor slab (-3.1 and -4.4 levels). From this stage the first floor slab was built and construction of the super structure continued as usual, thus underground excavation and construction of the foundation mat and first basement slab were removed from the critical route in the construction program.

After the piles had been constructed and the central area was excavated to 9 m, a maximum heave of 20 cm (8”) was measured with the extensometers. Then the columns and upper structure were built and no additional heave occurred. This is a variation of the up-down construction method, which is a must in this project. It is very important to load the soil (construct the structure) to be able to unload (excavate).

It should be noted that although this was the excavation program, the central area was constructed with “caissons de aproximación” from level -4.5 m to gain some advantage on the time charts (these caissons, built manually with concrete lining, are easily constructed in Bogotá, and employ three workers per pit which is good for employment of unqualified labor). In the same manner the surrounding first floor slabs, from the belt and covering the 25m wide shoulders, were built using the “caissons de aproximación” from -4.5 m level to reach the pile heads and construct the corresponding pile caps and columns. Caissons with their corresponding column built from -4.5m level had to be filled with sand to avoid weakening of the soil in the shoulder, which at this stage is supporting the retaining walls.

Figure 5.5 Construction of mat under first floor slab.

In the central areas excavation proceeded from -9.0 m to -11.5 m. and the mat foundation was built as excavation progressed (Fig 5.5). The surrounding berms were lowered, simultaneously with mat construction in central areas, to the level of first basement floor by the alternating trench method (10 m wide trenches) , and the first basement wale slab was built within the trenches at levels -7.5 and -8.8 m. After construction of the first basement belt or wale slab, the lowest level of the shoulder was removed using the trench method, but very slowly and carefully, with widely spaced trenches 4.0 m wide at the most, all to avoid bottom failure due to the weight of the soil outside the retaining walls. Daily results of the precision instruments were crucial at this stage to advance excavation of the trenches. Of course the soil removed from each trench had to be replaced by the structural mat slab in a very expedient manner and no excavation of nearby soils could be made until the mat had the strength to support bottom soil pressure.

6. INSTRUMENTATION

The geotechnical instrumentation includes: nine inclinometers at chosen locations around the site and close to the walls, to a depth of 30 m; eighteen Casagrande and eleven vibrating wire piezometer batteries (at -10 and -20 m)(figure 5.4); three spider type extensometers located at the center of the main areas of excavation; very detailed topographic monitoring, controlling movements of the walls, surrounding sidewalks and buildings, and a water main on Avenida Boyacá to the west; strain gages placed on reinforcing bars at chosen locations to monitor strains and stresses on belt and strut slabs.

The readings were taken three times a week or more when needed.

7. RESULTS

The construction of the foundation and excavation to a depth of 4.5 m developed well as expected. The retaining wall at the south side, which was constructed from the surface, moved about 20 cm close to the surface until the wale and strut slabs at first floor level were constructed. Then construction went smoothly even when open pit excavation reached a depth of 9.0 m. The spider extensometers, installed from -4.5m level, showed very small expansion of the bottom soils, smaller than 15 cm (6").

On the other hand, when excavations reached the mat foundation level and they got to a distance of about 25m from the retaining walls the inclinometers showed movements of up to 30 to 40 cm, within depths of 5 and 20m bellow the sidewalk level. When this happened (twice during construction at two different sites) immediate action was taken constructing the mat as soon as possible and completing the wale slab and beams projected to the central columns at first basement level. These measures were needed to avoid a bottom failure which might have developed breaking the slurry walls and with very negative consequences to the structure adjacent to the excavation.

Figure 7.1 shows the location of geotechnical instruments. Figure 7.2 has the results of inclinometer 6 at the critical point in time when immediate action was taken.

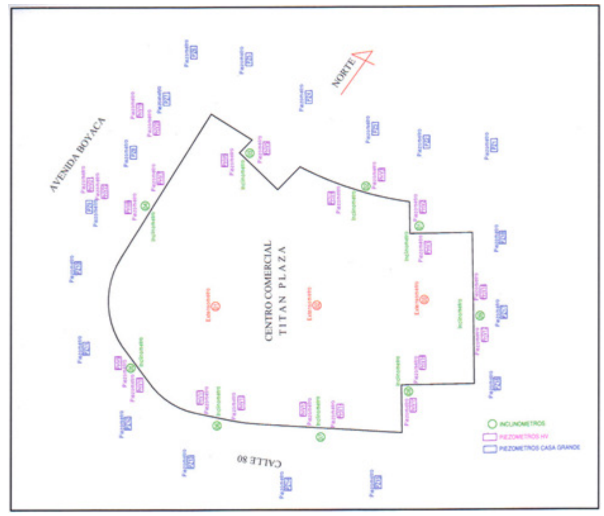


Figure 7.1 Location of geotechnical instruments.(9)

8. CONCLUSIONS

The soils in the Bogotá Sabana imply great challenges for all those involved, including construction contractors, structural engineers, and most of all for the soils engineer. Construction of excavations should be carefully planned and the soft soils must be supported and loaded at all times as excavation of basement levels advance. As it has been shown even relatively small excavations produce some movements of the walls and surrounding soils.

The up-down construction, and variations of it, is a valuable method for advancing excavations in this very soft soils, but it should be modified to be able make large excavations, as permitted by the behavior of the soil mass. In this case the unloading to a depth of 4.5 m (6.7 T/m² or 65.7 KPa) before piles construction proved particularly helpful since it helped reduce elastic and future plastic heave. The extensometer showed heaves as high as 20 cm (8") after construction of the piles and excavation to 9 m.

The precision geotechnical instruments are of great help to adjust the pace of excavations, but these must be taken from the critical route as early as possible. Another important point is to make the constructor aware of the importance of following the planned steps and to work hand in hand with the structural and geotechnical engineers.

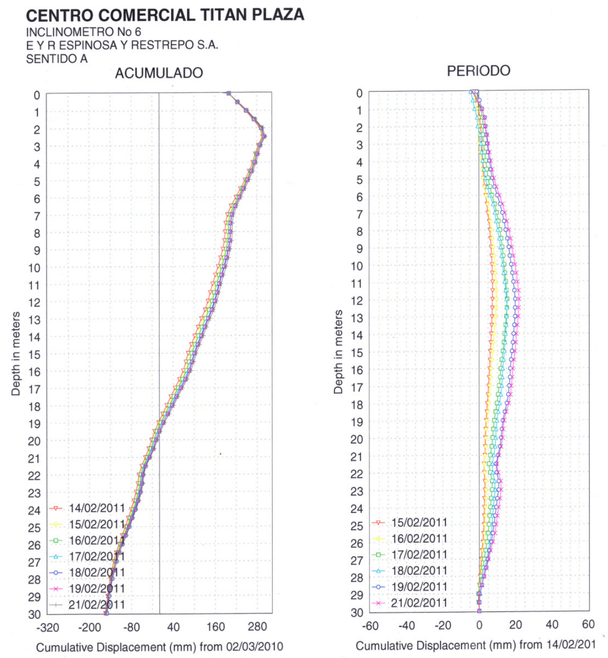


Figure 7.2 Results of inclinometer number 6. (9)

9. REFERENCES

(1). DPAE. 2010. *Decreto 523 Microzonificación Sísmica de Bogotá D.C.* Alcaldía Mayor de Bogotá, Bogotá, COL.

(2) Espinosa, A.1999. *… And Back to Theory.* Geo-engineering for Undergrounds Facilities, edited by Fernandez, G. Champaign, ILL, USA.

.

(3) LFO Ingenieros de Suelos. 2007. *Estudio de Suelos y Análisis de Cimentación Centro Comercial TITAN PLAZA – LFO 11109*, Bogotá, COL.

(4) PCA. 2007. *Structural Engineering Design.* Bogotá, COL

(5) Orozco. L, Orozco. M. 2011. *Difficult Excavations and Foundations for Buildings on Soft Soils in Bogota.* Geo-Frontiers 2011,Dallas TX. USA

(6) Zeevaert, L.1983.*Foundation Engineering for Difficult Conditions*, 2nd ed.,VAN NOSTRAND REINHOLD, New York, NY, USA.

(7) Poulos, H.G.,Davis, E.H. 1980. *Pile foundation Analysis and Design*. 1th ed. JOHN WILEY & SONS. New York, NY, USA.

(8) SAFISA. 2009. *Prueba de Carga Pilote Centro Comercial TITAN PLAZA.* Bogotá. COL.

(9) Espinosa y Restrepo 2010 a 2011. *Informes de Instrumentación* Bogotá COL.

10. ACKNOWLEDGMENTS

This is the result of the work of many Engineers and Architects from the following companies:

CUSEZAR S.A., OSPINAS S.A., P.C.A. Proyectistas Civiles Asociados, EYR Espinosa y Restrepo S.A., LFO Ingenieros de Suelos LTDA. Alfonso Tamayo Arquitectos.