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Differential Settlement Problem of a Large Apartment Building in Bogotá, Cause and Solution

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DIFFERENTIAL SETTLEMENT PROBLEM OF A LARGE APARTMENT BUILDING IN BOGOTÁ, CAUSE AND SOLUTION

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ABSTRACT

Foundation analysis for any structure is based primarily on the results of the soil exploration and testing, but there are other sources of information which must be studied carefully and thoroughly, depending on the zone where the project is to be located. This paper deals with a condominium of three large apartments buildings which were constructed at a site on the foothill of the eastern mountains of the city of Bogotá. The soil borings showed the existence of a uniform gravel stratum at a depth of 29 m., but the truth was different and its analysis more complex than was thought at the time of the soils study. This article includes a review of the information in preliminary soils studies for the greater urban development, which were not known by the geotechnical engineers who designed the pile foundation. It also includes a description of the resulting differential settlement, its cause and the characteristics of the underpinning project which had to be constructed to stabilize one of the three towers in the condominium.

INTRODUCTION

For any project the geotechnical engineer bases his design recommendations on his experience, a thorough knowledge of the geologic characteristics of the area and soil exploration and testing results. He uses this information to idealize the soil mass under his feet and predict its behavior for the solicitations involved.

This paper shows a case located in the piedmont area of Bogotá for which flawed, and insufficient, information about the foundation soils resulted in a pile foundation too short, and large differential settlement. Thus underpinning, with micropiles, was designed at a large cost for the owners of the project. The problem, causes and solution are described.

SITE, LOCATION AND HISTORY

Bogotá is located on a large plain, 2600 m above sea level on the eastern cordillera of Colombia. This plain is a lacustrine deposit, of recent quaternary origin about 230 m thick in most of the city. It is surrounded by mountain ranges up to 400 m high above the plain, and these are conformed by sedimentary rocks, from the early tertiary or late cretaceous eras. The rock formations- Guadalupe and Bogotá Formations also underlie the soft soil of the plain in most of the city.

Close to the foothill there are transition soils of colluvial and alluvial origin interbedded with the lake deposits as shown in Fig. 1. The larger buildings in the downtown area, as well as in the north eastern strip, along Carrera Séptima (7^{th} avenue), are mostly founded on the erratic, but sound, gravel and sand layers or sometimes on the clayey and sandy rocks underneath.

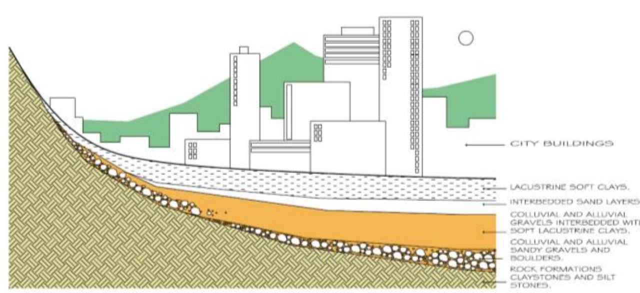


Fig.1. Geological profile at the foothill zone

Figure 2 shows the site in the city, between Carreras Séptima (7^{th}) and Novena (9^{th}) to the north of Calle 134. This site had a late development because it used to be the location of a large cement production plant. (See figure 3)

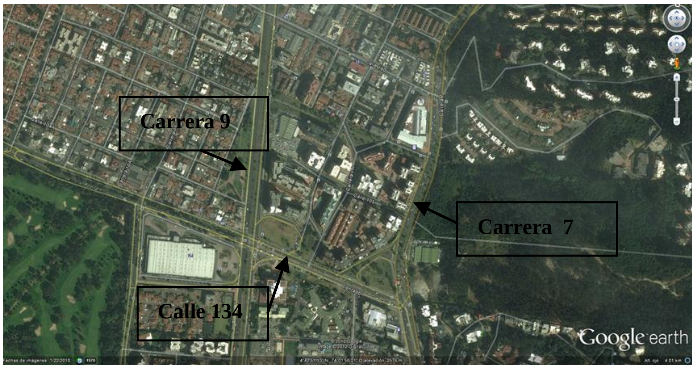


Fig. 2. Project Location - Google earth

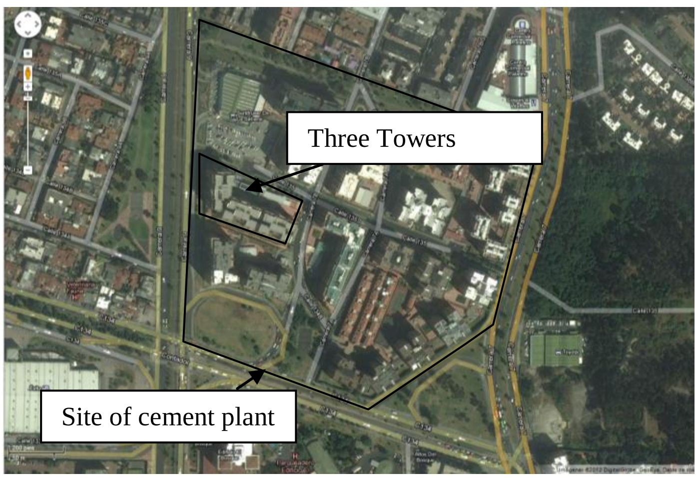


Fig. 3 Urban development - Google Maps

Figure 4 has a description of the geology of this area of the city. It is a detail of the geotechnical map developed by Fopae (Fondo para Prevención y Atención de Emergencias del Distito Capital) – POT (Plan de Ordenamiento Territorial Bogotá) 2010.

In 1983 and 1990, two independent preliminary geotechnical explorations were performed at the greater site (cement plant site), to establish foundation conditions for large apartment buildings (8 to 15 stories high) according to city regulations. The greater site was developed, streets built, and it was divided into smaller plots that were sold at an auction by El Banco Popular, owner of the project at that time.

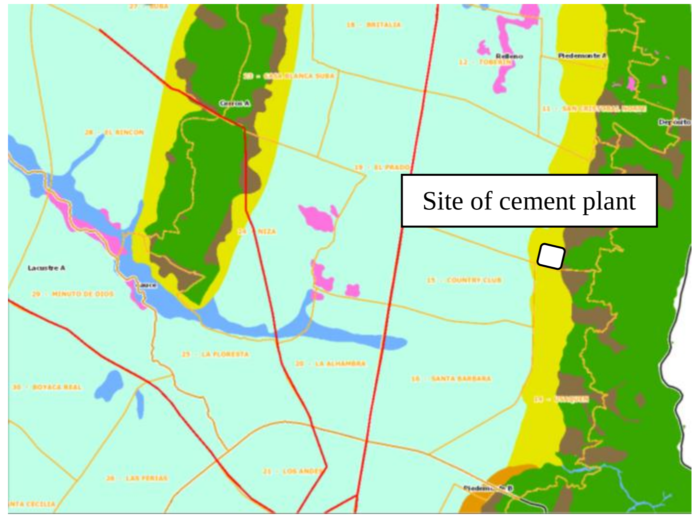


Fig.4. Geology - from www.sire.gov.co (government of Colombia page)

(The site of the cement plant is in yellow – piedmont A)

THE PROJECT

Figure 5 is the satellite photograph by Google Earth of the three towers which are the subject of this presentation. These are 12 stories high with 2 partially underground floors for parking area.

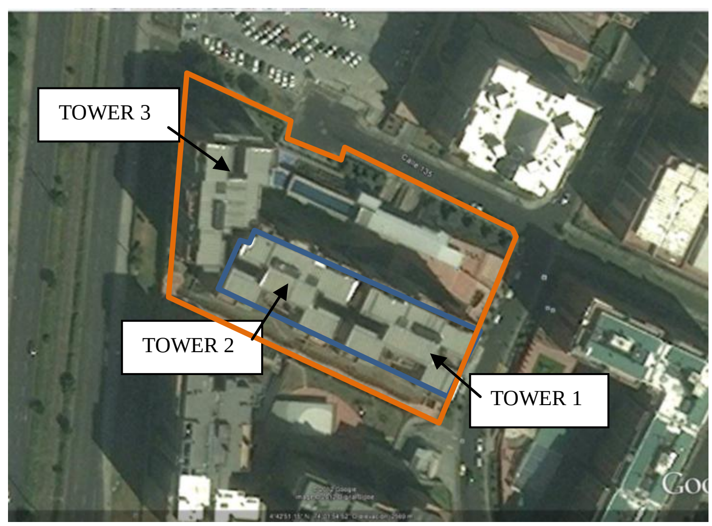
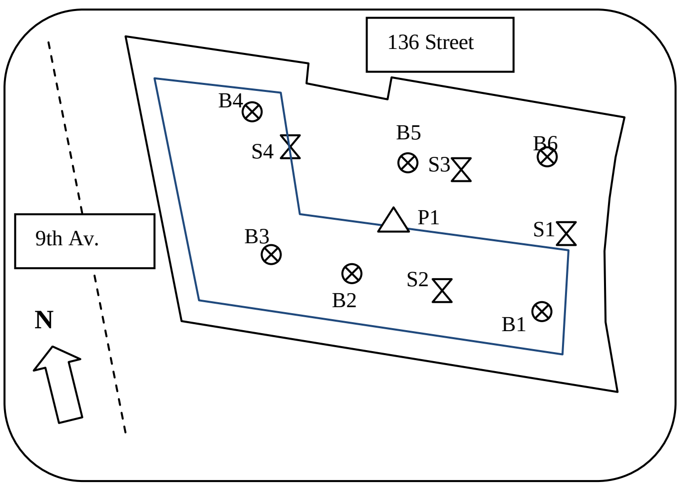


Fig. 5. Project towers - Google earth

SOIL STUDY

In 2003 two definitive soil studies were performed to define the foundation system for the three towers. These were performed by two different geotechnical engineering consultants, who shall not be named due to the sensitivity of this information; they will referred to as consultants A and B. It should also be mentioned that the preliminary soil studies were given to potential buyers in 1996, but were not known by the soil consultants in 2003, the time when the new definitive soil studies were performed. The first definitive study, by consultant A, was performed on the basis of 4 wash borings (18 to 44 m deep S-1 to S-4) and 6 hand auger boring holes (8 m deep B-1 to B-6)located as shown in figure 6. It included a geological description of the site, the soil boring logs and a definition of the foundation for the buildings with piles down to sand and gravel layers bellow 38 m depth for towers 2 and 3.

Figure 6 includes the soil profile obtained from the deeper borings and their location. As it may be deduced there is not enough information to design the pile foundation unless geotechnical engineer A had other information from adjacent properties which is not known by the authors at present.



SPT Wash Borings ⧖ - Hand auger boring holes ⊗
Consultant B Additional Boring hole △

S-1	S-2	S-3	S-4	P1
0 - 10m	0 - 6 m	0 - 5 m	0 - 7 m	0 - 9 m
10 - 16m	6 - 8 m	5 - 6 m	7 - 9 m	9 – 14 m
16 - 18m	8 - 15 m	6 - 15 m	9 - 15 m	14 -16.5 m
18 - 22m	15 - 17 m	15 - 22 m	15 - 25 m	16.5 -17.5 m
22 - 26m				17.5 – 19.5 m
26 - 32m				19.5 - 27.5 m
32 - 37m				27.5 – 29.5 m
37 - 44m				29.5 – 40 m

Yellow: Sand and gravel - Beige: Silts and Clays

Fig. 6. Boring logs and location, definitive reports

The project was owned and developed by two construction companies. They studied the foundation designed according to that soils report, A, and decided that it was a very costly and inefficient foundation; then they retained a second geotechnical engineer, B, to study the first solution and give new foundation recommendations.

Soils engineer consultant B, made one additional soil boring at the center of the area (Figure 6), for the performance of a down hole seismic refraction test, and the specific site seismic response analysis, and to corroborate the results obtained by geotechnical consultant A.

Consultant B concluded that the first results were representative of soil conditions at the site, but calculations by consultant A were conservative and he could give a safe and efficient solution. Consultant B designed a pile foundation to be founded on gravel or sandy soils at a depth of 29 m for tower # 2. The parameters and design values are shown in Table 1.

Table 1 Parameters and design values Tower # 2
Consultant B

Friction length	27 m
Skin friction	4.8 T/m²
Bearing capacity base	584.38 T/m²

Diameter (m)	Load (Ton)
0.6	199.00
0.7	270.64
0.8	353.48
0.9	447.38
1.0	552.32

The structural engineer followed recommendations by geotechnical consultant B, but he introduced a small variation. Since the soils engineer had given the point bearing capacity plus the friction parameters he had used to obtain the total capacity for each pile, the structural designer varied the lengths, he used piles with depths between 29 and 32 m to get the most efficient (less piles) support for each column. Although the piles were designed by the geotechnical consultant as point bearing piles, the young engineering residents interpreted this variation in depth as meaning that these were friction piles and did not have to reach a specific bearing stratum (they did not read the geotechnical report or did not understand it and used only the structural engineer´s blue print for the foundation).

TOWER #2 AND SETTLEMENT

Tower # 1 was built first, founded on a competent gravel layer at the depth established by consultant B. Then tower # 2 was built, over the piles with specific lengths, but the western piles of the building did not reach the good gravel layer, only some thin sand layers. Tower # 3 was built on these shorter piles (29 to 32 m depth below surface) but its foundation is on a more homogeneous soil, although rather soft.

Table 2 Settlement values Tower # 2

Ubicación Punto	FECHA									
	15/03/2005	16/06/2005	13/09/2005	06/12/2005	14/03/2006	12/06/2006	12/09/2006	04/12/2006	23/01/2007	
R-3	-33	-35	-35	-35	-35	-36	-37	-37	-37	
R-5	-38	-42	-42	-42	-44	-45	-45	-45	-45	East
R-6	-32	-34	-34	-34	-34	-35	-37	-37	-37	
R-7	-38	-43	-43	-43	-42	-42	-43	-43	-43	
							-3	-5	-5	
Q-3	-55	-60	-60	-60	-60	-61	-63	-64	-64	
Q-5	-59	-65	-65	-68	-68	-69	-72	-72	-72	
Q-6	-59	-63	-63	-65	-65	-68	-71	-71	-71	
Q-7	-59	-62	-62	-64	-64	-66	-69	-69	-69	
							-6	-6	-6	
							-5	-5	-5	
O-3	-72	-75	-75	-75	-75	-77	-78	-78	-78	
							-7	-7	-7	Middle
O-5	-78	-85	-87	-90	-93	-95	-101	-102	-102	
O-6	-69	-74	-76	-82	-81	-82	-89	-90	-90	
O-7	-69	-73	-75	-81	-81	-84	-89	-89	-89	
N-5		-90	-93	-102	-102	-107	-112	-113	-114	
							-8	-9	-10	
							-5	-8	-9	
							-7	-9	-11	
							-6	-8	-11	
L-3	-89	-100	-101	-108	-109	-112	-116	-117	-119	West
L-5	-88	-100	-104	-115	-118	-124	-130	-132	-133	
L-6	-85	-99	-104	-114	-116	-122	-130	-131	-133	
L-7	-86	-99	-103	-113	-114	-120	-130	-132	-133	
K-3		-130	-132	-138	-138	-143	-150	-154	-155	
K-5	-113	-130	-138	-149	-154	-162	-173	-177	-178	
k-6	-113	-130	-138	-148	-154	-162	-175	-178	-179	
K-7	-102	-117	-123	-133	-137	-146	-157	-161	-163	

Tower # 1 had settlements values smaller than one inch. Tower # 2 began experiencing a larger settlement towards its western half, noticed from the construction of the structure and during the first one or two years of use (2005 and 2006). Table # 2 and Figure #8 show the values of settlement as a function of time.

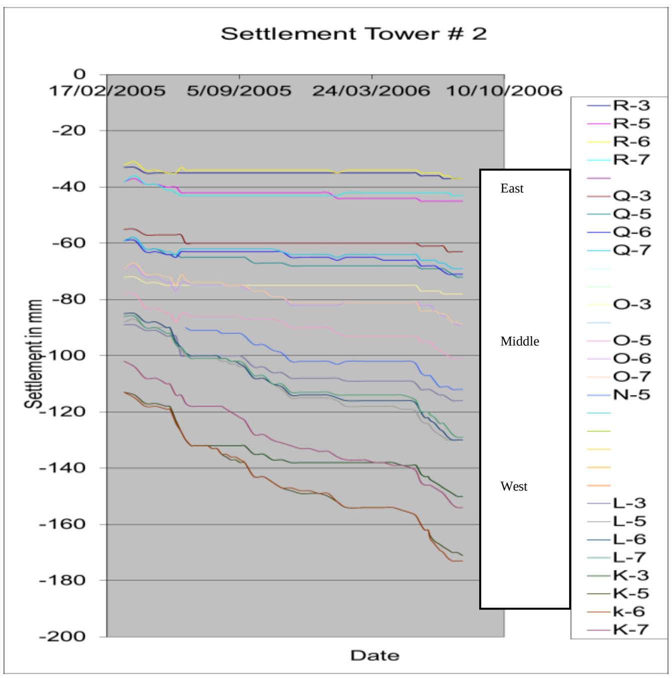


Fig. 8. Settlements Tower # 2

THE PROBLEM

Since Bogotá is on a lacustrine soft clay deposit and settlement values, for this type of building sometimes amount to 4 or 5 inches, at first, the engineers were expecting the stabilization of the settlement. Besides, analysis of the capacity of the piles as friction piles showed that there would not be a bearing capacity failure, just a large settlement toward the west.

But when the differential settlement had reached about 5" (12 cm) between east and west sides of the building, in a 40 m length it was decided that the values were above tolerable, and would get worse. At this point the building had an angular rotation of about 1/333 and there was no internal damage in brick wall divisions, it had settled towards its western end as a rigid block.

THE CAUSE

Figure 9 shows the plan view of the larger site as described in 1990, it has the geotechnical zoning by consultant C, who made the preliminary soil report of 1990. The site had been divided in three different zones. In zone 1 (green) the competent soils gravel and sand layers as well as basal rocks are close to the surface. The good soils dip towards the south west and in zone 3 (orange) these are below 45 or 50 m depth. Zone 2 (yellow) is the transition zone, where the best soil gets deeper as one moves towards the south west.

Fig. 9. Geotechnical zoning preliminary report1996

The larger picture, and thus this variation in depth of the competent soils was not known by the consultants A and B; besides the soft clay layers are interbedded erratically with thin sand and gravel layers which make things more confusing, when soil boring information is scarce and the larger picture is missing.

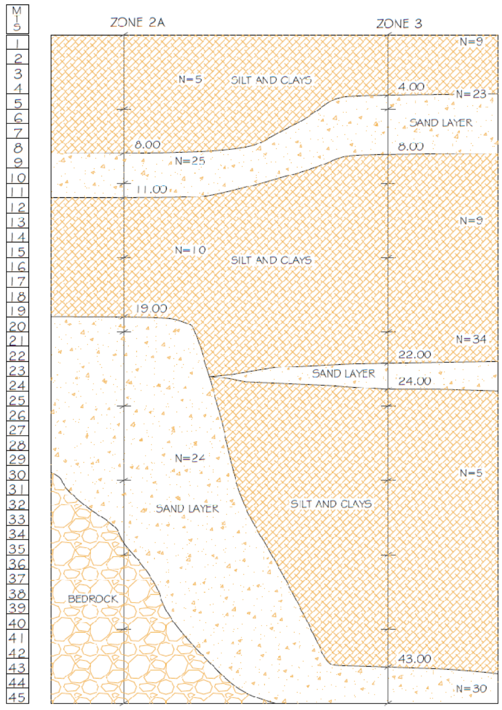


Fig. 10 a. Stratigraphy profiles

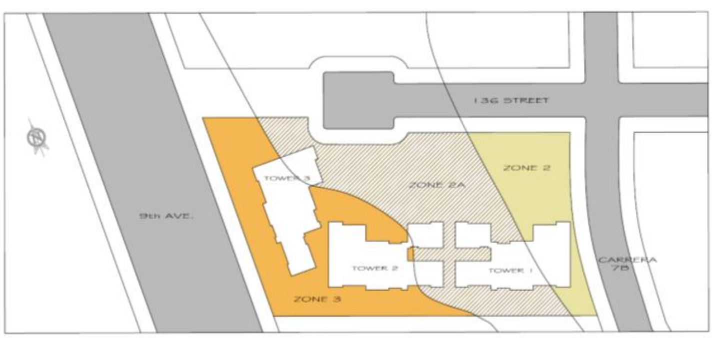


Fig. 10b. Zone 2 A final geotechnical interpretation

THE SOLUTION

It was decided to underpin the structure using micropiles or root piles. Two new soil borings were excavated to study the soil strata variation and since the company in charge of the solution, consultant C, had performed the preliminary soil study in 1990, the results of that study, shown above, were recovered and this, with more borings and the larger picture, complemented the results of the soil exploration.

The new soil borings and the complete information were used for the design of the underpinning micropiles, to the sounder gravel layer at a variable depth between 29 m at the east side of tower # 2 and 43 m at the south western side of the same tower.

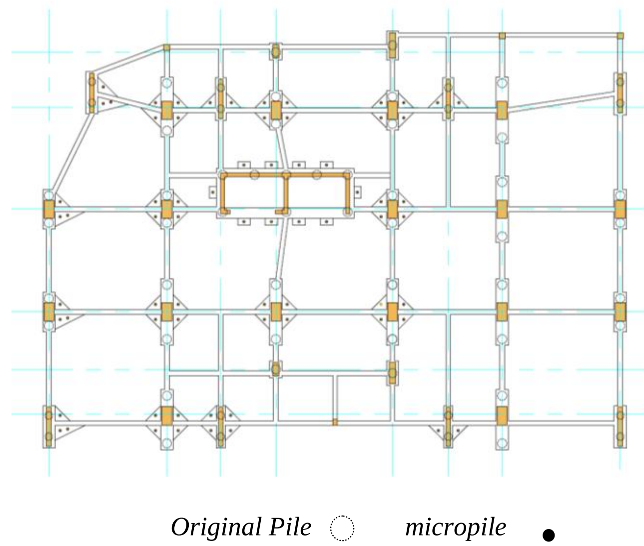


Fig. 11. Plan view of original piles and underpinning micropiles

The micropiles were placed and built during the last months of 2006, as shown in Figure # 11 – Plan drawing view of the foundation.

As soon as the gravel was found in the boring hole for the micropile, and corroborated with all the information acquired for the underpinning soils report by consultant C, the reinforcement shown in the Figure #12, was placed and the micropile injected using large injection pressures (Up to 10 atmospheres) but taking care to avoid soil fracturing.

After the solution was constructed settlement measurements have been made and continue to this day. Initially they were taken every month and now every three months approximately. These readings have shown and confirmed that tower # 2 is stable and further settlement, after underpinning, was bellow a few millimeters in the beginning. The total angular rotation of the tower was below 1/300, which is acceptable according to the Building Code NSR-10, Chap. H.4.9.3.

CONCLUSIONS

Owners, sometimes with little engineering knowledge, try to obtain the best geotechnical solutions with a little money as possible for the soil exploration. They also induce the cheapest solution by consulting with different geotechnical professionals, and also sometimes, find the cheapest but also unsafe solution.

In this case, the cost of repair was close to half a million dollars, a lot in terms of Colombian pesos, and of course they lost the project's profit.

Table 3 Parameters and design values Tower # 2

Parameters	Micropile 20 cm diameter (Ton)		
	ZONE 3	ZONE 2A	
Su (T/m²)	0,16 Z + 1,6	0,18 Z + 1,8	0,25 Z + 2,5
α	0,5	0,5	0,5
Nc	9	9	9
Z (Depht m)	0 a 43 m	0 a 20 m	20 a 43
25	33,25	37,72	
26	35,61	40,39	
27	38,03	43,13	
28	40,52	45,94	
29	43,08	48,83	
30	45,71	51,8	
31	48,40	54,84	
32	51,16	52,96	
33	53,99	61,15	
34	56,88	64,42	
35	59,84	67,76	
36	62,87	71,18	
37	65,96	74,67	
38	69,13	78,24	
39	72,35	81,89	
40	75,65	85,61	
41	79,01	89,4	
42	82,44	93,28	
43	85,94	97,22	

It is advisable to use the best criteria in deciding who the geotechnical consultant for the project should be, and if needed include a peer review. A sound and safe solution should be chosen, according to the best criteria for the area under construction. The owner should not try to limit the amount of boring holes and test quantity, it is better business.

FINAL NOTE

As a final note it should be said that the building code published in Colombia in 2010 is stricter and includes a minimum of soil borings, depth and testing, as mandatory, which is good for better soil exploration programs.

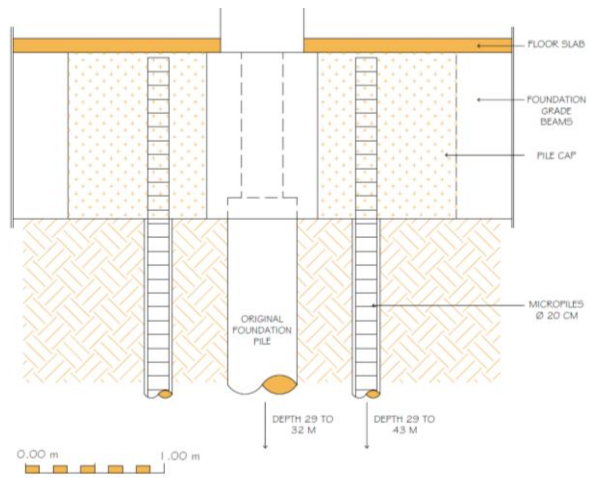


Fig. 12. Plan view of reinforcement with micropiles

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