Foundations and Soil Treatment using the Full Displacement Piles Technique

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Abstract

Following the evolution of times, the need to create new techniques for deep foundations has increased thus optimizing the resources that are used for their execution, mainly caused by the need to reduce production costs. Full Displacement Piles (FDP) appeared as an evolution of the most used techniques and are currently growing significantly within some markets.

This dissertation intends to illustrate the FDP concept, namely its installation process, the specific parameters of this technique, its field of application, its applicability in Portugal and also present the several advantages and disadvantages that it of this kind of rotation.

At a later stage, the software Plaxis 2D is used to simulate an FDP static load test, based on the geotechnical profile that resulted from a case study where FDP was used as foundation rotation. For the same geotechnical features, a static load test for a bored pile was simulated in order to compare the two load-settlement curves and establish the main existing differences between them.

1. Introduction

In order to reach formats with a superior drilling efficiency, modern engineering has developed multiple technologies such as the one presented by this project.

The technology used for the FDP installation was developed by the BAUER group, namely by the Bauer Maschinen GmbH (segment accountable for this technology's development) and has been successfully applied in several countries, such as Italy, for construction sites where the foundations were piles. This technology's success resulted from the engineers responsible for the project, to the fact that the specialized company works along with the manufacturer in order to adjust the operational details, and also to the fact that the equipment was designed taking into consideration the need of a higher torsional movement.

Keywords: Deep foundations; *Full Displacement Piles*; Bored piles; Static load test.

2. Full displacement piles (FDP)

FDP are a type of reinforced concrete pile that are built *in situ*. This technology combines the advantages of driven piles (displacement piles) and bored piles (piles without displacement). Despite being executed *in situ*, along with bored piles, they are classified as displacement piles due to the fact that, throughout its execution, it exists the soil consolidation around the pile, as a result of an horizontal displacement imposed by the drilling equipment. This compaction intends to improve the soil characteristics thus increasing the available area at the time of the loading application.

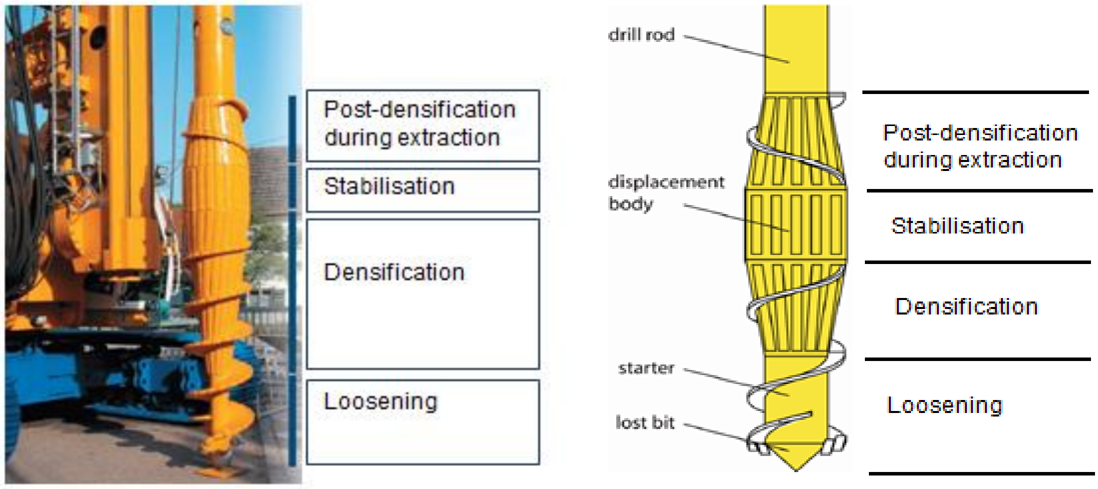
This technique uses a specific drilling equipment which is inserted in the soil by virtue of the application of a torsional movement, applied in the auger rod, and a downward thrust. The main difference between this technique and the remaining techniques is the drilling tool configuration that causes an horizontal displacement during the drilling process due to a zone with a greater diameter.

According to Fiorotto et al (2008), this technique's most frequent diameter is 620 mm, being also possible the existence of 360, 440 and 510 mm. Since this technique is applied to different soil types, being the drills also adjustable, it is possible to obtain a greater equipment performance.

2.1. Equipment

The equipment used for this pile construction technique consists of a rotative drilling equipment that allows the application of a high torsional movement and downward thrust.

The auger's inferior section, the drilling tool, provides the unique characteristics to this deep foundations technique and consists of several implements with multiple functions. The image below represents the drilling tool along with the respective functions, being the standard technique on the left and the lost bit technique on the right.



a) b)

Figure 1 - Implements and respective functions which constitute the drilling tool - a) standard technique (Bauer Maschinen GmbH, 2013); b) lost bit technique (Busch, 2009)

As the previous image illustrates, both tools are similar and present the same functions, being the main difference the fact that b) includes a bit on the tool base which stands out at the end of the drilling.

The first implement, counting from the top, has the job of post-densifying that from the soil, which means that, during the auger extraction, this conical shaped body densifies all the decompressed zones throughout the drilling process. The cylindrical body that follows assures the drilling walls stabilization. The third tool, which also has a conical shape such as the first one, is used to densify the soil during the drilling process. Consequently, it will induce horizontal thrusts, moving and densifying the soil that surrounds the pile. Finally, the last implement is the first to be inserted in the soil and it should decompress the soil thus allowing the cavity drilling.

2.2. Installation process

As previously mentioned, there are two variations of this technique, the standard technique and the lost bit technique that despite having a similar drilling tool, their installation phasing shows significant differences during the last two stages.

The first three stages, identical in both variations, consist of:

i) The positioning and creation of a drilling platform on the pile position;

ii) The beginning of the drilling process with the auger. The drilling process is made by rotating the equipment (application of torsional movement) and by enforcing a downward vertical thrust. The soil is loosened as a result of the starter auger movement and as the drilling continues, it pushes the soil to the side by virtue of the drilling tool shape, namely the displacement body;

iii) The drilling is made until the desired depth.

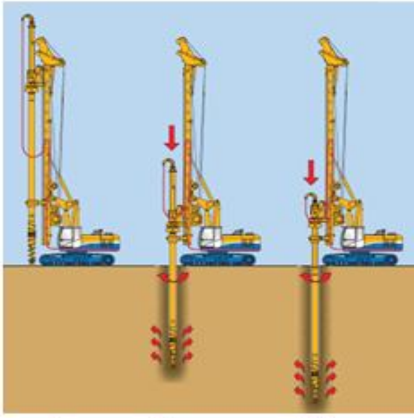


Figure 2 - Initial stages of the FDP installation process.

The last two stages differentiate the standard technique from the lost bit technique.

<u>STANDARD TECHNIQUE</u>

iv) Once the desired depth is reached, the drilling equipment is extracted and the concrete is simultaneously pumped through a hollow tube that is placed inside the equipment. It is important to note that during the drilling process, and after the tool with the greater diameter passes through, the soil is decompressed since the drill is no longer contained. Therefore, as the equipment is pulled up to the surface, on the same direction in which the drilling was made, the same tool applies the pre-existing tension on the drill walls and this one is kept by the inserted concrete on the pile cavity.

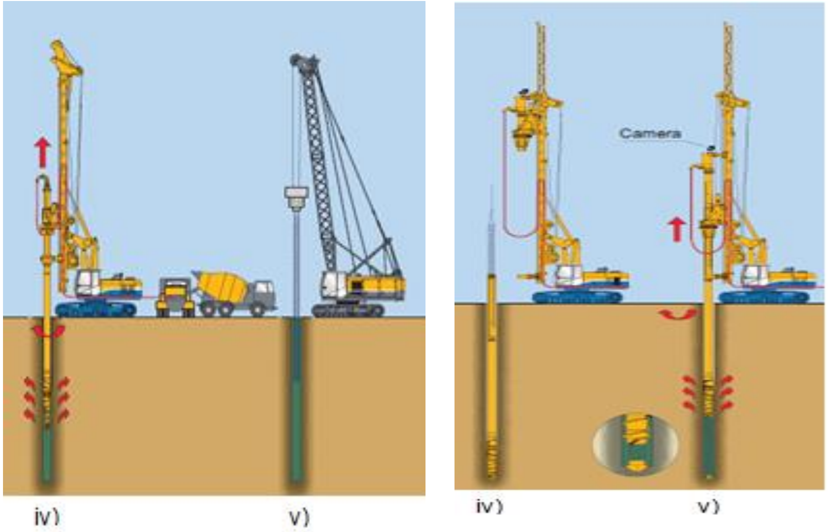
v) Lastly, the cage is inserted with the help of a crane while the concrete is still fresh.

<u>LOST BIT TECHNIQUE</u>

iv) After reaching the desired depth, the bit is disconnected from the drilling tool and the cage is inserted in the hollow auger stem with the help of a crane;

v) Consequently, the auger is extracted and simultaneously the concrete is unloaded without using pressure through a hopper that is established on the top of the auger.

The figure bellow illustrates the last two stages of the installation process. The figure to the right represents the standard technique and the one to the left represents the lost bit technique.



a) b)

Figure 3 - Finishing stages of the installation process - a) standard technique; b) lost bit technique

2.3. Penetration Resistance (α)

The equipment that this technique entails has the ability to determinate, automatically, the pile's penetration resistance. In fact, it is a parameter that is determined through the drilling feature thus being an indicator for the soil density. Consequently, the greater this parameter, the harder will it become to drill the soil. The main goal for the use of this parameter is to optimize the pile length due to the fact that, if during the drilling process a value greater than α is obtained, then the reached depth will be enough for the desired loading capacity. This parameter is directly related to the cone resistance obtained from the CPT test which in case of resistance increase, the α value will increase as well.

By using several field tests made in several studies, the expression that defines the penetration resistance was improved since it initially depended solely on the torsional movement and the drilling rate being that the new expression takes into consideration other extremely important parameters.

The expression that defines the penetration resistance is the following:

$$\alpha_{new} = \frac{F \times s + M \times \varphi}{s + \varphi} \qquad (1)$$

Being F - downward thrust applied by the drilling equipment, s - penetration depth, M - torsional movement applied by the drilling equipment, φ - rotation angle.

2.4. Application field

The factors which affect FDP use are: type, tension and soil density, construction site location and the drilling required energy.

The soils that are appropriate to the use of FDP are silt, alluvium, soft clay, loose sand and organic soils, that is, loose thin granular soils to slightly dense and thick granular soils. This does not render impossible its use on thicker and more dense soils, but it requires more drilling energy in order to decrease the technical efficiency thus increasing the total cost of the construction which makes it impracticable. According to Bauer

Maschinen GmbH (2013), as a rule of thumb, the application of this technique, N_{SPT} < 30 blows e CPT < 10 MPa.

The main regions of the mainland Portugal and the Azores and Madeira Islands were characterized in order to reflect on the applicability of this technique.

This technique can be applied in a numbers of cities, such as: Faro, Olhão, Setúbal, Lisboa, Vila Franca de Xira, Leiria and Aveiro. The main FDP applications in the above mentioned Portuguese areas occur due to the fact that they are located along the coast or close to rivers (Tagus and Sado), where the majority of soil consist of alluvial deposits. Regarding the Azores and Madeira Islands, and since they have a volcanic origin and its ground formation are igneous rocks (with a high level of hardness), they do not gather the appropriate conditions for a possible application.

2.5. Advantages and disadvantages

The use of this technique has significantly increased in several countries. This method presents a wide range of benefits that correspond to the combination of the bored and driven piles' advantages. This technique's main advantages and disadvantages are listed below.

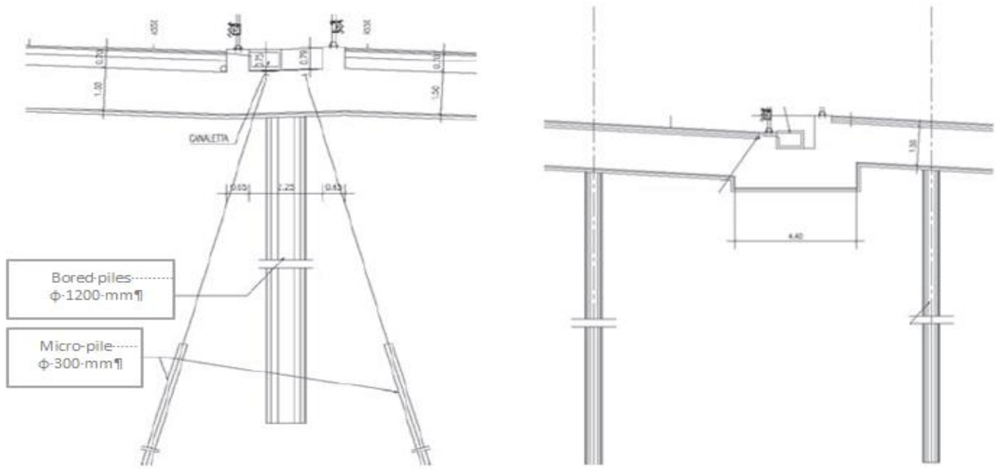
Table 1– Advantages and Disadvantages

Advantages	Disadvantages
• High loading capacity	• Damage to neighbors structures
• Cement consumption reduction	• Damage to the piles next to it
• Low residue level	• Concrete cannot be exanimated after the construction
• Installation process without vibrations	• Incapable of executing large diameters
• High productivity level	
• Ability to change the pile length during the execution process	
• Reduced execution costs	

3. Case Study - *Galleria del Passante di Mestre*

This case study involved the construction of a road at the north of Italy that connects Torino to Sistiana. During its construction, it was required to build tunnels with reduced length, that served as a level crossing along the *Passante di Mestre* road. The first constructions located on that road are the "Vetrego" and "Caltana" tunnels which were built with the "cut and cover" technique. This type of construction with a high ground-water level always brings up the problem of how to neutralize the water pressure that exists on the bottom slab so that it does not blister. The problem around this case study arises from the previously mentioned subject where there was the need to install piles throughout the road in order to neutralize the existing water pressure since the pavement's weight was not enough to accomplish it.

The anchor systems initially defined consisted of bored piles with 1200 mm diameter combined with 300 mm diameter micropiles, both with a length of 18 m. However, during the site construction stage it was decided to replace this methodology with FDP thus decreasing the construction's costs and increasing the productivity. The FDP was used by applying the lost bit technique with 20 m long starting with a depth of 8 m and a diameter of 620 mm. The figure below shows the installation detail of the initial solution on the right and the FDP final solution on the left.



a) b)

Figure 4 - Installation detail - a) of bored piles and micropile solution; b) with FDP (Bringiotti et al, 2008)

It's important to mention that although the FDP piles work under traction, the numerical modeling was made under compression, since it is the most common situation of this type of foundation. It was only possible to follow this approach, since it was made a pre-analysis (Plaxis software) which concluded that FDP piles simply resist by lateral friction, being equivalent to a pile subjected to traction

3.1. Geotechnical Description

For the geotechnical characterization of the ground, laboratory tests and results from several geotechnical researches that were made *in situ* are used. This geotechnical research entailed CPTU tests and piezometer installation.

The following table summarizes the layers that constitute the soil and its respective parameters.

Table 2 - Geotechnical Characterization (Bringiotti et al, 2008)

Layers	Description	Depth		Ɣ [kN/m³]	ϕ' [º]	c' [kPa]
		Begin	End			
1	Medium-fine silty sand	0	5,0	18,5	36	0
2	Silty clay	5,0	7,0	19,0	28	5
3	Medium-fine silty sand	7,0	8,5	18,50	38	0
4	Silty clay	8,5	11,0	19,0	28	5
5	Slightly silty sand	11,0	19,0	19,0	39	0
6	Silty clay with sand layers in between	19,0	35,0	20,0	32	10

3.2. Numerical modelling

For the modelling of this particular case, thefinite element software *Plaxis 2D 8.2 version*, was used. It was also used a triangular finite element mesher with 15 knots and the axisymmetric model. Figure 5 represents the numerical modelling used for the FDP in which, with the help of the *Prescribed displacement* control, it is possible to simulate the horizontal displacement that occurs during the FDP installation. It is important to note that the model with the bored piles does not contain that displacement. The value set for the *Prescribed displacement* is 0,057mm, a value that assures the increase of the cross-section at 40% and 9100 kPa corresponds to the value of the load that was applied at the pile head during the static load test simulation (equivalent to 2750 kN). Note that the pile was executed from the layer 3 (Table 2) due to the previously made excavation.

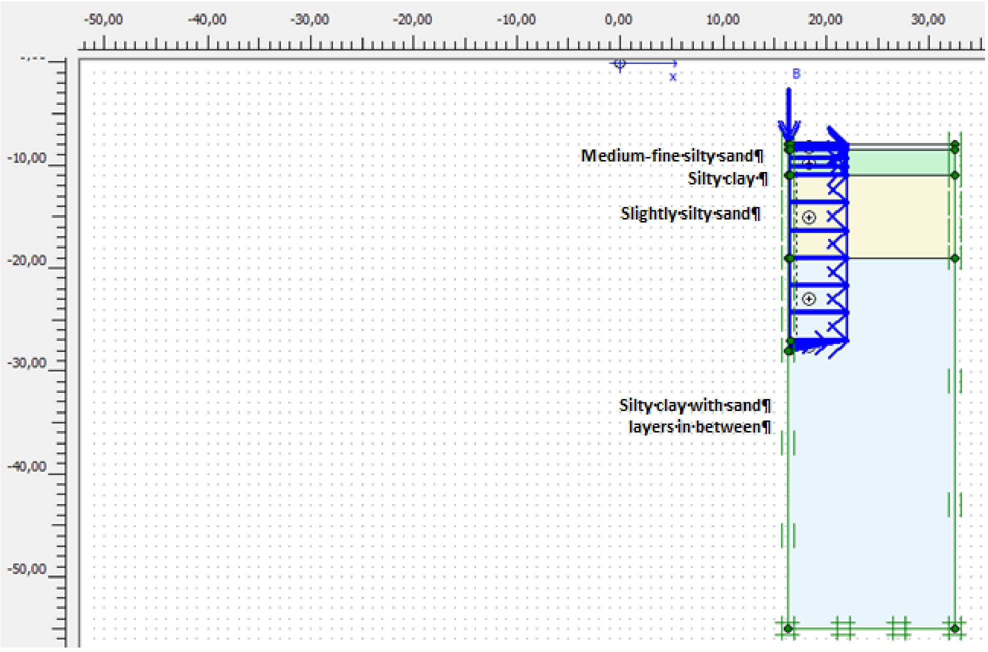


Figure 5 - Representation of the numerical modelling of an FDP (*Plaxis 2D software*)

The type of soil model as well as the description of the parameters used for the modelling are summarized in the following table.

Table 3 -Listing of the parameters used for the interface modelling and characterization

Layers	**E (MPa)**	E_{50}^{ref} **(MPa)**	E_{oed}^{ref} **(MPa)**	E_{ur}^{ref} **(MPa)**	**m**	**ν**	**ϕ' (º)**	**c' (kPa)**	**Ψ (º)**	**Material model**
3	125	125	125	375	0,5	0,30	38	0	8	HS
4	30	--	--	--		0,35	28	5	0	MC
5	150	150	150	450		0,30	38	0	9	HS
6	80	--	--	--		0,35	32	10	0	MC
HS – *Hardening soil*; MC – *Mohr-Coulomb;*										
Material type	Undrained									
Interface	Rigid									

The pile was simulated as a soil layer, being its characteristics represented by the Table 4.

Table 4 - Pile characterization

Material model	Linear elastic
Material type	Non-porous
γ (kN/m^3)	25
E (GPa)	32
ν	0,2

3.2.1. Modelling outcomes

As expected for the same applied load, it was obtained an inferior displacement for the FDP model when compared with that of the bored pile. Table 5 represents the displacements obtained with the two models. It should also be noted that for a better perception of the load capacity difference between the two types of foundations, it was determined the load on the bored pile model which causes a displacement similar to that obtained with FDP.

Table 5 - Outcomes obtained with the numerical modelling

	FDP	Bored pile	
Load [kN]	2750	2750	1700
Settlement [mm]	26,5	66,1	27,1
Strain [MPa]	9,1	9,1	5,6

The following figure shows the displacement fields obtained with the two numerical models, FDP and bored pile. It is clear that, during the simulation of the static load test, both piles present a similar behaviour despite having some distinct aspects. The only factor that affects the greatness of the obtained displacement is due to the horizontal displacement application during the FDP drilling stage.

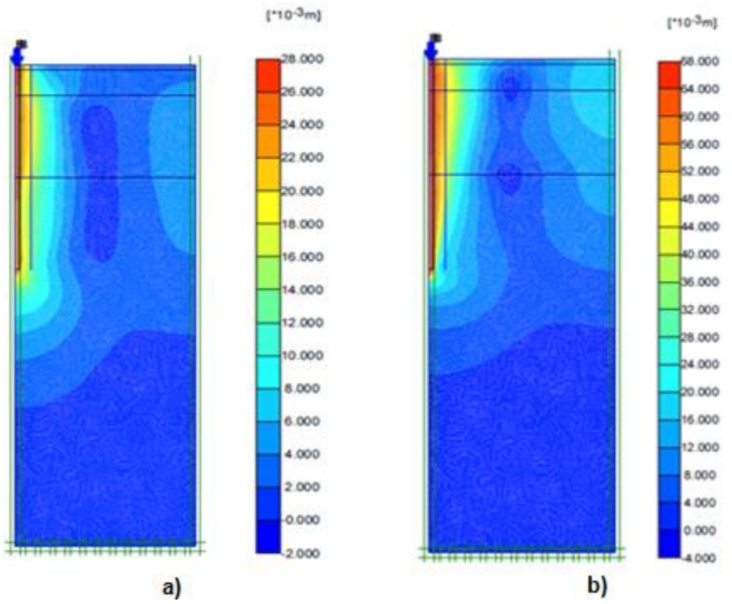


Figure 6 - Total displacement during the static load test a) FDP model; b) bored pile model

Consequently, the load-settlement curves obtained from the static load test simulation are presented. Note that the curve obtained from the in situ execution of the case study is represented in solid line. In comparison with the dash type curve (obtained from the Plaxis 8.2 version software) it was concluded that the obtained proximity is not identical, despite being very similar, and this discrepancy is caused by the soil parameters since the deformability modules of each layer were determined iteratively. By comparing the dash type curve (FDP model) with the dot curve (bored pile model) it is clear the discrepancy between them thus illustrating the load capacity difference.

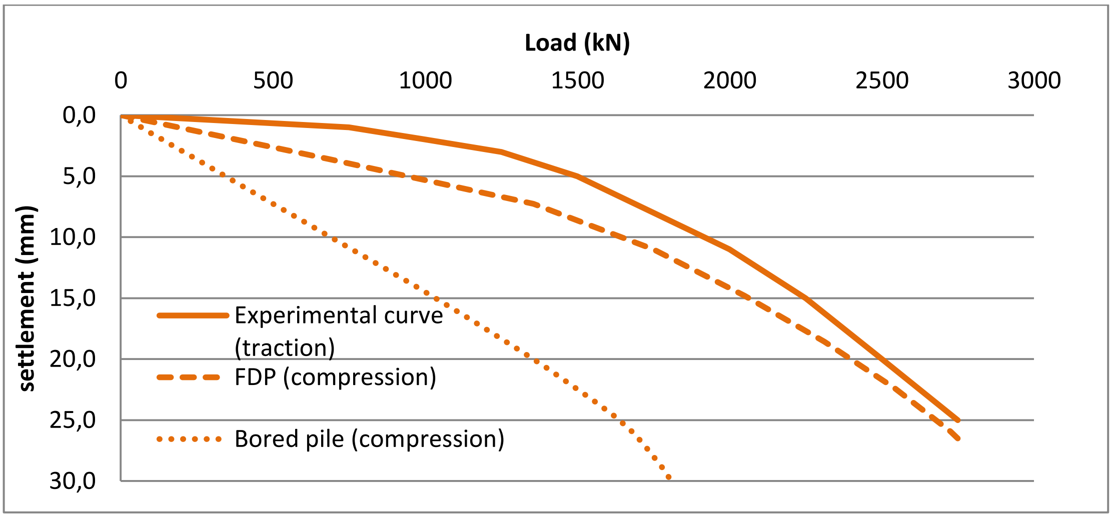


Figure 7 - Load-settlement curves of the numerical and experimental solutions

4. Conclusions

The main objectives were reached and the obtained outcomes were satisfactory. Firstly, it was necessary to define this technique as well as its particularities. Therefore, in §2, it was presented a wide range of information about this technique such as the required equipment for its execution, its installation process and the main parameters that influence its completion.

It should also be noted that the characterization of the Portuguese soils carried out was merely an introduction to the existent soils since it is a very heterogeneous country. Consequently, in order to obtain conclusions regarding this technique's feasibility in a specific construction site, it is necessary to make a soil study so that the geotechnical profile of the concerned site can be determined.

Lastly, the numerical modelling carried out, with the use of finite elements software (Plaxis 8.2 version), illustrated the expected outcomes, which means that the FDP has a greater loading capacity than the bored pile. This conclusion was attained through the analysis of the displacements and load-settlement curve obtained in §3.2.1 since in order to occur an identical settlement (about 26mm in this particular case) are required 2750kN and 1700kN for an FDP and for a bored pile, respectively. It is possible to confirm that the applied load on the FDP is 1.5 times higher than that applied to the bored pile. This loading capacity increase is caused by the installation process, that is the horizontal displacement that occurs during the an FDP drilling stage.

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