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Pathologies in deep foundations, recovery method – Practical applications

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ABSTRACT
The term "foundation" refers to the establishment of a foundation for construction, playing a crucial role in the transmission of loads and stresses to the ground, as highlighted by Milititsky (2015) and Azeredo (1997). In the context of Civil Engineering and Geotechnics, the diversity of soils requires detailed studies to ensure the safety and stability of the structure in the face of variable and static loads, also considering economic and environmental factors. Pathological structural problems may arise, requiring adequate investigation and treatment to preserve the stability of the building without compromising the safety of people and property. This work aims to present the possible pathologies in foundations, along with the methodologies of structural control and reinforcement.

Keywords: Pathological problems, Geotechnics, Structural reinforcement.

INTRODUCTION

According to the dictionary definition, the term "foundation" refers to the process, act or result of establishing something, being a structure or base on which a building will be built (MICHAELIS, 2018).

According to Milititsky (2015), the foundation of a structure plays a fundamental role in transmitting loads and stresses to the ground. Following the same line of reasoning, Azeredo (1997) argues that the structural elements of the foundation have as their primary function the distribution of loads and stresses to the soil of the building.

In the field of Civil Engineering and Geotechnics, we find a wide variety of soils with distinct characteristics. Therefore, in the context of foundations, it is of paramount importance to carry out studies and analyses of the soil in relation to the variable and static loads that will be applied, taking into account the loading of the structure. Of course, the factors of economic viability and sustainability must be considered, but without compromising the safety and stability of the building.

Every structure, whether during its construction or during use, can face structural pathological problems due to its inadequate performance in transmitting forces to the ground, resulting in fissures and cracks that require investigation and treatment. In this context, the main objective of this work is to present the possible pathologies resulting from problems in the foundations, as well as the methodologies and technical procedures for structural control and reinforcement, aiming to maintain the stability of the building without endangering the safety of people and property.

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OBJECTIVE

The main objective is to present the factors and consequences arising from the negligence or lack of knowledge on the part of professionals in relation to the technical premises related to the investigation of the soil versus the foundation structure. In addition to highlighting the importance of the preliminary study of the soil in choosing the most appropriate type of foundation, in order to avoid a series of potential structural problems that can partially or totally affect the construction. These problems can include differential settlements in the foundation, often requiring the evacuation of buildings or residences to conduct an investigation of the true causes of the pathology. In such circumstances, it may be necessary to implement structural reinforcement such as Mega Piles, Roots, Lever Beams, and Structural Reinforcement. To enrich the work and promote knowledge about foundation reinforcements, a table will be presented to compare the characteristics of the different types and solutions of structural reinforcement.

METHODOLOGY

This is a literature review, developed with articles published in the period from 2010 to 2024 in the electronic databases: Capes Portal, Scientific Electronic Library Online – Scielo, Google Scholar, portal of the Regional Council of Engineering of São Paulo. In addition to master's dissertations, doctoral thesis related to the topic published from 2010 to 2024, diagnostic engineering books, pathologies books in reinforced concrete structures.

4STRUCTURAL FOUNDATION

A foundation arises from the need to transmit the loads of the structure to the ground. Its behavior over time can be influenced by several factors, starting with the design aspects, which include understanding the characteristics of the soil. Then, the construction procedures play a crucial role, followed by the effects of events that occurred after the completion of the construction, including possible degradation processes.

As established by NBR 6122:2022, a deep foundation is the one responsible for transmitting the load of the superstructure to the ground through the base (tip resistance), the lateral surface (stem resistance) or through a combination of both. In addition, according to this standard, in deep foundations, the laying depth must be more than twice the smallest dimension in plan of the foundation element.

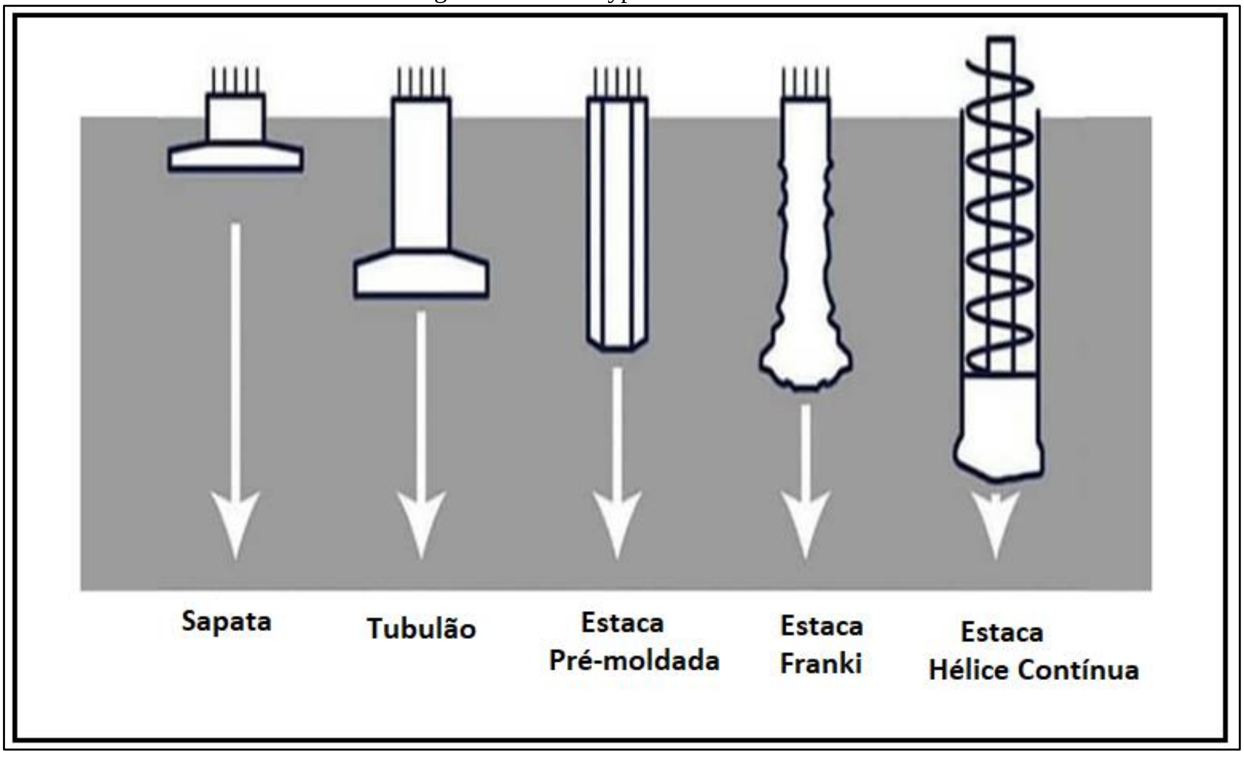
Deep foundations are often employed when surface soils are unable to withstand high loads or are subject to erosion processes. In addition, they are used when there is a possibility of future excavations in the vicinity of the work. This type of foundation allows the structure's loads to be transmitted to deeper layers of the soil, offering greater stability and safety to the building.

In NBR 6122:2022, the types of deep foundations presented are:

- **Piles:** these are deep foundation elements that are executed with the help of tools or equipment, without the need for workers to descend at any stage of the execution. This process may involve methods such as percussion crimping, pressing, vibration, or even digging. Piles can be made of various materials, including wood, steel, concrete, among others;
- **Pipes:** these are cylindrical elements with a deep foundation in which, at least in their final phase, the descent of workers occurs. These elements can be performed both in the open air and in environments with compressed air, and may or may not have an enlarged base;
- **Coffins:** These are prismatic-shaped foundation elements that are concreted into the surface of the site and installed through internal excavation. During its installation, compressed air may or may not be used, and the coffin may or may not have its base enlarged.

Figure 1 shows the most commonly used types of foundation:

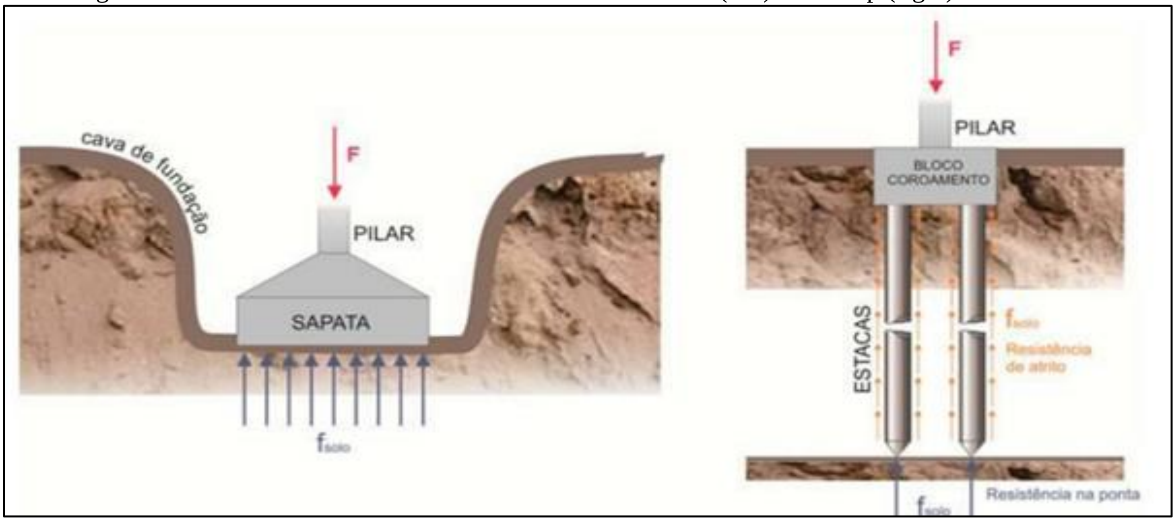
Figure 1 – Main Types of Foundations.



Source: Silvio (2020).

It is confirmed that the foundation is the structure responsible for transferring the loads acting on a building to the ground, being classified into shallow or direct foundations and deep foundations. In shallow foundations, stresses are transmitted to the ground via the contact area of the base of footings, foundation blocks or radier, as per the design specifications. In deep foundations, on the other hand, the stresses are passed on to the ground through the lateral friction resistance and the tip resistance of piles or pipes.

Figure 2 – Transmission of Loads to the Ground of Shallow (left) and Deep (right) Foundations.

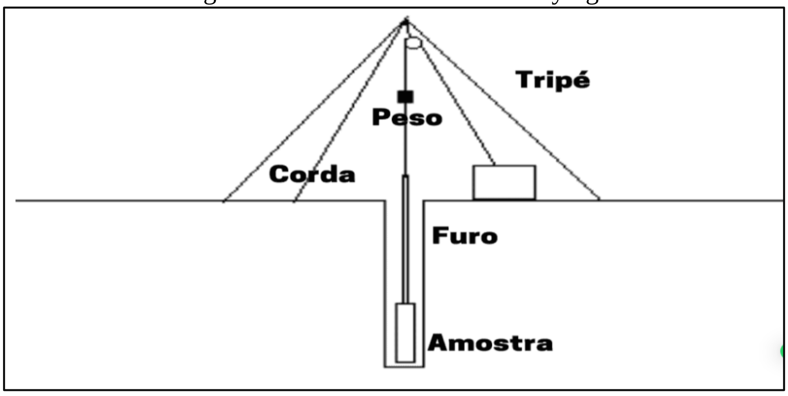


Source: Barros (2011).

SOIL PROBING

The most common method is probing with SPT (Standard Penetration Test), according to the NBR 6484:2020 standard. From the surveys and issuance of the drilling report, it is possible to recognize the type of soil and its respective characteristics and layer thicknesses, the conditions of compactness (degree of compaction of a material), consistency (degree of workability of a material) and bearing capacity, as well as the level of the water table.

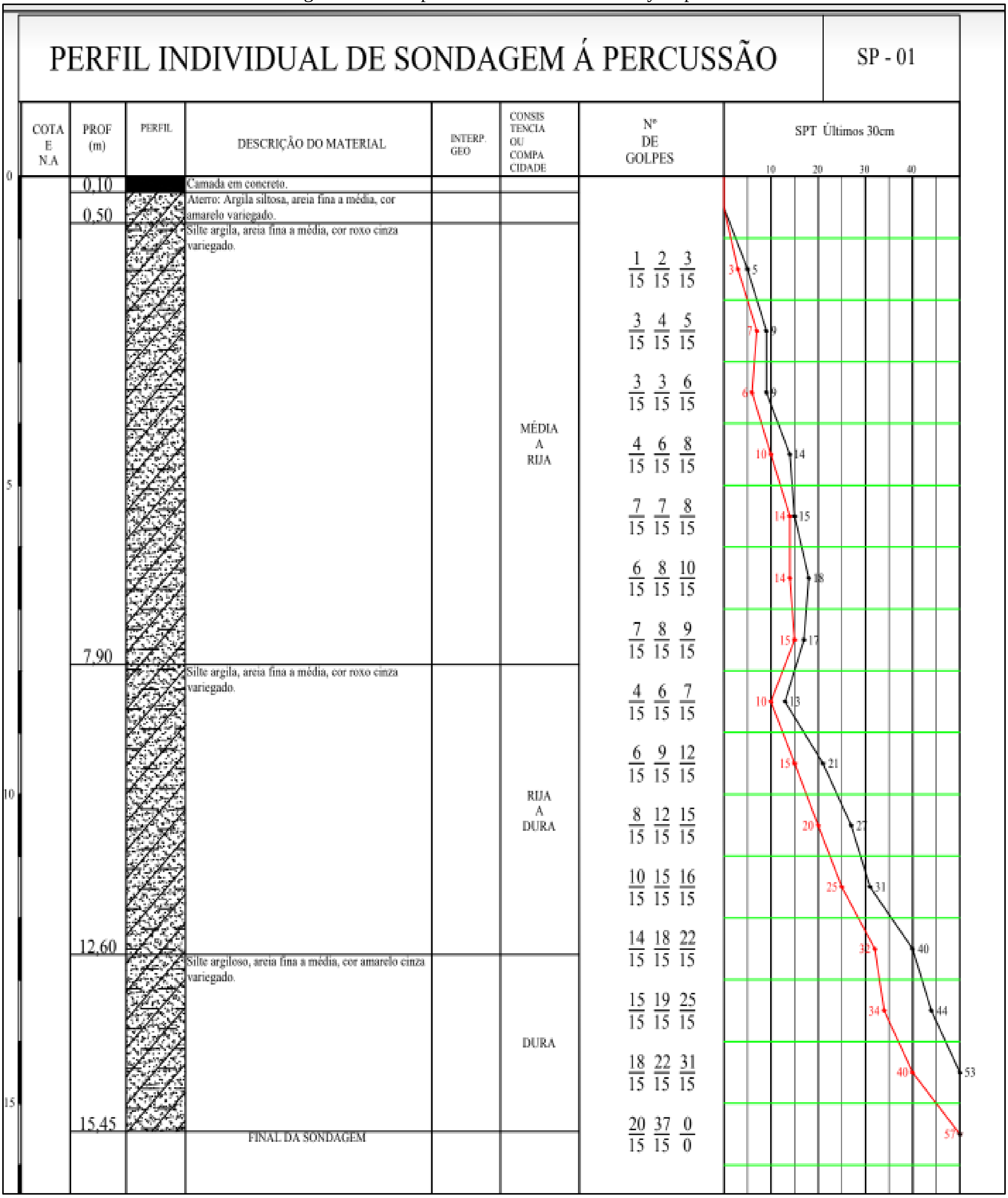
Figure 3 – Structure for Soil Surveying.



Source: Surveys (2021).

Figure 4 shows an example of a percussion soil survey report.

Figure 4 – Example of Percussion Soil Survey Report.



Source: Author's Personal Collection

PATHOLOGIES IN FOUNDATIONS

Most pathologies are associated with a superficial analysis of the soil or the lack of drilling tests, and in some cases, the incorrect interpretation of the data obtained. These errors can lead to an inadequate understanding of the actual behavior of the soil and its interaction with the structure. According to Milititsky, Consoli and Schnaid (2015), about 85% of the cases of failure in the performance of foundations in small and medium-sized works are directly related to the complete absence of soil investigation and the adoption of inadequate solutions.

The authors add that another part of the lack of performance can be attributed to foundation designers, due to a lack of knowledge and/or experience in geotechnics and soil, as well as their interaction with the different types of structures. In addition, the absence of oversight in all foundation-related events, such as investigation, excavation, and execution, can also contribute to this lack of performance.

Neves (2010) reinforces that the structure of a building is subject to movements during its occupation and use. It is a fact that these movements generate stresses that, when they exceed the resistance limits of the building components established in the project, result in pathologies in the structural elements, such as cracks and fissures, as stated by Milititsky, Consoli and Schnaid (2015). The author also establishes relationships and similarities between characteristic problems often caused by the lack of adequate soil investigation for foundation design, as described in chart 1.

Chart 1 – Typical Problems Caused by the Absence of Correct Soil Investigation.

Type of Foundation	Typical Problems Arising
Direct Foundations	Excessive contact stresses, incompatible with the real characteristics of the soil, resulting in inadmissible settlements or rupture.
	Foundations in heterogeneous soils/embankments, causing differential settlements
	Foundations on compressible soils without settlement studies, resulting in large deformations
	Foundations supported by materials of very different behavior, without joints, causing the appearance of differential settlements
	Foundations supported on hard crust on soft soils, without settlement analysis, causing rupture or large displacements of the foundation

Deep Foundations	Piles of inappropriate type to the subsoil, resulting in poor behavior
	Inadequate geometry, length or diameter less than required
	Piles supported in resistant layers on soft soils, with settlements incompatible with the work
	Occurrence of unforeseen negative friction, reducing the nominal allowable load adopted for the pile.

Source: Milititsky, Consoli e Schnaid (2015).

For Milititsky, Consoli and Schnaid (2015), the foundation problems related to the construction processes adopted are directly linked to the lack of data on the soil. Without an adequate characterization of all the representative situations of the terrain, it is common to adopt a behavior, load or type of foundation that does not correspond to the reality of the work.

The authors attribute to foundation designers the responsibility for the lack of knowledge and/or experience about the peculiarities of the soil and its interaction with different types of structures. They also mention the lack of follow-up of all foundation-related events, such as investigation, excavation, and execution, as an example of problems at this stage.

- Design of nearby foundations that do not take into account the overlapping of stresses;
- Disregard of the occurrence of negative friction in piles;
- Foundations near or supported by embankments.

FOUNDATION SETTLEMENT

According to Rebello (2008), when the soil is subjected to loads naturally undergoes deformation, which is called settlement. The consequences of this phenomenon result in the movement of the soil-structure interaction, which can cause serious damage.

In the same line of reasoning, Milititsky (2015) states that there are at least three types of damage caused by settlements, namely:

- Visual or aesthetic, which do not present a danger to the structure;
- Damage that compromises the functionality of the structure;
- Structural damage, which endangers the safety of the user.

Regarding settlements and their intensity, in the case of direct or shallow foundations, it is important to consider not only the soil and its characteristics, but also the dimensions of the foundation structure. Generally, in sandy soils, which have high permeability, settlements occur quickly after the application of the load, while in clayey soils, which are less permeable, settlements tend to happen more slowly, and may take many years to manifest.

According to Mello (1975), the preference for deep foundations is due to the consequences of different settlements. In the case of floating piles, for example, the effect of grouping the piles and very deep piles is observed. The author emphasizes that the maximum lateral friction mobilized usually occurs in small settlements, regardless of the diameter of the foundation component (piles). This means that there is a greater likelihood of intense settlements if these small limits are exceeded.

FOUNDATION SETTLEMENT

Foundation settlement refers to the vertical deformation of the soil and foundation structure due to the application of loads. This phenomenon occurs when the load exerted by the structure on the soil causes it to compress, resulting in a gradual sinking of the foundation. Settlement can be differential, when it occurs unevenly in different parts of the structure, or uniform, when it is evenly distributed along the foundation. The control and minimization of settlement are essential to ensure the stability and safety of buildings over time. Several factors, such as the characteristics of the soil, the type and depth of the foundation, and the magnitude and distribution of the applied loads, influence the behavior of the foundation settlement.

TYPES OF UNDERPINS

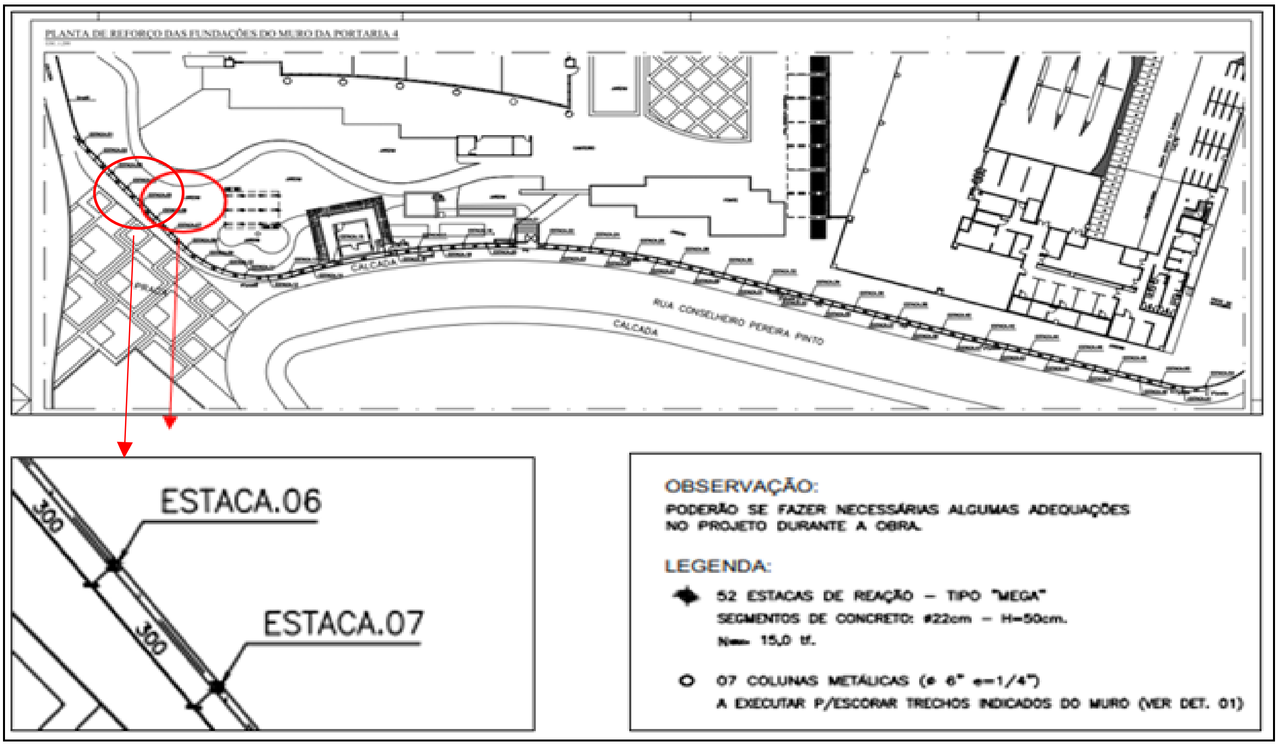
The most common types of foundation settlement, their causes and main manifestations, as well as the reduction of these settlements by means of reinforcements, will be pointed out below. According to Alonso (1991), when a vertical displacement of a foundation element occurs, it is characterized as absolute settlement: Having 02 foundation elements with a difference between the absolute settlements, it is called differential settlement, which causes deformation in the structure and cracks. Regarding static loads, there are 03 types of frequent settlements: settlement by densification, elastic settlement and settlement by lateral flow.

Table 2 – Types of settlements.

Types	Author's Comments
Settlement by Densification	Caputo (2012). It alleges that the deformation of the soil due to densification occurs due to the closure of the voids by the expulsion of water due to the pressure of the foundation applied to it, causing the reduction of the soil mass. In the case of clays, the action of densification is very slow due to the low permeability coefficient. Rebello (2008) adds that when all water is expelled from the voids, the settlement by densification is stabilized, and there is no further reduction in the volume of the soil.
Elastic underpinning	According to Rebello (2008), also known as immediate settlement, this pathology usually occurs in non-cohesive soils, or rather, in non-clayey soils, which undergo deformation after the application of the foundation elements. Teixeira and Godoy (1998) add that the stiffness of the foundation, depth, its shape and the thickness of the deformable layer are relevant factors to be considered.
Lateral Flow Settlement	According to Caputo (2012), lateral runoff deformation occurs more markedly in non-cohesive soils under shallow or shallow foundations. Rebello (2008) defines this pathology as the movement of the soil located in a region of high tensions, moving to regions of low tensions, therefore, the displacement occurs from the center to the lateral

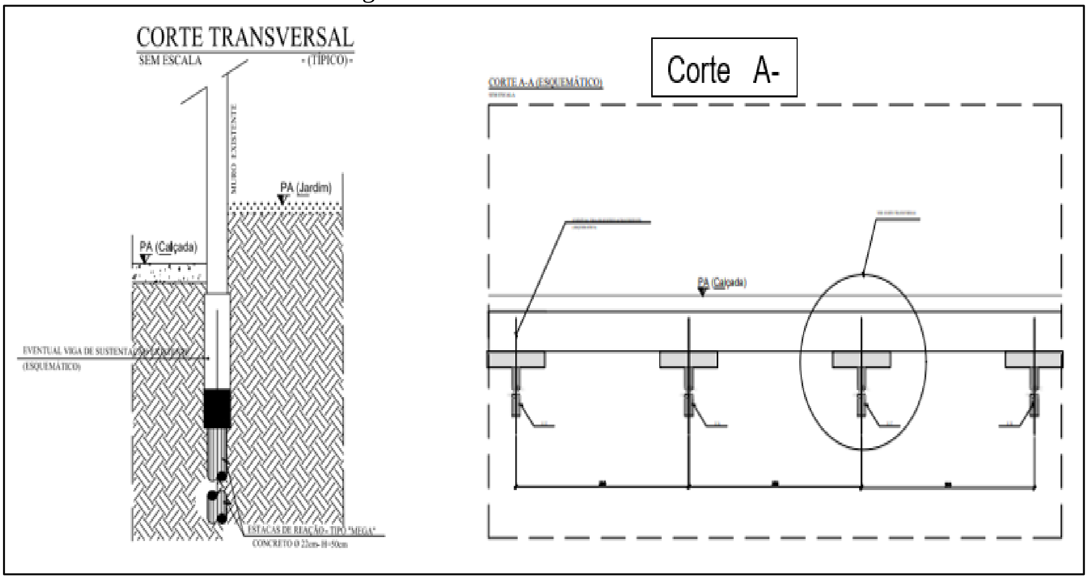
Source: Author's Personal Collection.

Figure 5 – Project with the Distribution of Stakes.



Source: Author's Personal Collection.

Figure 6 – Detail of the Cross Section.



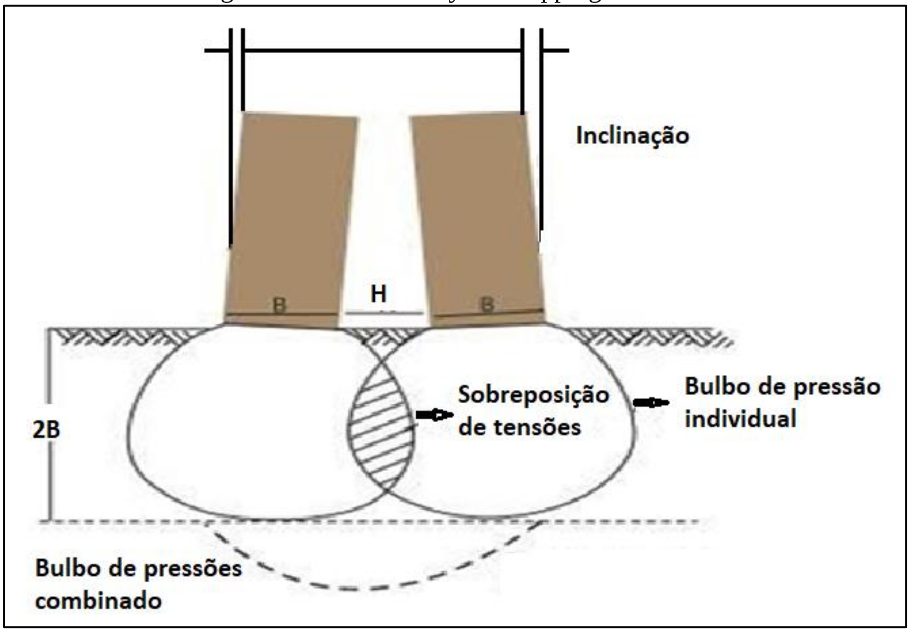
Source: Author's Personal Collection.

Other causes and consequences of settlement in the foundations will be pointed out below:

- Overlapping pressures
- Deficiency in geotechnical investigation
- Influence of vegetation
- Overlapping pressures

This type of manifestation is defined by the installation of another load load, which modifies the stresses in the soil mass with a previously existing soil load, causing settlements (MILITITSKY; CONSOLI; SCHNAID, 2015).

Figure 7 – Settlement by Overlapping Tensions.



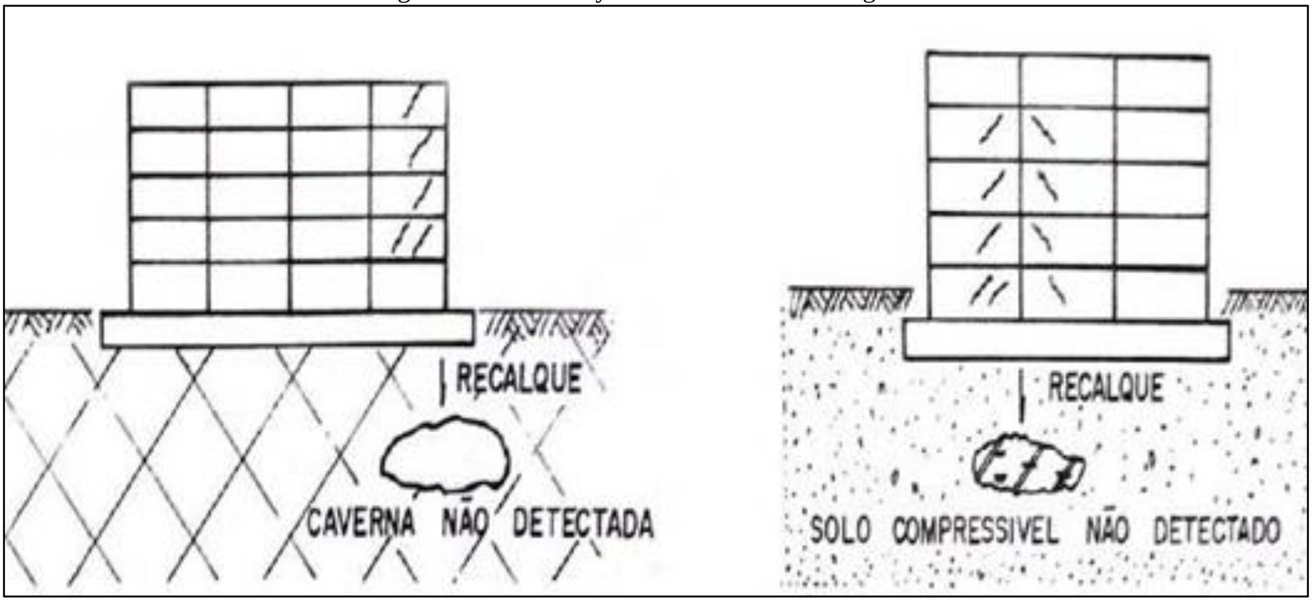
Fonte: Milititsky, Consoli e Schnaid (2015).

DEFICIENCY IN GEOTECHNICAL INVESTIGATION

It usually occurs frequently in small and medium-sized works, for financial and economic reasons, more than 80% of the cases of foundation settlement refer to the complete absence of investigations (SPT probing test), resulting in the adoption of irregular methods and solutions in the project. The absence of boreholes can cause future problems, because the soil that is not investigated, or even superficially investigated, can vary in its composition, and it is possible to have more than one type of soil on the site (MILITITSKY; CONSOLI; SCHNAID, 2015).

There are great risks located mainly in caves (very common in regions where there are limestone rocks) and compressible soils cause the movement of foundations and generate the occurrence of cracks and fissures, as shown in figure 06.

Figure 8 – Deficiency in Geotechnical Investigation.



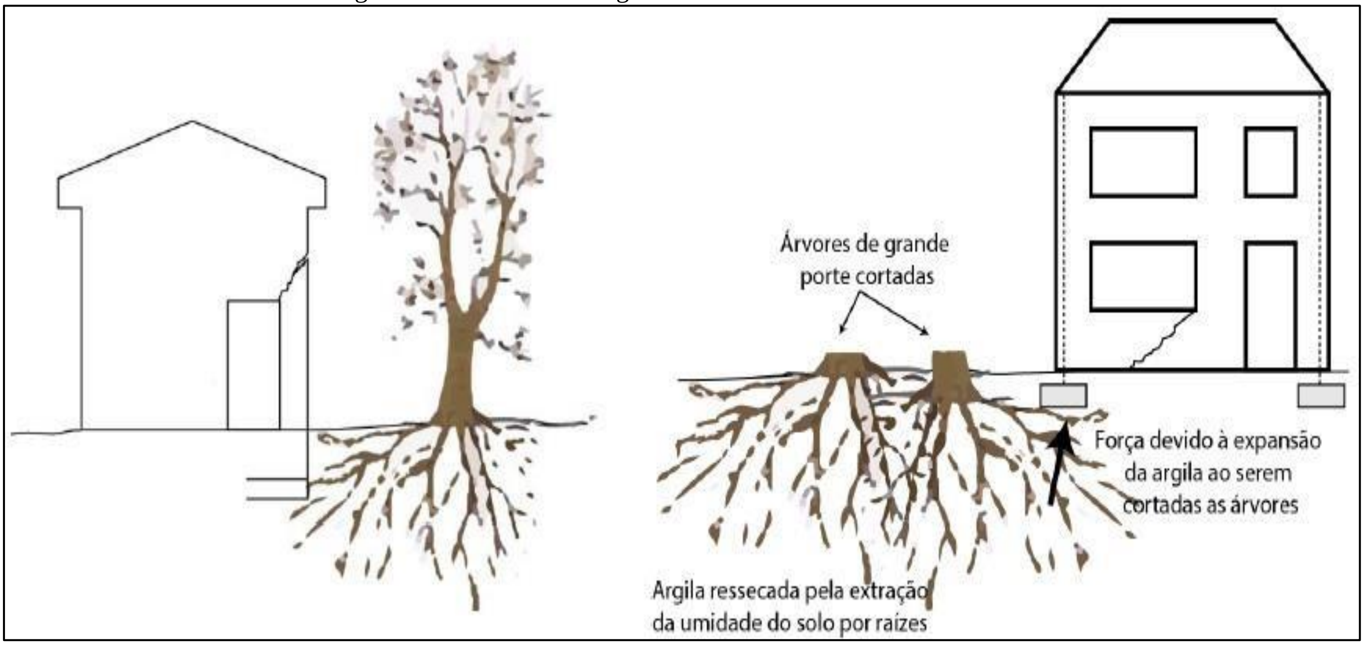
Fonte: Alonso (1991).

INFLUENCE OF VEGETATION

According to Milititsky; Consoli; According to Schnaid (2015), the roots of vegetation cause physical interference in the built areas when their proximity is ignored, since to maintain their growth, the roots extract water from the soil, so the moisture content will be lower compared to the region where there are no roots. Also according to the author, there are several factors that contribute to the influence of vegetation, such as: the type of vegetation present, the type of soil in the place, the distance from the vegetation, the climate and the level of the water table.

It is worth emphasizing that the presence of vegetation near buildings, such as walls, walls and foundations, can contribute significantly to the alteration of soil moisture, absorbing the water present in the soil, generating settlement by densification, as shown in figure 9.

Figure 9 – Influence of Vegetation on the Occurrence of Fissures.



Fonte: Milititsky, Consoli e Schnaid (2015).

TYPES OF REINFORCEMENT FOR FOUNDATION

According to Neves (2010), when a foundation presents poor performance in the transmission of stresses to the ground, whether due to changes in ground conditions, increased loads or both, it is necessary to carry out reinforcements. The main objective of the foundation reinforcements is to increase the original strength of the structure, in order to adapt it to the new boundary conditions and to the pre-established safety criteria. This allows the structure to be able to withstand the additional loads applied and transmit them to stronger layers of the soil.

Foundation reinforcement is the best measure to intervene when the soil, foundation or structure does not perform satisfactorily in the face of the loads and stresses exerted on them. It is possible that complications may occur in the materials that make up the foundation elements, such as corrosion of the reinforcement, for example. In this case, it is a pathology associated with the structure and not with the transmission of load from the structure to the ground. Therefore, it is recommended that these elements undergo a recovery or reinforcement process to ensure the stability and safety of the building.

The choice of techniques to be employed in the reinforcement of foundations must be appropriate to the specific situation of the structure and soil. It is crucial to carry out in-depth surveys of the various techniques available to ensure the efficiency and recovery of the structure, as Silva (2015) points out. In terms of foundation reinforcement solutions, there are many options, which depend on the condition of the problem and its actual cause, such as the type of soil, the urgency of the service, the load exerted, and the space in which the structure sits.

It is important to note that in cases where it is necessary to reinforce the foundation due to pathologies, the costs can be significantly higher than the initial costs of the work, not to mention the impact on the reputation of the engineers and professionals involved. The prolonged time to identify the actual causes, which may result in the evacuation of buildings or homes, is another aggravating factor. As a consequence, this type of problem can lead the company to bankruptcy, as Milititsky (2015) warns. As already mentioned, the choice of the type of reinforcement to be used as a definitive solution varies according to several factors, including the type of soil, the level of loading, the costs, the urgency of the intervention and external influences.

MEGA STAKES

It is interesting to note that the practice of reinforcing foundations dates back to Roman times, however, the first examples of more intensive use date back to the thirteenth century, mainly in the context of cathedral restoration. However, there were no major breakthroughs until around 1900, when the construction of the New York City subway ushered in a new era in this field.

In Brazil, the first record of the use of pressed piles dates back to November 13, 1935, as mentioned by (DONADON, 2021).

According to Schneider (2020), there are several situations that require the reinforcement of foundations, one of the most common solutions being mega piles or reaction piles. These piles are designed to withstand the additional loads for which the reinforcement was requested. This technique is widely used due to its ability to dispense with demolitions during execution, as well as reducing impacts and vibrations in the construction process.

Regarding the advantages and disadvantages, Schneider (2020) and Pereira (2015) emphasize, such as:

Advantages:

- Low impact, vibrations and noise;
- Easy execution in small places that are difficult for machines and people to access;
- Immediate increase in the safety of the building after pile driving;
- Organization and cleaning of the environment during execution, that is, it does not generate a significant amount of waste.

Disadvantages:

- High cost and time, due to the presence of different sizes of piles that will be used in construction, depending on the land on which it is located.
- It depends on the productivity of the execution of the workforce, there is a possibility that it will take a long time to install each pile.

MEGA STAKE TYPES

The equipment used for the use of mega piles is small, small, lightweight, to work in confined and difficult to access spaces. Under favorable working conditions, a team can drive two piles per day. All mega piles, after being completed, transfer the load from the pile to the structure by what is called wedging load, already defined in the technical standard. Due to the small size of this piece, the use of traditional reinforcement is contraindicated and in the case of mega piles with a breaking load above 100 t. (Oliveira, 2016). Another great advantage of reinforcement with metal fibers is to avoid a fragile breakage of the part with dangerous and unpredictable consequences.

MEGA CONCRETE PILES – PRECAST

The mega precast pile, its composition consists of several concrete segments driven through hydraulic jacks. Generally, the elements have the following dimensions: 50 cm long by 25 cm in diameter with a hole of 8 cm in the middle due to the centrifugation method in manufacturing. As for the cost of this type of reinforcement, it is approximately 50% lower than other options, such as the Mega metallic, injected metal pile.

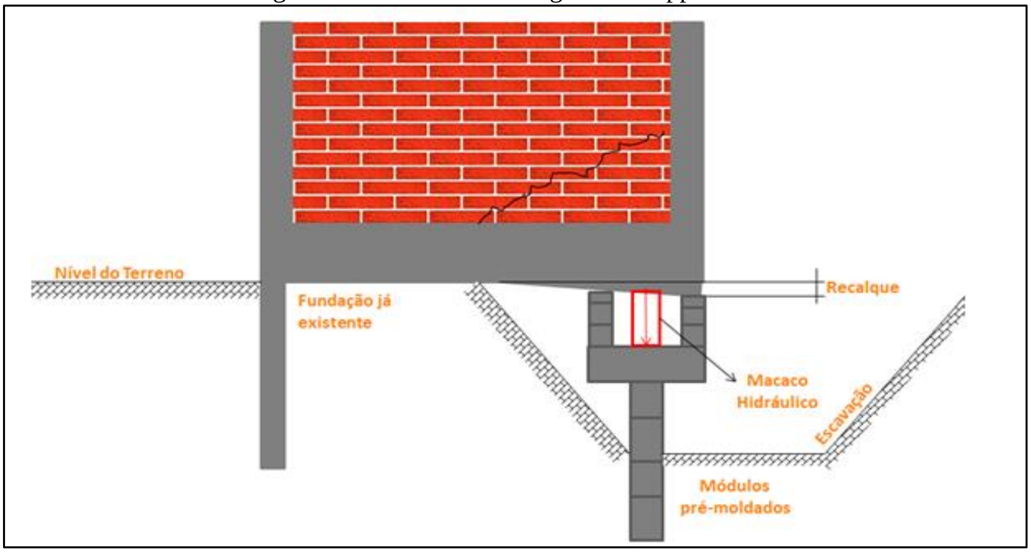
Figure 10 – Mega Precast Pile.

Source: Faraggi (2022).

The method of driving the precast Mega pile is carried out by expelling the pile itself, which results in an increase in the neutral pressure inside the soil, creating a relaxation of the driving later. This is an important aspect of reinforcement that should be considered by engineers and designers who wish to adopt this type of technique, as highlighted by (OLIVEIRA, 2016).

Importantly, the Mega pile is designed for capacities of up to 10 meters and supports a load of up to 45 tons. However, if piles with lengths of more than 10 meters are used or if they hit very soft clay soil layers, the bearing capacity of the reinforcement may decrease due to the buckling effect. This is a crucial aspect to consider during the design and execution of Mega pile foundation reinforcement.

Figure 11 – Sketch with Mega Stake Application.



Fonte: Schneider (2022).

Figure 12 – Mega Staking Application.

Fonte: Schneider (2022).

MEGA METAL STAKES

Installation techniques for this type of pile involve shearing driving the ground. After driving, the pile is filled with fiber-reinforced concrete, which increases the strength, stability and safety coefficient of the reinforcement structure. Then, the top of the pile is wedded and to fill the voids left between the wedging and the pile body, the head is concreted, as mentioned by Oliveira (2016). These procedures ensure a solid integration between the pile and the structure, providing effective reinforcement of the foundation.

They are metal tubes with a diameter of 75 cm, and the connections between tubes are made through threads and sleeves, which are used for the consolidation of the pile structure, as shown in the photo below:

Figure 13 – Elements of the Metal Piles of 75cm Diameter.

Source: Lima (2020).

Figure 14 – Mega metal stake installed.

Fonte: Fonseca (2020).

INJECTED MEGA METAL PILES

It has the function of expelling the mud inside the metal tubes of the injectable piles (MMI) and later injecting cement cream with a pressure of up to 30 kg/cm², forming a new bulb at the tip of the pile and increasing the adhesion between the pile and the soil in the stem. As for the tests and measurements carried out on this type of pile, they point to a workload gain of around 50% compared to traditional piles.

Oliveira (2016) highlights the following advantages:

- In cases where the reaction is limited, the crimping load also remains, and it is impossible to guarantee the safety coefficient of 1.5 for the workload. For example: in a column with 30 t, when we drive a metal pile (MM) and the driving load reaches 30 t, the structure begins to lift and it is not possible to reconcile the driving load with the working load. In this case, we can solve it in two ways: drive two MM piles with 30 t each or drive an injected metal pile (MMI) with 30 t, clean it and inject cement cream so that the breaking load increases to ≈ 45 t, which guarantees a working load of 30 t. In addition, the cost of an MMI pile is less than two MM, as there are the costs of the structural block, eccentric reaction, etc.;
- Another advantage is the possibility of obtaining piles with very high breaking and/or working loads. In some cases, the computerized measurement saw the MMI piles exceed the load of 120 t, having been driven with 80 t and wedged with 55 t each;
- In emergency works, with unacceptable risks, MMI are not only the best, but the only solution;
- Similar to the omega stake and others, the MMI is patent-pending.

ROOT TAG

The history of the Root Stake dates back to Europe, considered the birthplace of most of the technologies used in Civil Engineering today. One of these pioneering technologies originated in Italy, in Naples, in the early 1950s, under the name "Pali Radice" (Root Stake). Initially, the concept of "Pali Radice" was a lattice where the piles would be inclined in various directions, transforming the ground into a "reinforced terrain", in which the loads would be transmitted through blocks dimensioned as direct foundations.

Over time, this concept was changed, and injected excavated piles came to be considered normal piles, provided only with longer lengths, in which the main lateral friction or, to a large extent, the same working capacity in tensile and compressive are counted.

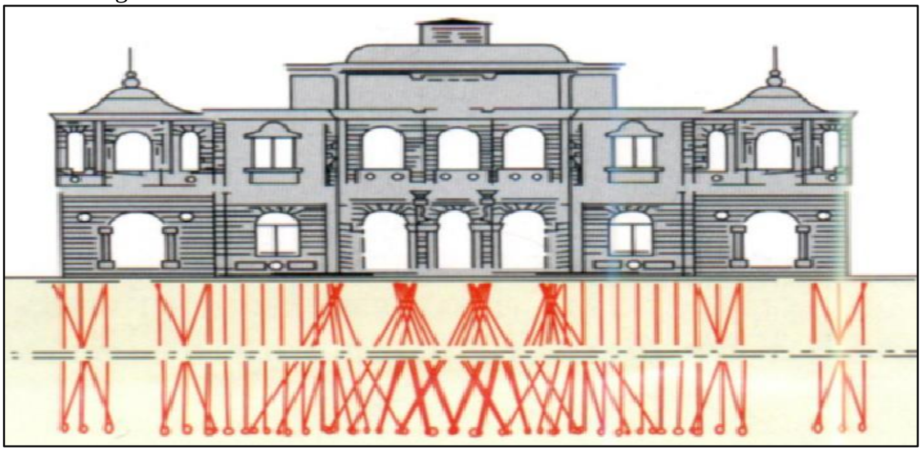
Being the first model of small diameter injected pile, the root pile was designed by the Technical Director of the company FONDEDILE S.A., Engineer Fernando Lizzi, who applied for the first patents on 03/11/1952 under number 497.736 and on 12/29/1952 under number 502.416, (LIZZI apud SODRÉ, 1995). This construction technique, originally developed with the aim of its use in the reinforcement of foundations, promoted a complete change and great ascension in this field of Civil Engineering, solving several problems not satisfactorily solved in the past, having been presented internationally in 1970 on the occasion of the X Convegno di Geotecnia, held in Bari, Italy.

A few years after its development, the practice and results of load tests have provided convincing and definitive evidence of the efficiency of the Root Pile construction system. This inevitably led to the broadening of its field of application. The Italian technique has been widely used on the European continent, where several studies and the improvement of its construction process have been frequently presented and developed.

In Brazil, the root pile technology was introduced in the 70's by the engineering company BRASFOND S.A., which has since been applying it in many construction projects. From that decade on, when the first patents on root piling expired, several other similar piles, generically called micro piles, were widely used. Terms such as mini piles, anchor piles, small-diameter press-injected piles, excavated-injected, injected piles, or a combination of these have been commonly used to refer to them.

Professor Lizzi's initial concept was to create a lattice with piles in various directions, aiming to induce the consolidation of the soil and transform it into a "reinforced terrain", to which the loads would be transmitted by means of a direct foundation. However, over time, this concept has been modified and the root piles have acquired a character of reinforcement of existing foundations. An example of this use was the work carried out by Euller Magalhães da Rocha at the Palácio da Liberdade in Belo Horizonte, as illustrated in figures 13.

Figure 15 – Reinforcement of Foundations of Historical Monuments.



Source: BRASFOND (2022).

Briefly, root pile is characterized as one in which compressed air injections are applied immediately after molding the shaft and on top of it, concomitantly with the removal of the coating. Low pressures (less than 0.5MPa) are used, which aim only to ensure the integrity of the pile (BENATI, 2007).

This procedure contributes to the consolidation of the cracked terrain, compacts the soft soils and causes irregularities in the stem, increasing lateral friction, transforming the site into a "reinforced terrain" (AMANN, 2000).

We have the definition according to NBR 6122:2022, which says that the root pile is a pile molded "in situ", in which the drilling is integrally coated in soil, by means of metal segments that are threaded as the drilling is performed, being recovered after injection. Among its main features, we can highlight:

- High load capacity with very low settlements;
- Possibility of execution in restricted areas and limited heights, with minimal disturbance to the surrounding environment;
- Execution on any type of terrain and in special directions;
- Execution with the use of compression or traction;
- Small diameter;
- Drilling by rotary processes lined with water circulation, bentonite mud;
- No enlarged base;
- After concreting, the coating is removed.
- There are several advantages associated with it, among which the following stand out:
- The reduced dimensions of the equipment allowing work in places of difficult access such as: slopes, buildings with limited ceiling height, etc.;
- The rotary drilling process that avoids vibrations, reducing the possibility of damage to nearby buildings;

- The fact that they are suitable for any type of terrain, because even in those with precarious characteristics they generate high load capacity, with lengths no greater than 30.0m;
- The fact that they resist both compressive and tensile forces in an almost equivalent way, which facilitates their use in structures subject to alternating forces, such as: transmission towers, crane pillars, etc.

The possibility of execution, without major inconveniences, of inclined piles, allowing the absorption of horizontal forces.

In this way, the root pile has been confirmed as a modern technique of special foundations and an effective tool in the solution of the most diverse and complex geotechnical problems, being used in:

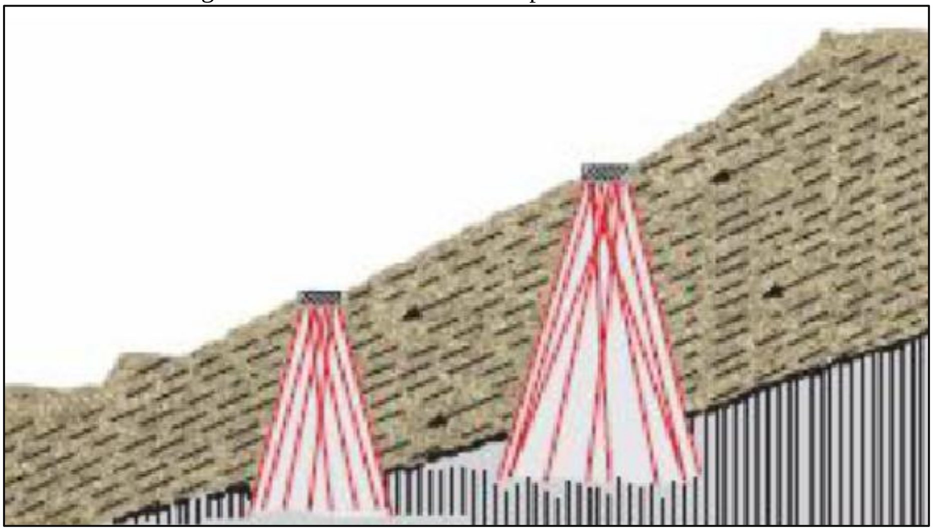
- Retaining walls for protection of excavations in the immediate vicinity of existing buildings (juxtaposed piles);
- Slope containment;
- Anchors of retaining wall and diaphragm walls;
- Tirante-raiz;
- Protection for excavation of subway galleries in inhabited centers;
- Foundations of machines subject to vibration;
- Bridge foundations;
- Foundation of equipment bases in industrial units in operation;
- Reinforcement of mooring piers;
- Foundations that are difficult to execute by traditional methods, either due to the occurrence of thickets in the subsoil, or due to the small space on the surface and ceiling height.

According to the concepts of CABRAL (1986), with the development of executive techniques and knowledge of soil mechanics, it was possible to increase the load capacity and productivity of this type of pile. The author also points out that the root pile is a widely used solution for strengthening foundations, since they can overcome obstacles such as existing foundation blocks, boulders and rocks.

The root pile equipment has reduced dimensions, being able to work in restricted areas with reduced ceiling height, as is the case of the recovery of an element inside a building.

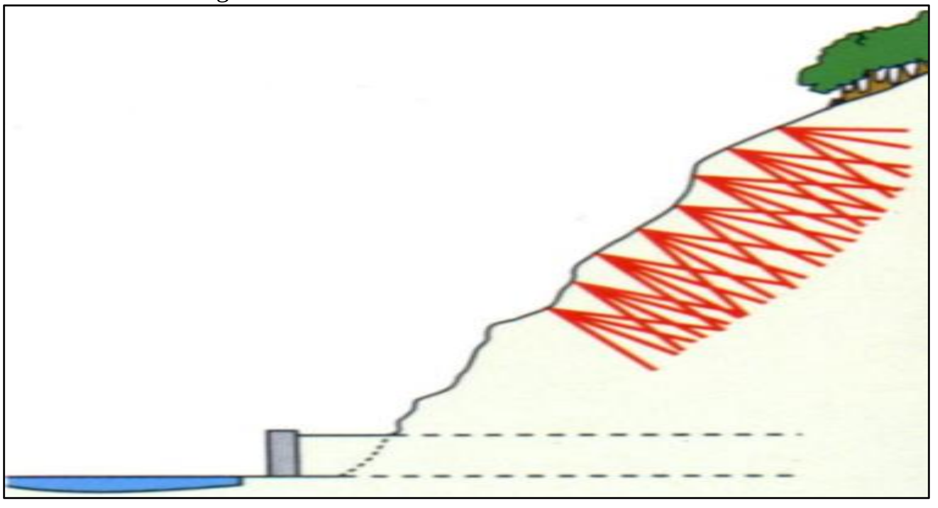
One of its applicabilities is related to slope stabilization and slope containment with unstable soils, the application of the root pile lattice works as an interception wall, intended to contain the mass of the descending soil, as shown in figure 16. In figure 17, we have the case of rock formations, where the lattice works as a seam for the formation of a cyclopean wall. Figure 18 shows the consolidation of the bridge foundation blocks. And figure 19 shows a building subfoundation with root pile reticulation to prevent settlements resulting from the excavation of subway galleries. Figure 20 shows the three-dimensional reticular structure of root piles for building underfoundation.

Figure 16 – Consolidation of Slopes in Loose Terrain.



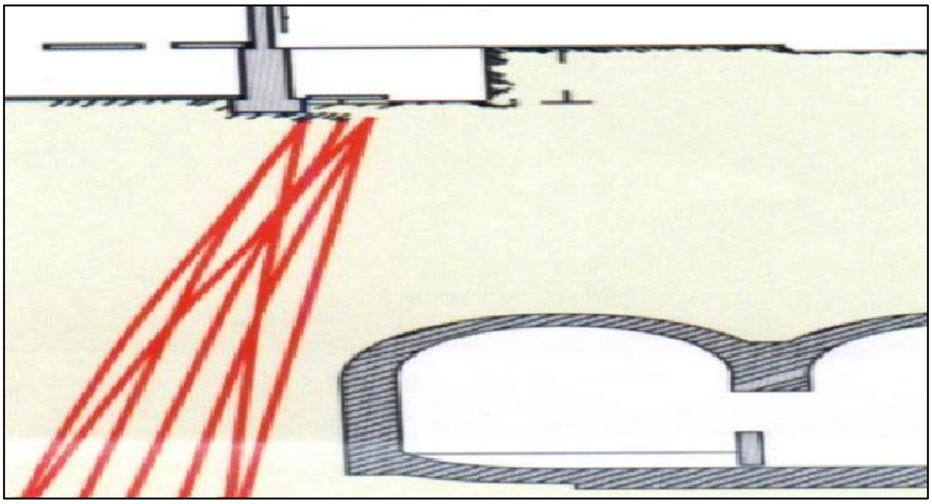
Source: BRASFOND (2022).

Figure 17 – Reticular Structure in Rock Formation.



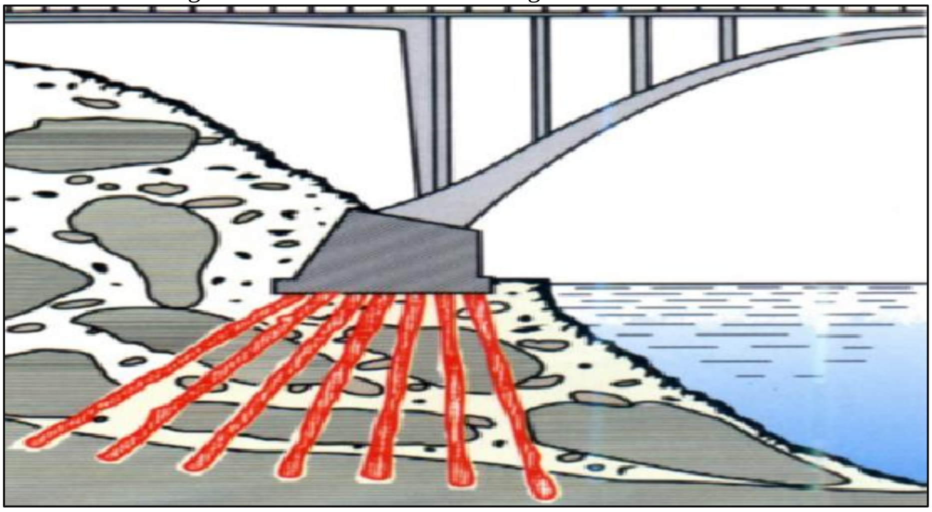
Source: BRASFOND (2022).

Figure 18 – Building Subfoundation with Root Pie Lattice to Prevent Settlements Resulting from Excavation of Subway Galleries.



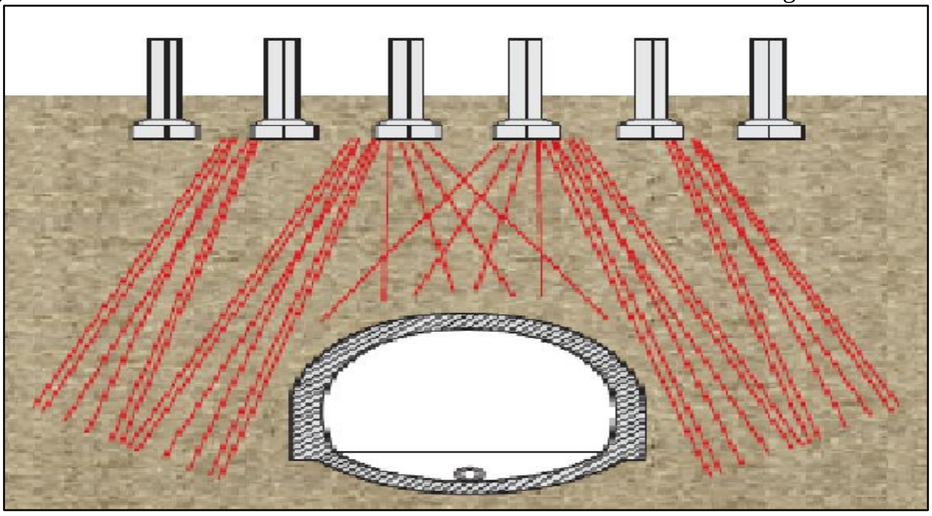
Source: BRASFOND (2022).

Figure 19 – Consolidation of Bridge Foundation Blocks.



Source: BRASFOND (2022).

Figure 20 – Three-Dimensional Reticular Structure of Root Piles for Building Subfoundation.

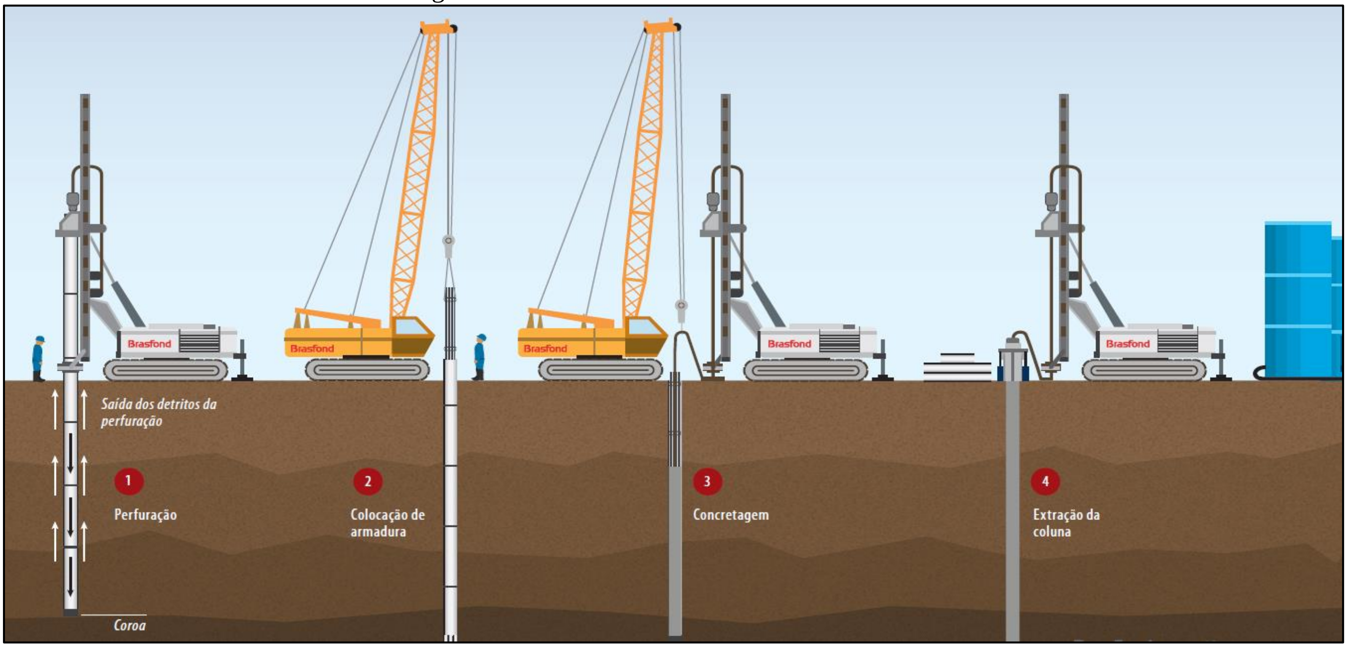


Source: BRASFOND (2022).

ROOT PILE EXECUTION PROCESS

The following is the executive process of the root pile, carried out by the company BRASFOND (2022).

Figure 21 – Phases of Execution of the Root Pile.



Source: BRASFOND (2022).

In detail we have:

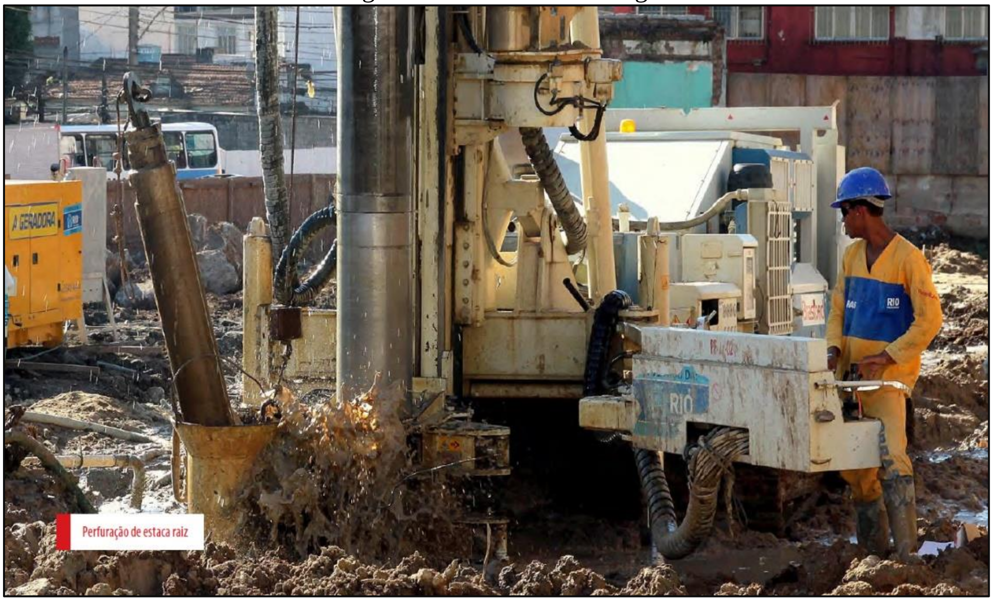
- **Drilling:** drilling is performed by rotation, with continuous lining of the hole and with the aid of a circulating fluid (usually water). The base of the coating is a crown made of carbide inserts, slightly larger in diameter than the coating. The debris resulting from drilling is brought to the surface by the circulating fluid through the ring interstice that forms between the pipe and the ground. This determines that the finished diameter of the pile is always larger than the nominal diameter of the drilling instrument.

As the drilling proceeds, the metal casing is inserted into the ground and the various segments are connected to each other by threaded joints. In the case of rock drilling, this is usually done using a bottom hammer and roto-percussion, up to the design level.

Figure 22: Root Pile Drilling.

Source: BRASFOND (2022).

Figure 23: Root Pile Drilling.



Source: BRASFOND (2022).

- **Placement of the reinforcement:** once the drilling is completed, the metal reinforcement is placed inside the coating. This may consist of one or more steel bars with improved adhesion, several cage-mounted bars or a tube. In the case of partial coatings, the reinforcement must have centralizing rollers to prevent it from removing the soil or being out of position.
- **Placement of the filling material:** the concreting pipe is introduced to the bottom of the drill string and through it the cement mortar is poured. The mortar, cast from the bottom up, ensures that the drilling fluid is displaced outwards and is replaced by the mortar itself. During this

operation, the hole always remains coated and therefore the operation is carried out with maximum safety.

Figure 24: Concreting of the Root Pile.

Source: BRASFOND (2022).

- **Extraction of the drill string:** once the drill pipe is filled with mortar, the drill string is extracted, while compressed air is applied in cases where the characteristics of the ground require it.

LOAD CAPACITY ESTIMATION

The load capacity Pr (tensile load) at compression of a root pile can be estimated based on the results of percussion reconnaissance soundings with SPT measurements, performed in accordance with the ABNT NBR-6484:2020 standard, by the following formula:

$$Pr = \alpha \, Np \, Ap + \beta \, NPL$$

Where:

α = coefficient that depends on the type of soil where the tip of the pile is located.

Np = mean of the values of the penetration resistance indices (SPT) determined at one meter above and one meter below the tip of the pile. SPT values greater than 40 should be taken equal to 40.

Ap = area of the tip of the stake.

β = lateral friction index.

N = mean of the values of the penetration resistance indices (SPT) measured along the stem of the pile.

SPT values greater than 40 should be taken equal to 40.

P = perimeter of the pile shaft.

L = useful length of the stake.

The permissible load Pa of the root pile shall be estimated by:

$$Pa = Pr/2$$

Table 03 – Comparison of Types of Structural Reinforcement

Reinforcement Type	Place of application	Load Capacity (tf)	Production	Demerits	Positives	Value/Costs
ROOT	Foundations in hard-to-reach places, such as inside buildings; Foundations of land with a high density of boulders (rock blocks); Foundation and/or reinforcement of industrial equipment; Slope stabilization; Retaining walls;	10 to 180 tf	30 meters daily	High cost due to its high consumption of cement and hardware for reinforcement	Absence of vibrations	The average value, including labor and materials, is approximately R$290.00 per meter of cutting.
MEGA	Reinforcement of the existing foundation or for correction of pathologies, such as a differential settlement of the structure. (swimming pools, walls, houses, buildings)	Mega concrete piles have their driving load limited to 45 t. for piles with a length of less than 10 m.	50 meters daily	High cost and time, due to the presence of different sizes of piles.	Low impact, vibrations and noise; Easy to execute in small, hard-to-reach places Immediate increase in building safety	The average value, including labor and materials, is approximately **25 to 55 reais per meter**.

PANEL BEAM	Locking of footings or blocks with eccentric loads	According to project sizing	According to the skill of the work team, which is usually composed of 4 employees with a daily production of 10 linear meters.	The cut/bend hardware does not have prompt delivery.	No reinforcement pile is required and there is no equipment mobilization fee	The value is related to the type of beam, with an approximate value of R$ 1780.00 m3

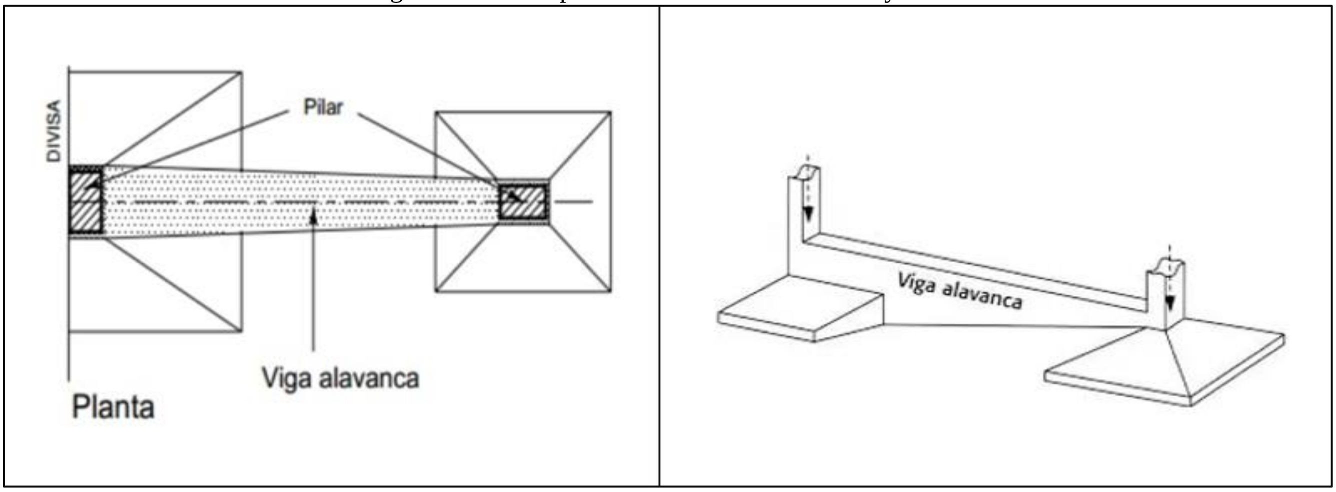
Source: Author's Personal Collection.

LEVER BEAMS

A lever beam is a reinforced concrete structure designed to receive eccentric loads and distribute them in order to contain the bending moment and generate a balance of forces in shallow or deep foundations. This beam is designed to distribute eccentric loads, often coming from boundary wall foundations or even vertical loads from the main structure of the building.

In situations where the structural element receives the load of a column on the boundary and the center of gravity of the column does not coincide with the center of gravity of the structural foundation elements, such as footings or blocks, the ground does not receive the correctly distributed loads. In such cases, a common solution is to use a balance beam or lever beam. This beam redistributes the loads appropriately, ensuring the balance of forces and the stability of the foundation.

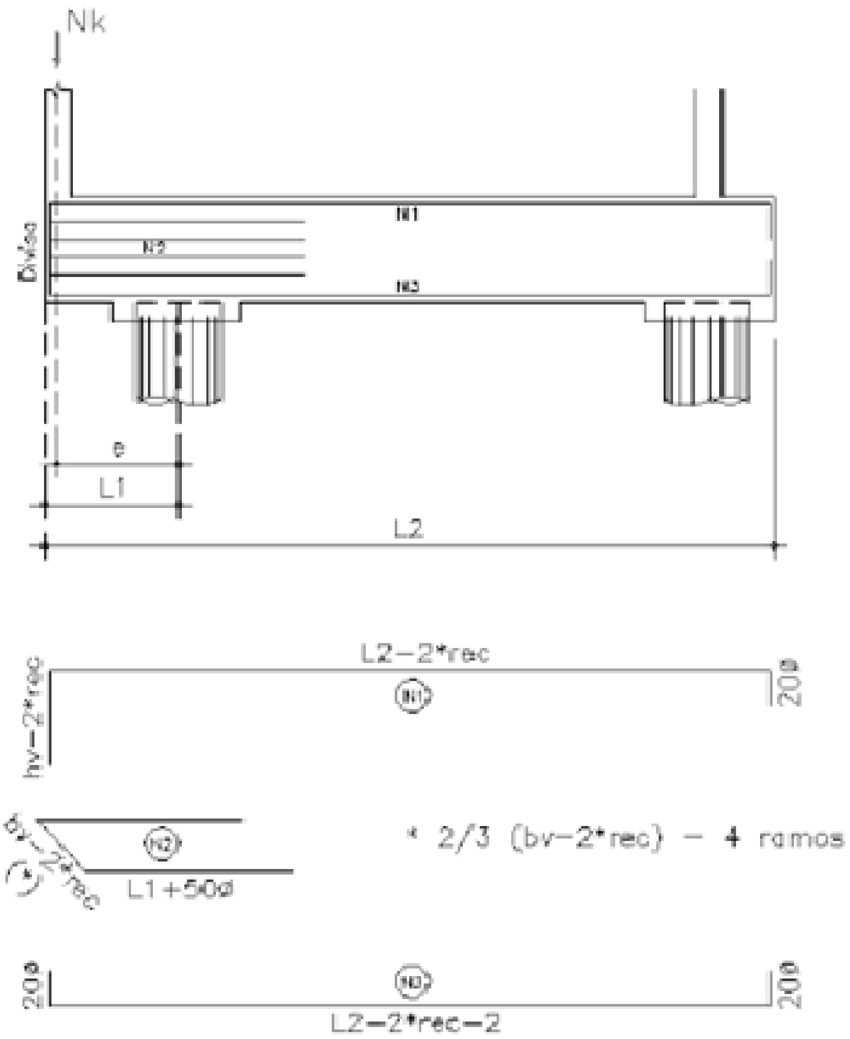
Figure 25 – Example of Lever Beam in Boundary Land.



Source: Author's Personal Collection.

Figure 26 – Design of Lever Beams in Boundary Wall.

No caso de pilares próximos a divisa, onde não é possível a execução de fundação, usamos a viga alavanca para levar a carga até a estaca.



N1 – Armação negativo $Md = 1{,}4 * Nk * L1$

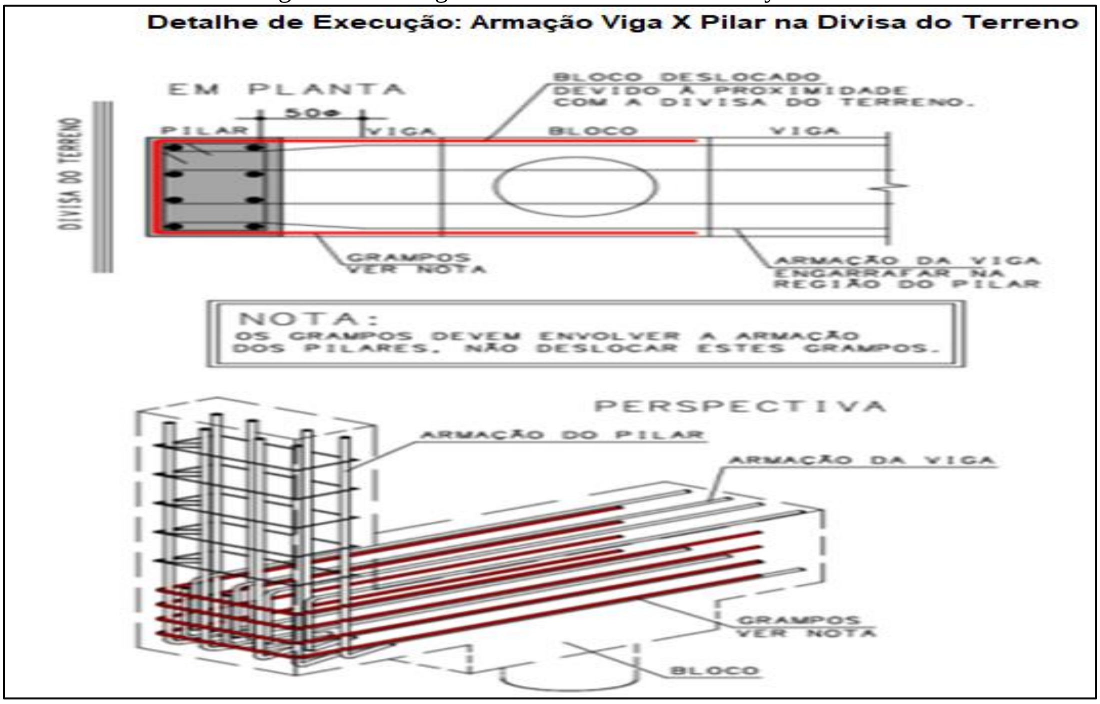
N2 – Grampos $As = \frac{Nk}{n*2500}$ **É Nk mesmo** Estribos - Ø5 c/20

N3 – Armação positiva $As \geq \begin{cases} \frac{Asneg}{5} \\ 2Ø10 \end{cases}$

Verificar a existência de outros esforços na viga para complementar a armação.

Source: Author's Personal Collection.

Figure 27 – Design of Lever Beams in Boundary Wall.



Source: Author's Personal Collection.

Lever beams designed as foundation reinforcement, which in this case the beam serves as structural reinforcement, their purpose is to transfer or absolve eccentric loads from a foundation element wrongly located in situ, and with this the center of gravity of the foundation element will not coincide with the structural element in this case a column. In the case of the lever beam as structural reinforcement, it is necessary that some execution errors occur in the work.

In view of this, it is necessary to pay extra attention at the time of marking, the presence of a topography professional is essential for the rental of the template and also of all the setbacks of the building in relation to the street, in addition to checking the altimetric plan and also the elevations of the neighboring lands and the building itself, With this we are sure that the building will be in the correct position and also that there is no need for permanent or temporary shoring of neighboring buildings. After all the topographic markings of the gauge and the appropriate dimensions adjusted according to the projects, it is time to mark the template according to the rental project, after this step it is recommended a conference by another engineer in order to avoid errors.

Even with all these steps executed, we still have a chance of having errors in the execution of the piles, which is often due to the fact that the soil is bad and the equipment that will execute the pile moves at the time of execution, another recurring error is at the time of marking the paddock on the ground where the person responsible for this activity ends up taking wrong references from the template, or error in the interpretation of the project.

CASE STUDIES – PRACTICAL APPLICATIONS

STRUCTURAL REINFORCEMENT WITH MEGA PILE

Location: São Paulo – Capital

Building: Large commercial

Structure: Perimeter wall of the building – 149 linear meters

Remarks

1. The entire wall presents generalized discrete settlements as shown in the attached photos, perhaps influenced by the works of the Bus Terminal and the Pinheiros Metro Station, which have been completed for some time.
2. The wall presents some discrete signs of external displacement in the places where there are trees internally and next to the boundary wall, as shown in the attached photos, perhaps influenced by the thrust of the ground and mainly the growth of the roots of these trees, in any case also influenced by the works of the Bus Terminal and the Pinheiros Metro Station. This misalignment occurs more located between Stake 05 and Stake 10 of the annex project and has as its main cause the thrust of the roots of the trees on the other side of the wall.
3. The wall presents some misalignments in the plumb line of the walls in the planned expansion joints and that we can consider them normal because they were designed for this purpose, to allow free movement without breaking in the wall.
4. The entire length of the wall has cracks and fissures, mainly inclined ones, showing that the entire support foundation is suffering irregular settlements.
5. As reported, the wall in its entire length presents cracks and fissures mainly inclined showing that the entire support foundation is suffering irregular settlements, only that detachment of the wall to the side of the sidewalk only happens where there are trees at the back of the wall, the garden of the Condominium. The unevenness from the garden to the external sidewalk does not exceed 1.15m, which we consider little for this thrust of ground to be causing the unevenness that the wall is presenting in this region today.

We consider that the roots of the trees are causing this localized vertical movement of the wall.

Recommendations

A. As everything indicates, the most comprehensive problem is that of differential settlements that are occurring or that have already occurred, our recommendation in this case is to pave the foundations of the wall with reaction piles (concrete segments) along its entire length according to the attached reinforcement project.

B. In the case where the wall is leaning towards the bus terminal, we recommend opening a trench with a width of 0.80m and a height of 1.00m along the inner side of the wall and only in front of the tree area, cutting all existing roots and then refilling it with clean soil.

C. Finally, repair the cracks and fissures that exist in a conventional way to control their behavior in the future.

Figure 28 – View of the Crack in the Wall.

Source: Source: Author's Personal Collection.

Figure 29 – View of the Crack in the Wall.

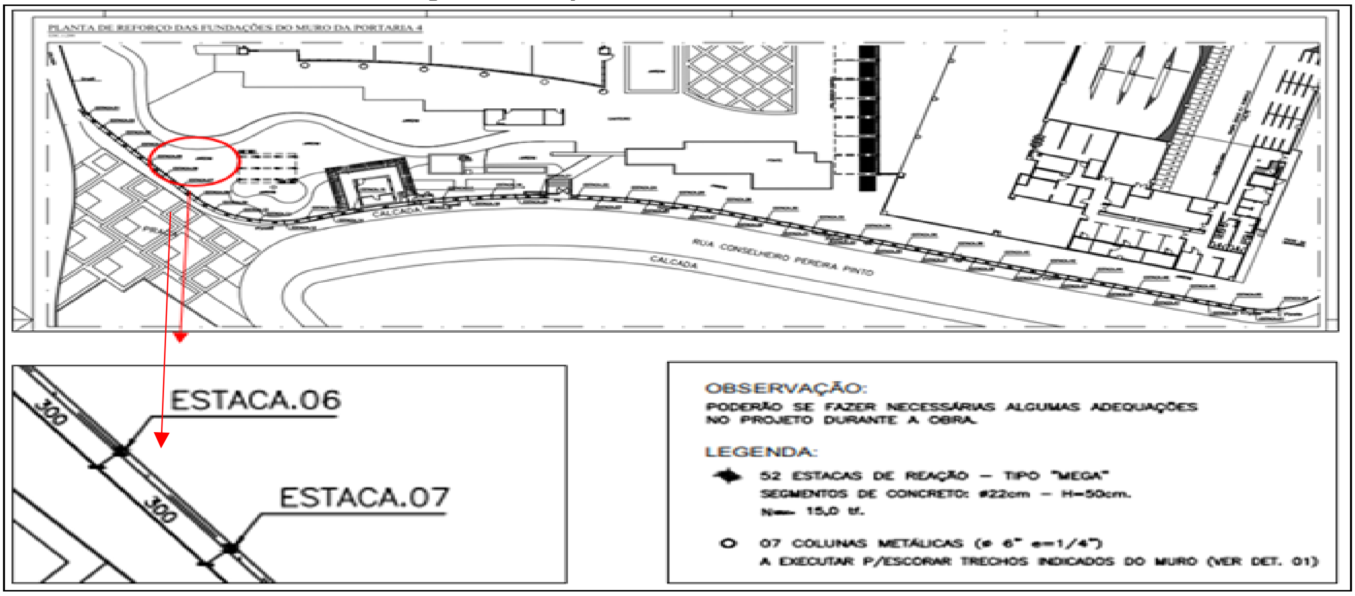
Source: Author's Personal Collection.

Figure 30 – View of the Crack in the Wall and Shoring.

Source: Author's Personal Collection.

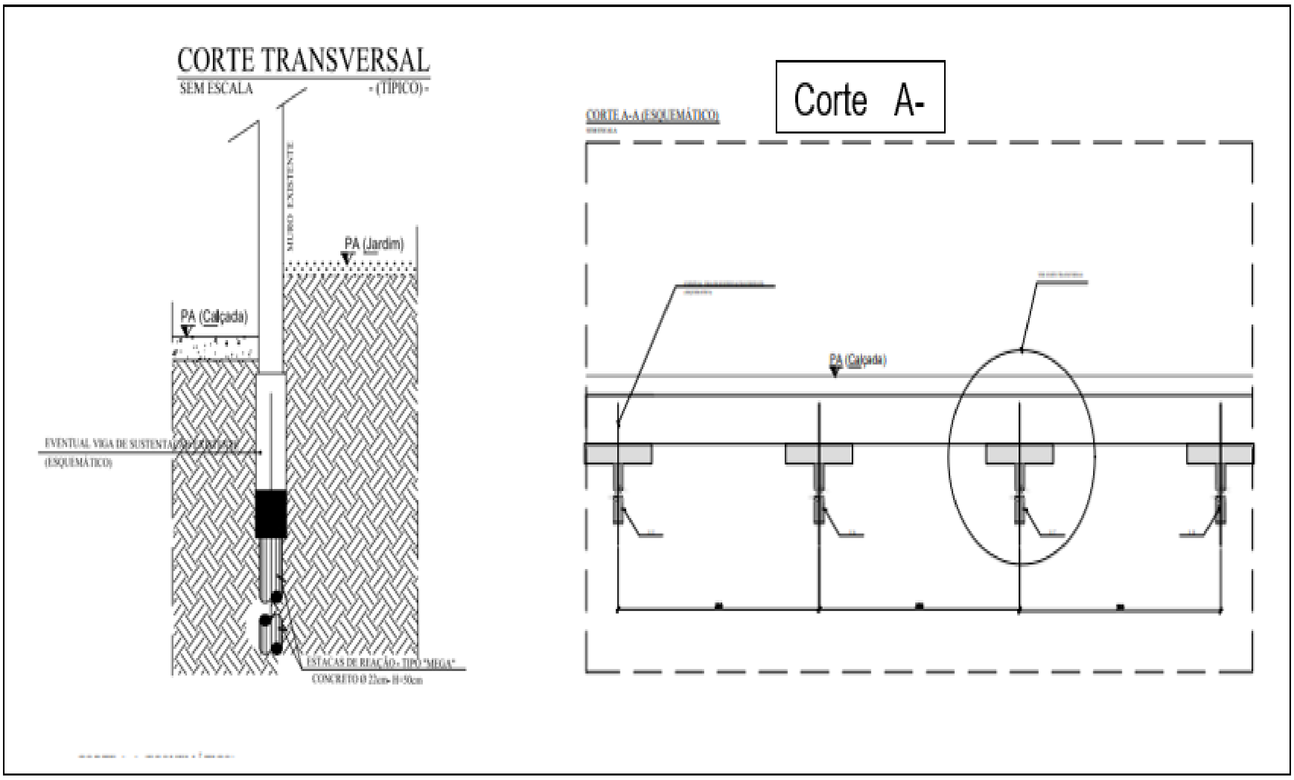
Mega Stake Distribution

Figure 31 – Project with the Distribution of Stakes.



Source: Author's Personal Collection.

Figure 32 – Source: Author's Personal Collection.



Source: Author's Personal Collection.

Work Completed – Mega Pile

Figure 33 – Work Completed with Mega Pile Reinforcement.

Source: Author's Personal Collection.

Figure 34 – Work Completed with Mega Pile Reinforcement.

Source: Author's Personal Collection.

Figure 35 – Work Completed with Mega Pile Reinforcement.

Source: Author's Personal Collection.

STRUCTURAL REINFORCEMENT WITH LEVER BEAMS

City: São Paulo - SP

Project: HIS Social Interest Apartments

Foundation Type: Continuous Propeller

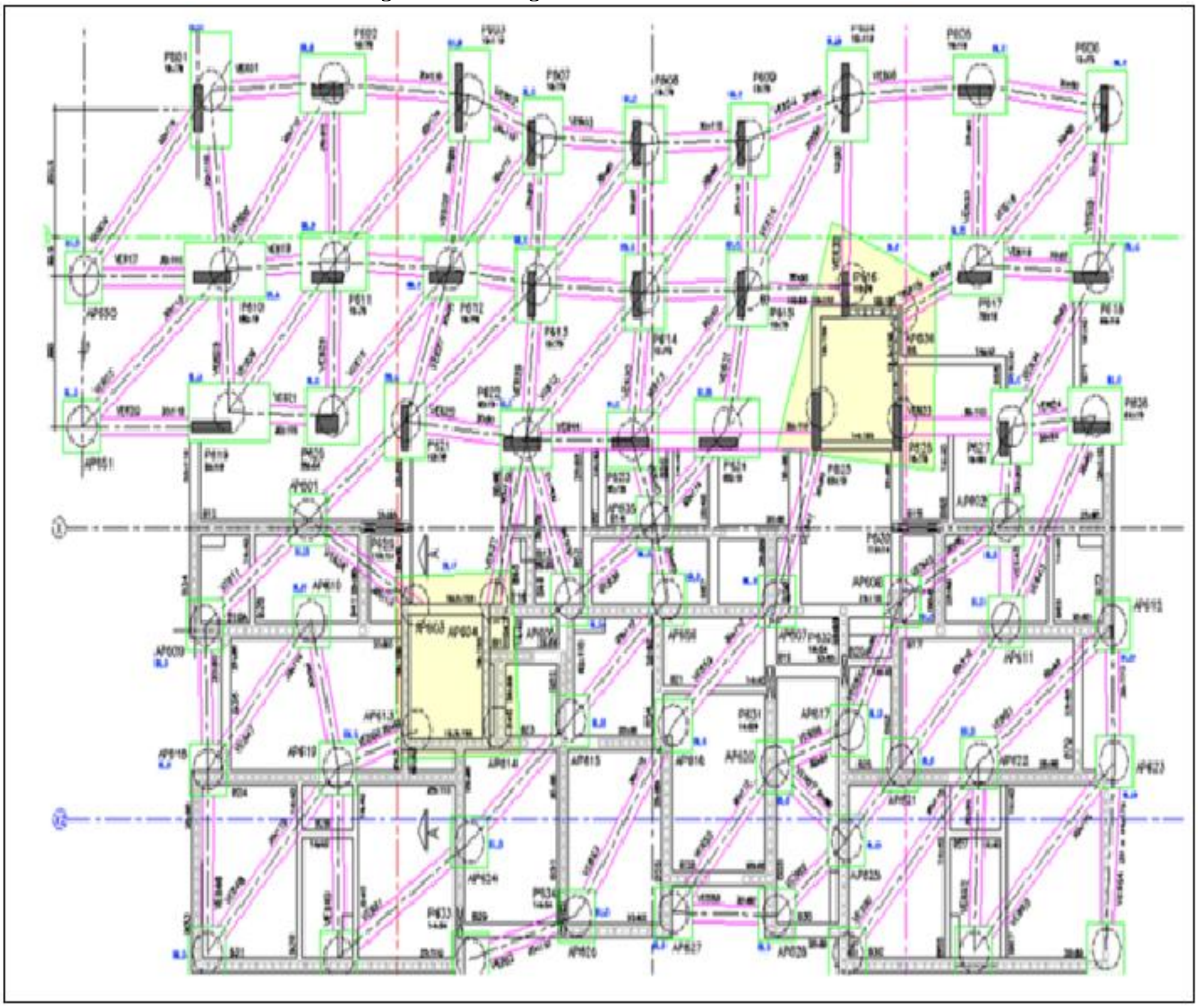
Type of Structure: Structural Masonry with 14 floors

This case, which will be presented in this work, refers to a location error of all the piles, where the engineering team did not hire a topography team to lease the template and also the level levels of the neighbors' land and also the building itself. For the execution of the piles, the engineering team believed that the location was correct, but when they went to lease the piles that are embedded in the foundation blocks, there was a great divergence in all the piles that until now were devastated, with this a doubt was generated and a topography team went to the site to check these piles and the starts of the pillars. The surveyor found that the piles had been wrongly located, and from there it was necessary to call in the foundation and structure designers.

The first step was to raze all the piles of the building and not concrete any blocks so that they could do all the locking of the blocks with each other, and avoid a greater expense with start-ups, not to mention that these steel materials were mainly not on site, as they would have to be dimensioned by the designers, after 30 days of analysis and verification of all the piles, The work had a return of all the necessary reinforcements, all the blocks would have to have a lever beam as shown in Figure 33.

There were approximately 90 lever beams for the building to be built with the location of the wrong piles, and the concreting had to be unique because there were many lever beams together, and many frames with diameter bars of 16mm, 20mm and 25mm, below is a photo of the foundation just before concreting.

Figure 36 – Design and Rental of Lever Beams.



Source: Author's Personal Collection.

Figure 37 –Detail of Beam Frame Levers

Source: Author's Personal Collection.

Figure 38 – Detail of Beam Frame Levers.

Source: Author's Personal Collection.

FINAL THOUGHTS

Investigations of the subsoil are intrinsically related to the most frequent causes of pathologies associated with foundations, since the soil is the medium that will support the loads transmitted by the foundation. Therefore, soil identification and behavior are essential for the solution of any related problem.

For common small-scale constructions, some soil properties may be disregarded due to the lack of need to know them specifically. In such cases, drilling studies are usually carried out to obtain basic information about the soil. However, in situations where pathologies occur, it is essential to know in detail the types of soil on which the work is supported, which may require specific laboratory tests to be carried out. These tests provide more accurate data on soil characteristics, enabling more detailed analysis and better decision-making regarding solutions to foundation problems.

The forces that will be transmitted to the ground occur due to the contact between the particles, which can generate inclined forces with vertical and horizontal components. In the design of foundations, the stresses to which the soils are subjected, divided by an area of soil, are important. Vertical forces give rise to normal compressive stresses, while horizontal forces generate shear stresses.

Although the Standard Penetration Test (SPT) is not the most perfect probing method, it is the most widely used in Brazil and around the world, being recognized as percussion probing due to its way of execution. Soil surveying plays a crucial role in constructions as it allows important indicators such as soil density, consistency of cohesive soils and soil strength to be identified based on the results of the survey. This information is essential for the design and dimensioning of foundations, ensuring the safety and stability of the built structures.

Collapsible soils are composed of unsaturated porous soils that, when flooded, undergo volumetric variation due to air expulsion and rearrangement of particles. This characteristic can result in differential settlements, causing fissures and cracks in buildings, and in more severe cases, structural collapses. To deal with collapsible soils, it is recommended to use deep foundations, so as to support the structure on a more stable soil. There are techniques for the treatment of collapsible soils that can enable the use of direct foundations. One of these is soil replacement, which involves removing the collapsible soil layer and replacing it with new soil, followed by compacting this new soil to achieve a degree of compaction between 95% and 100%. This technique helps to stabilize the soil and reduce the risks associated with collapsible soils, allowing for the use of direct foundations with greater safety.

Collapsible soils often pose a difficult challenge to solve, as soil saturation usually occurs, resulting in water thickening in the subsoil. Often, the presence of saturated soil is not identified due to the high costs of boreholes, especially in small-scale works.

A well-dimensioned foundation must consider an adequate safety factor, foreseeing the possible pathologies that may occur, such as ruptures and admissible settlements as specified in the project, in order to ensure that the structure is not harmed. Regarding the process of executing the reinforcement method and its feasibility, Mega Piles are an interesting option. As they are introduced into the ground by means of a hydraulic pump, they do not cause significant vibrations, which reduces the risks of instability related to the precariousness of existing foundations. This makes Mega Piles a viable and effective solution for reinforcing faulty foundations.

The Mega Pile is often used for the reinforcement of foundations affected by differential settlements in the structure. Its application is highly feasible due to the absence of vibration production during the crimping process, which avoids possible instabilities in the existing foundation. In addition, the Mega Stake can be performed in small and hard-to-reach spaces, which makes it a versatile option for various situations.

One of the main benefits of Mega Pile is that there is no specific limit on driving depth. The depth of the pile will depend on the stabilization of the soil-structure relationship, ensuring that the pile is supported at the proper depth to support the load of the structure. This provides greater flexibility in the design and execution of foundation reinforcement with Mega Piles.

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