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Foundation practice and design in Brazil: a brief review of past and future developments

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Abstract

Brazilian experience in the design and execution of foundations to support superstructures of distinct sorts goes way back to the early colonial period of the XVI century, a few years after the discovery of this land (Katinsky, 1994). Since then, the geotechnical technology related to such constructions has been considerably upgraded and expanded to new system types. The present manuscript aims to briefly review some key aspects of the foundation practice in Brazil during its last decades of development, from the mid-20th century to the present daytime. It does not intend to make a state-of-the-art of the subject but rather highlights the most interesting and relevant points in this evolutionary process of design and construction techniques. Prospective or future foundation technologies will also be envisaged. Given space limitations, it will definitively be narrowed, absent or eventually unfair in some topics or comments. Still, it will serve to highlight the importance of this particular field in the context of the special celebration issue of the 75 years of the Brazilian Soil Mechanics Association. It has been collectively written by some of the most experienced and renowned practitioners and researchers of the Brazilian geotechnical society, despite the absence of so many high-quality others that could equally be present herein. Time and space, unfortunately, have deprived this manuscript of a broader participation and scope.

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Preface from Emeritus Prof. Harry G. Poulos, University of Sydney.

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Brazil has a rich history of geotechnical engineering, particularly over the past 100 years or so. As a graduate student researching foundation settlements, I encountered papers by Grillo and Vargas, and subsequently, I benefitted greatly from the work of such pioneers as Victor de Mello and Luciano Decourt. As an academic, and later a practitioner, I had the privilege of interacting with both of them. Their work related to the uses and limitations of the SPT have stood the test of time and continue to be a reference for many of us that are practicing foundation engineering. Subsequently, I have had the pleasure of interacting with a number of other Brazilian experts, including Professors Renato Cunha and Mauricio Sales, Dr. Luiz Guilherme de Mello, and Dr. Ricardo Born.

In September 2024, I had the privilege of attending and participating in COBRAMSEG 2024, the biennial conference of the Brazilian Society for Soil Mechanics. This was a remarkable event which almost 2200 people attended and provided me with an opportunity to renew some old acquaintances and make many new ones. Photographs of some of these re-acquaintances are shown below through Figures 1 to 3.

This present paper provides a detailed history of the evolution of foundation engineering practice in Brazil. It sets out details of some of the early projects and then presents the results of an interesting survey of current practice. It is noted that while the SPT appears to remain the primary source of quantitative soil data, there is an increasing use of more modern in-situ testing techniques such as the CPT, geophysical methods, and various forms of pile load test, including static, dynamic, and bi-directional load testing. The monitoring of foundation settlements during and after construction of a structure has been quite limited, but it is pleasing to note that the recent Brazilian Standard provides recommendations and mandatory requirements for pile testing and settlement monitoring for buildings of 20 floors or more.

As well as reviewing the past and current practices in foundation engineering, the paper also discusses some of the emerging methods and technologies of investigation, design and testing. These include:

1. The use of more sophisticated in-situ testing techniques, including geophysical methods.
2. The use of piled raft foundations as a means of producing more robust, economical and sustainable foundation systems.
3. Improved methods of estimating the settlement of buildings, particularly high-rise structures, incorporating pile-soil-pile-raft interaction, and the effects of superstructure stiffness.
4. The evolution of super-tall structures, such as the proposed Senna Tower in Balneário Camboriu. I am delighted to look forward to an involvement in the foundation design for this landmark structure.
5. The prospective future use of geothermal energy piles in foundation systems.

The authors are to be commended on their efforts to encapsulate the past, present and future foundation engineering practices in Brazil into a single paper. This paper

Figure 1. Field visit to the pile test at the Senna Tower site, September 2024.

Figure 2. With Professors Renato Cunha and Mauricio Sales, September 2024.

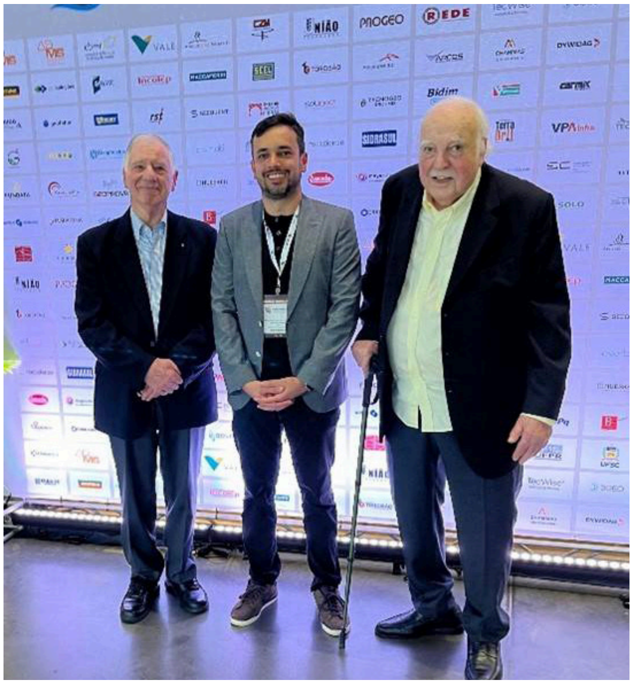


Figure 3. With Dr. Ricardo Born and Professor Luciano Decourt, September 2024.

will extend the already impressive contributions of Brazilian engineers to our discipline and will indicate a path forward for the emerging geotechnical specialists to follow in this remarkable country.

Harry G. Poulos.

1. Introduction

With the evolution of civil engineering and the high level of demand from both construction and habitational areas, given ascendent urbanization and incipient demand for more houses, buildings, viaducts, bridges, ports and other sorts of superstructures, new types of foundation practices were required in the geotechnical field. This necessity has particularly increased with the acceleration of Brazilian industrialization during the 20th. century, together with an intensified rural exodus that has taken place in the last 50 to 70 years.

The present manuscript starts with a brief and summarized recollection of the key historical developments in the foundation area that took place in Brazil since the early 20th. century, gathered from pinpointed historically related articles in journals and books, some of which were based on oral or written recounts that survived through time. The first main section of this manuscript focuses on such past developments and has been extensively based on a previous landmark work of Nápoles Neto (1970) and Sayão (2010), with selected passages incorporated and rewritten herein.

It is followed by a second section centered on more recent aspects of practice and foundation design of the 21st. century. This section attempts to focus on the four most relevant aspects of the foundation area, common geotechnical design, assessment and key practices of this whole period. Future tendencies will also be displayed, although their implementation or eventual success is not yet guaranteed, given economic, political or technological unpredicted turnovers.

2. Historical developments in the 20th and early 21st centuries

At the beginning of the twentieth century designers and contractors started to count on one of the best construction materials of the modern civil engineering industry: concrete. It is the knowledge that concrete multi-layer structures of this era could be built over shallow footings of reinforced concrete or on top of massive rigid blocks of non-reinforced concrete. Besides, deep foundations could be represented by reinforced concrete types in addition to the already in-use wood ones. This era was also initially marked by the entry into the market of the first specialized company on seaport construction and pile foundations in Rio de Janeiro and by the expansion of the port of Santos, where the first reinforced concrete pier supported by concrete piles and retained by a sheet piling wall was executed. Between 1926 and 1927 the dock of Rio de Janeiro was also expanded, and the foundations consisted of pressurized piers executed with driven shaft elements of reinforced concrete.

However, until the end of the ‘20s, empiricism was predominant in geotechnical engineering. “Experimentation, however scarce, was carried out directly in the stonemasonry of the work and a restrained fashion”, according to the former ABMS president, the engineer, Antonio Nápoles Neto (1970, apud Sayão, 2010). Possibly the first Brazilian geotechnical undertaking was described by Domingos da Silva Cunha in the Brazilian Journal of Engineering with the title “Experiments on terrain for the study of foundations”. In this paper, Silva Cunha warned of the variations in resistance and deformation of the soil as a function of chemical content variations in the terrain’s humidity and depth.

Nevertheless, it was precisely in the next decade that the first academic investigations were carried out by technological research institutes of the young Republic and by the Polytechnic School of São Paulo (USP), the latter more focused on the problems of the foundation engineering. In 1934, the Laboratory for Material Testing of the city of São Paulo was transformed into the Institute of Technological Research of São Paulo (IPT), attached to the academic activities of the Polytechnic School. Early work in IPT started in 1938 under the coordination of engineer Odair Grillo and aimed at both the correct paving of earth roads and the study of foundations of bridges and buildings.

Regarding foundation engineering, which is the scope herein, the first step to solving engineering problems was the development in 1939 (Grillo, 1939) of a drilling/sounding equipment for the exploration and analysis of the subsoil.

Thus, IPT standardized a soil exploratory device method, later published by Vargas (1945), which consisted of the introduction of a standard thin-walled steel sampler by a percussion method with water circulation, simultaneously to the counting of the required number of strokes of a falling impact hammer of 60kg in weight, from a gravity drop height of 75cm, to penetrate 30 cm into the soil. The number of blows necessary to penetrate this sampler to a standard length of 1 foot (30.48 cm) was termed N(IPT). The high variability of the testing results from both "Brazilian" techniques at the time, given differences in procedure and especially due to distinct "standard" N quantifications, posed serious problems of comparison and foundation design (via empirical rules, as still used nowadays). Therefore, over time, persuaded by periodic discussions at technical congresses, the IPT´s number N variable was replaced by the international SPT quantification method of Terzaghi & Peck (1948), which approach was later regulated and standardized for the whole country by the Normative ABNT NBR 6484 in its first version of 1980 (ABNT, 2020a).

Among the numerous construction sites and foundation works carried out in the country during the 20th century, some are worth mentioning and deserve to be described, especially given their innovative foundation solutions and the engineering difficulties they faced with the available technology of the time.

The first case that deserves mention is the Paulista Insurance Company Building in São Paulo. This is a 26-story building whose construction began in 1940, with a subsoil investigation partially conducted inside the construction area, given the existence of an old building about to be demolished (during further construction stages). Thus, the piles were designed based solely on one of the sides of the site, which allowed those foundations to behave as "end bearing" due to an existing shallow stiff clay stratum. However, on the other (non-surveyed) side a soft silt layer existed on the profile. This misconception in design was further aggravated by the (satisfactory) load tests solely carried out on piles that were executed on the investigated site. After three years, in 1943, the building was opened and soon afterwards, the IPT Institute detected in the monitoring records an accelerating tendency of column settlements from the building side located in the non-investigated part. Daily differences, or settlement increases, of up to 1mm from morning to afternoon readings, were noticed, together with a steady tilting of the building. This edification is presented in Figure 4.

According to Villares (1956), the solution to the problem was achieved by an overall freezing process of the subsoil in 162 freezing steps, in which the final temperature was kept at -20° Celsius. It was followed by the drilling of injection wells, where galvanized metallic pipes were installed up to 14m in length. With the hardened ground and transitory suspension of settlements, the injection of concrete through these pipes transformed them into cast-in-situ reinforcement piles. The building was finally realigned in the vertical direction by the temporary insertion and pumping of hydraulic jacks onto existing columns.

Figure 4. Historic picture from the end-of-construction building of the Paulista Insurance Company (after Sayão, 2010).

One decade later, in Rio de Janeiro, the project and construction of the building Marquês de Herval, conducted by Prof. Costa Nunes, also calls for attention. This building was constructed by subsoil excavation with simultaneous water level drawdown up to 9 meters depth in a region surrounded by older constructions founded on shallow foundations. Another successful case of high expertise and challenge.

It was also in the '50s that the construction of today's capital of the Federative Republic of Brazil, Brasilia, started. Rio de Janeiro's companies were responsible for conducting the site investigation of the subsoil, composed of sandstones and siltstones covered by a layer of residual soil, originating from the typical metamorphic rocks of the region. Faced with such distinctive (from the coastal zone) geological conditions, the contractors opted for deep foundations with Franki piles and uncased manually excavated caissons (locally denominated as "tubulão").

The '70s were marked by several works of great technical challenge and financial impact for the country, taking advantage of the good winds in which Brazil was sailing at the time (nowadays recalled as the "economic miracle" era). Among several works in the foundation field, the literature highlights the Rio-Niterói Bridge in 1974, where a tragic accident took place during a load test over Guanabara Bay, causing the death of eight workers in total, among them 3 engineers, Dr. José Machado, Eng. Raul Arends, both from IPT, and Eng. Nikon Vianna, of the Rio-Niterói Construction Consortium (Massad, 2025, personal communication).

This bridge is 13.3 km long and 26.6 m wide, with six lanes of traffic, and is still considered nowadays a national landmark of engineering, given all the executive difficulties and the geotechnical particularities. As for the bridge foundations themselves, in the dry (land) sections metallic and Franki-driven piles were used, whereas in the wet (sea) section pressurized 1.8 m diameter manually enlarged drilled caissons were constructed with lengths that varied according to the thickness of the superficial organic soft clay of the bay. This was indeed considered a pioneer solution for the time. Altogether 1138 caissons were executed, 462 were pressurized by air, 199 were of mixed type and 477 used the "Bade-Wirth" technology (Figure 5).

In the '90s the magnificence of the Brazilian economy slowed down, given international external problems, such as the "petrol crises", and national internal financial calamities, as hyperinflation and recession (nowadays recalled as the "lost" era). Nevertheless, some milestone works can be recalled, such as the excavation and foundation reinforcement of the Sears Mall in São Paulo in 1989, to what would be known as the Paulista Shopping Center. Located in an area of large commercial appeal and high acquisitive economic power, this work was marked by its great difficulty, as shown in Figure 6 through one of the few remaining pictures.

The original conception was the deployment of three additional basements to the original Sears Mall, built in 1949. It is reported that the original building consisted of three floors and a basement with a level difference of 4.3 m from the street. The first building block had shallow foundations 2 meters below the basement level, and the second block was supported by drilled caissons 14 meters long, which were constructed in 1972 during the initial expansion project of this mall.

The foundation solution adopted for the first building block was the substitution of the shallow foundations for deep ones, allowing the excavation of an extra 9 meters of soil, or the 3 additional required basements. For the second block, the strategy was the reinforcement of the existing caissons simultaneously with the excavation. At the end, the caisson's bases were enlarged and concreted with additional steel reinforcement cages. Besides the foundations, retaining structures made of (secant and non-secant) pile curtain walls with caissons of enlarged (and non-enlarged) bases were constructed to safely sustain the excavation process. It is worth mentioning that the commercial activities of the Sears Mall were not interrupted during the execution of such services. More details in Gotlieb (1991).

Like the readjusting tides, so are the economies of the world. After an era of depression and internal readjustments, which painfully demanded many personal sacrifices, political compromises and a new economic order, Brazil was able to turn over the table and reestablish itself on the path of sustained development and growth in the early years of the new millennium era or 21st. century. This was particularly due to the control of the hyperinflation of the previous decade, through the astonishing

Figure 5. Example of pressurized drilled caisson platform and site work over a river in the interior part of Brazil (Source: Personal databank from the authors).

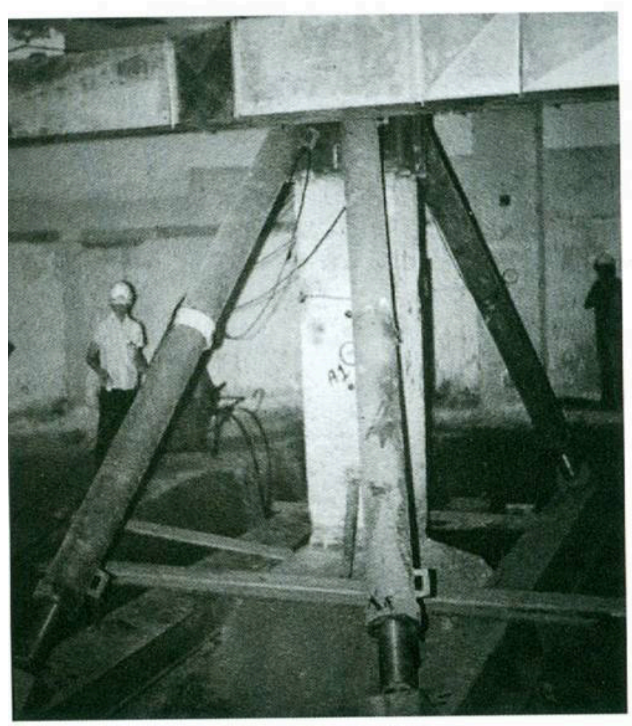


Figure 6. Foundation reinforcement at Paulista Mall (after Sayão, 2010).

and innovative "real plan", that introduced a new era of stable currency and financial control in the country.

The fast development of the country involves not only the use of more sophisticated techniques for foundations to support the increasing magnitude of the loads from superstructures that become slenderer and taller every day, but it also involves the formation of a skilled working force to safely deal with design and construct such demanding structures. This point is valid for all fields of engineering, from foundation to civil, mechanical, electrical, naval, energy and so on. Besides, the increasing demand for sustainable construction, space optimization and green areas has obliged urban constructions to use "less noble" subsoil areas for parking, transportation, storage and related items, leaving open environments for the more noble activities of living, entertaining and working.

More recently the demand for space in urban areas has taken a turn in some Brazilian cities, allowing the establishment of legally approved "tall buildings" in the Brazilian context. Cities like Goiânia and Balneário Camboriú started ahead, with the construction of slender buildings with more than 50 floors, such as the Orion Business in Goiânia (183 m, 2017) or the Yatchthouse Club in Camboriú (274 m, 2019). In Camboriú it is planned the construction of a +500 m building, named Senna Tower in memory of the famous Brazilian racer. With more than 150 floors, it will inaugurate a new stage of construction/foundation standards in the country, which will stress even more the refined investigation and meticulous design procedures. Figure 7 presents the idealized tower in the Camboriú scenario.

Figure 7. Artistic projection of the new Senna tower (Crédits FG Empreendimentos Ltda).

Therefore, for the years ahead, there is potential to develop and sustain an increasing demand for challenging technologies capable of producing and designing deep foundations with longer, slender and vibration/noise-free piles, that would intervene and disrupt to a minimum the surrounding environment, and would eliminate the production of undesirable (unfriendly environmental) by-products, as contaminated soil, soil-bentonite mixtures, etc. Carbon footprint calculations will probably be in high demand for future foundation developments, perhaps selecting bids or preliminary design decisions.

Indeed, it is with such spirit that one must realize that the foundation engineers of the future, the young generation still studying today, will face a new reality in which the foundation problems will be engaged and solved altogether with other perspectives, and eventually new demands. That means, from geometrical scales and geological/geotechnical points of view to environmental restrictions, as well as special construction characteristics, optimization procedures, and, definitively, with new sustainable attitudes of the new age.

3. Key aspects of the foundation practice and design for the new millennium

This main section is subdivided into four subsections, i.e., common foundation types and design and the construction experience in the referenced period; specialized or advanced procedures that have been developed and are used in current practice today, as piled raft assessments or soil-structure interaction (SSI) evaluations; quality assessment and assurance tests, as in situ tests for project and pile/plate load tests to validate the design; and finally the possible future applications for the foundations, for instance as part of superficial geothermal energy systems (SGES) to provide sustainable "green" energy to superstructures.

3.1 Common foundation types and experience

In recent decades, Brazil has experienced unprecedented urban growth and development, which has had a profound impact on the field of civil engineering. As cities expand and evolve, the demand for constructing increasingly slender and taller buildings has risen, placing new and complex requirements on foundation engineering. These requirements have driven the advancement of foundation technologies and methods, reflecting the ongoing evolution of engineering practices in response to the challenges of modern construction. The constraints of limited urban space have significantly influenced foundation design and installation. This has led to the adoption of advanced foundation techniques and the refinement of traditional methods to address the unique challenges posed by high-rise buildings and intricate urban environments (Cunha, 2011; Savaris et al., 2011; Cunha & Albuquerque, 2014; Monteiro et al., 2019; Gusmão et al., 2020).

This section aims to provide an overview of the current practices in foundation engineering in Brazil, highlighting the advancements made in response to these evolving demands. By examining the innovative techniques and solutions implemented to address the challenges of urban development and construction in diverse geographic regions, the Brazilian Association of Soil Mechanics (ABMS) celebrates the progress achieved in the foundation engineering field over the years.

3.1.1 Usual types of foundations in Brazil

In Brazil, foundation design and construction practices reflect the country's varied geological conditions and building requirements. The most used types of foundations can be broadly categorized into shallow and deep foundations. Shallow foundations include single and combined footings and rafts. The ABNT (2022) describes shallow foundations as a foundation in which the load is transferred to the ground through the stresses distributed under the foundation base, and the installation depth relative to the ground surface is less than twice the smallest dimension of the foundation. Deep foundations are also prevalent in Brazilian construction. They are defined by foundation elements that transfer the load to the ground through its base (tip resistance), lateral surface (shaft resistance), or a combination of both. Its tip or base must be embedded at a depth greater than eight times its smallest dimension and at least 3 m (ABNT, 2022).

Pile foundations are defined as slender elements with large lengths and small cross-sectional areas relative to their diameter. Caissons are deep foundation elements constructed by mechanical or manual excavation of a circular shaft (sometimes lined), commonly with an enlarged base, and later concreted (Albuquerque & Garcia, 2020). They differ from piles because, in the final stage, a worker must descend to complete the geometry (enlarged base) or perform the cleaning. These foundation types are selected based on soil characteristics, load requirements, and construction site constraints. The ongoing development in geotechnical engineering and construction techniques continue to influence foundation design practices in Brazil. Table 1 presents Brazil's most common pile types used in building construction.

An online survey was conducted to assess current foundation engineering practices in Brazil. ABMS members and foundation professionals were invited to participate via Google Forms. The survey comprised 8 questions (five multiple-choice, two checkboxes and one yes/no question) as described in Table 2.

Table 1. The usual type of piles in the Brazilian experience (Albuquerque & Garcia, 2020).

Pile type	Length (m)	Diameter (m)
Continuous Flight Auger (CFA)	3 – 34	0.30 – 1.20
Root pile	Variable	0.16 – 0.45
Steel pile	Variable splicing	Variable
Manually cast-in-situ pile	3 – 6	0.20 – 0.30
Timber pile	3 – 15	0.20 – 0.40
Precast concrete pile	Variable	Variable
Mechanically cast-in-situ pile	3 – 18	0.25 – 1.20
Bored cast-in-situ with support fluid	3 – 100	0.60 – 1.60
Hollow Auger	Variable	0.25 – 0.50
Strauss	3 – 25	0.25 – 0.45
Franki	15 – 40	0.30 – 0.70
Full displacement pile	3 – 28	0.27 – 0.47
Statically Pressed Pile (Mega Pile)	Variable	Variable

Table 2. Questions in the survey to evaluate the current state of foundation engineering in Brazil.

Question ID	Type	Question
Q1	Multiple-choice	What is your primary work type in the foundation engineering field?
Q2	Multiple- choice	In which states have you conducted work over the past ten years? (Select up to three states)
Q3	Checkboxes	Which tests have you employed in your foundation projects?
Q4	Checkboxes	Which quality control and performance tests for foundations have you conducted over the past ten years?
Q5	Yes/No	Have you prescribed/conducted pile load tests previously for your design projects?
Q6	Multiple- choice	In the buildings where you have worked, was settlement monitoring conducted?
Q7	Multiple choice	In the buildings where you have worked, what percentage underwent settlement monitoring?
Q8	Multiple choice	What is the primary type of foundation solution you have encountered in your practice over the past ten years?

The survey, completed by seventy-four participants, categorized respondents into five professional groups: designers, contractors, inspectors, academics (professors/researchers) and consultants. The participants were: designers 32%, contractors 20%, inspectors 2%, academics 32%, and consultants 14%. The survey aimed to assess the geographic distribution of foundation engineering practices in Brazil over the past decade (Figure 8). Participants were asked to indicate up to three states where they had conducted work. The results revealed significant regional variation. São Paulo was the most cited state, with 30 participants (40.5%) reporting activity there, followed by Rio de Janeiro (26 participants, 35.1%) and Minas Gerais (22 participants, 29.7%). Other states with notable activity included Pernambuco (21.6%), Bahia (20.3%), Ceará (17.6%), and Goiás (17.6%). In contrast, some states had lower reported activity, such as Acre (2 participants, 2.7%) and Roraima and Piauí (3 participants each, 4.1%).

Participants also responded to the question of site investigation methods. The results indicate that the SPT remains the most used method, with all respondents (100%) reporting its use. Laboratory tests were also frequently used, as noted by 36 participants (48.6%). Cone Penetration Tests (CPT/CPTU) were employed by 28 participants (37.8%), highlighting their relevance in geotechnical investigation. Geophysical methods, such as Ground Penetrating Radar (GPR) and electrical resistivity, were used by 17 participants (23%), indicating their growing role in subsurface analysis. Down-hole or Cross-hole tests were reported by 7 participants (9.5%). Less commonly used methods included the Flat Dilatometer Test (DMT), employed by 4 participants (5.4%), and the Pressuremeter Test (PMT), cited by only 2 participants (2.7%). In addition, 10 participants (13.5%) reported using other unspecified methods.

Figure 8. Geographic distribution of foundation engineering practices in Brazil over the past decade.

The survey also examined the use of performance and quality control tests for foundations over the past decade. Conventional static load tests (SLTs) were the most frequently employed method, with 67 participants (90.5%) reporting their use. Dynamic load testing was employed by 42 participants (56.8%), indicating its widespread use as an efficient and cost-effective alternative/complement to static methods. The Pile Integrity Test (PIT) was conducted by 45 respondents (60.8%), highlighting its importance in assessing structural integrity. Bidirectional static load testing was reported by 13 participants (17.6%), reflecting its growth, though still limited. Additionally, 8 respondents (10.8%) reported using other quality control methods. Participants were also asked about prescribing or conducting pile load tests before the production piling, allowing design adjustments to the design or verifying processes ahead of the actual construction. It was noticed that 59 out of 74 participants (79.7%) indicated that they specified or performed load tests in advance, while 15 participants (20.3%) reported not conducting such tests before the pilling.

The survey also investigated settlement monitoring practices in building projects among the 74 participants. A total of 33 respondents (44.6%) reported conducting settlement monitoring in compliance with the requirements of ABNT (2022), indicating adherence to national standards in nearly half of the cases. Additionally, 26 participants (35.1%) performed settlement monitoring even without ABNT requirements (which requires monitoring for medium to high-rise buildings), reflecting a proactive approach by some professionals to prioritize structural performance and safety beyond regulatory mandates. In contrast, 15 respondents (20.3%) stated that no settlement monitoring was carried out in their projects. In terms of the extent of settlement monitoring, 16 respondents (21.6%) indicated that none of the buildings they worked on underwent such monitoring. The majority, 33 respondents (44.6%), reported conducting settlement monitoring in only 1 to 10% of the buildings, implying that monitoring is generally confined to specific projects. Furthermore, 11 participants (14.9%) stated that 11 to 25% of the buildings were monitored, while 6 respondents (8.1%) indicated settlement monitoring in 26 to 50% of their projects. Notably, 8 participants (10.8%) reported that more than 50% of the buildings they worked on were monitored for settlement.

Finally, the survey inquired about the predominant foundation solutions used over the past ten years. The results revealed that the Continuous Flight Auger (CFA) pile was the most widely used solution, with 46 respondents (62.2%) selecting this option. Mechanically cast-in-situ piles were reported by 7 participants (9.5%), while mixed foundation systems (footings/piles or raft/piles) were employed by 3 respondents (4.1%). Isolated footings, raft foundations, bored cast-in-situ piles with support fluid, and jacked piles were each selected by 2 respondents (2.7%). Steel piles and root piles (or micro-piles) were used by 4 respondents (5.4%), while concrete and full displacement piles were reported by 1 respondent each (1.4%). Notably, open and pneumatic caissons, Strauss piles, manually bored cast-in-situ piles and Franki piles were not reported by any of the participants, indicating limited use of these methods in contemporary foundation practices (Figure 9).

3.1.2 Notes on the Brazilian foundation practice

1. Site investigation and more common tests

The most common site investigation for foundation works in Brazil is carried out using the SPT. This test was introduced in the country in the late 1930s, and after a few years of using a slightly smaller sampler designed by the São Paulo Research Institute (IPT), the American standard, later international, was adopted. This test is also used as the first investigation in cases where other tests will be performed. A standard on programming investigations for buildings, ABNT (1983), establishes at least 2 SPTs per building, and at least 1 SPT for every 200 m^2 of the building's projection.

Until recently, SPT was performed in Brazil by manually lifting the weight, which gave the test a net energy of between 75 and 90% of the nominal potential energy. Hence, the SPT result here is considered N_{80}. Compared to SPT performed in the USA, for example, where automated equipment leads to efficiencies of around 60% (resulting in N_{60}), the tests in Brazil would require around 20% fewer blows for the same material. In the last decade, mechanical equipment began to be used in Brazil and designers are having to pay attention to this fact. The correct evaluation of SPT results is important for gathering experience and establishing/comparing correlations – in addition to saving costs on the project. Other correction factors for the N value, such as rod length (or test depth), are not relevant, according to national research, noting that geostatic stresses at the test level (function of depth) are important for obtaining geotechnical parameters.

Other available in-situ tests are CPT/CPTU, DMT, PMT, and seismic tests. The first three types follow international standards/recommendations and are increasingly used in Brazil, with PMT on a smaller scale (sometimes used in weathered rocks). The first seismic tests were of the cross-hole type and were carried out in the 1970s in nuclear power plant construction. Today, the CPT and DMT tests themselves include seismic testing in a very practical way, providing a profile of the initial shear modulus G_o together with the usual test results.

Given the increasing possibility of obtaining G_o (which would have direct application in the case of machine foundations), there is interest in establishing G/G_o decay curves for the expected strain level of each type of foundation.

Usual laboratory tests, such as characterization and oedometer tests, are also used, particularly in the design of shallow foundations.

2. Standards applicable to building foundations

The Brazilian standard that deals exclusively with building foundations is ABNT (2022). It establishes terminology to be used throughout the country and provides basic criteria for design. It also presents recommendations for quality control, such as load tests on piles (mandatory works with more than 100 piles, in a typical proportion of 1% of the piles) and settlement measurements, mandatory in buildings with more than 20 floors. In its appendix, the main processes for installing deep foundations are described in some detail, as well as specific design criteria.

The standard recommends safety factors for load capacity, both global - working stress design– (3.0 for shallow foundations and 2.0 for deep foundations) and partial, or -

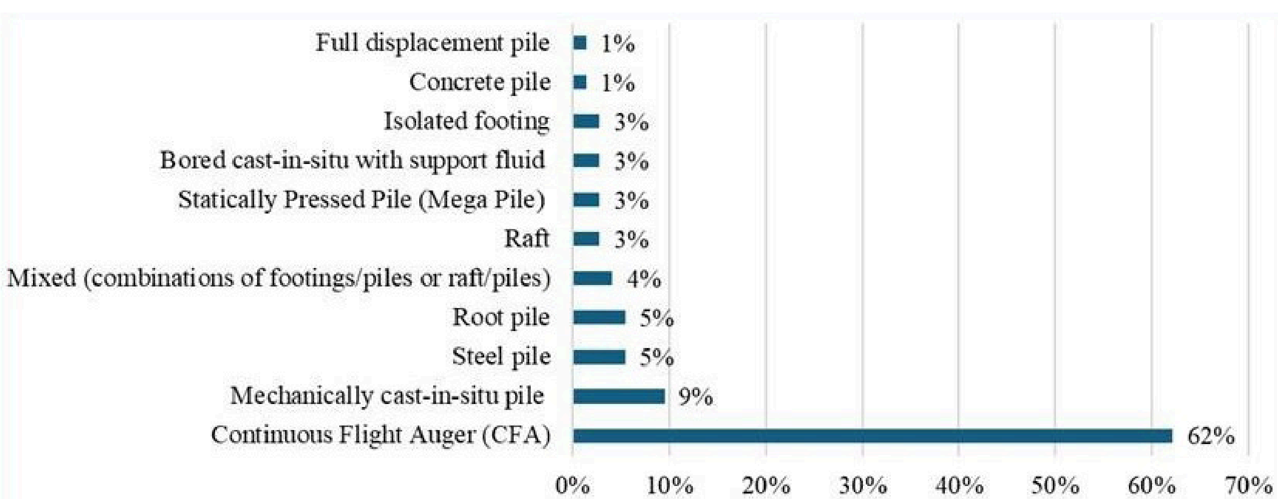


Figure 9. Main foundation solutions over the past ten years in Braz. engineering practice - Percentage.

load and resistance factor design – similar to Eurocode 7 (Geotechnical Design). The use of load and resistance factor design has not yet been incorporated into common practice, as it has been in Structural Engineering, but apparently, it has not been in most countries either.

The standard allows reducing the usual safety factor if a set of load tests is carried out a priori, before the actual pilling. With a considerable number of load tests a priori, a reduction in the (overall) safety factor from 2.0 to 1.6 would be possible. The standard draws attention to the need to evaluate settlements (and other displacements and rotations) but does not provide limit values, unlike Eurocode 7.

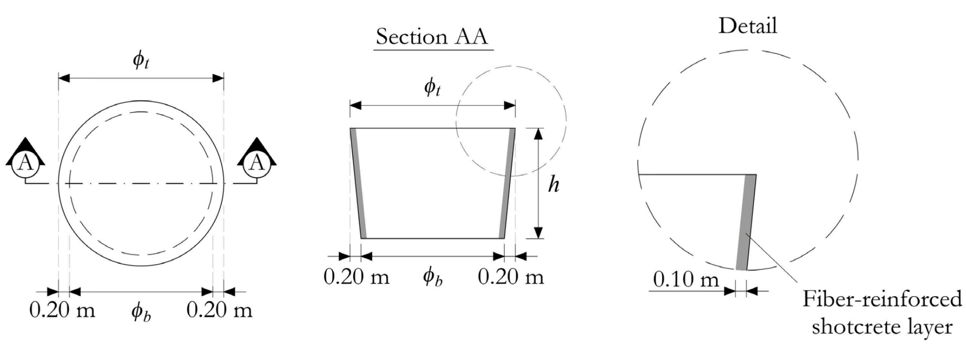
Other standards that apply to building foundations are dedicated to static load tests on piles (ABNT, 2020b), high-strain dynamic tests (ABNT, 2007) and load tests on plates and footings (ABNT, 2019). The standard for static load tests on piles allows for different loading modes and suggests an interpretation of the ultimate load. When a particular pile test is unavailable in Brazilian standards, ASTM, ISO and Eurocode 7 standards are used. A proposal for the use of the "equilibrium method" was also suggested by Lopes et al. (2021).

3.1.3 Trends in Brazilian foundation engineering

Many advances have been made in Brazilian foundation engineering, reflecting the challenges and opportunities in this rapidly evolving field. One notable advance is the development of short caisson ("tubulão") foundations, referred to by the authors as 'Décourt caisson', a term linked to the foundation design approach described by Aguiar et al. (2024). These foundations are known for their lack of an enlarged base and lengths ranging from 2.0 to 3.0 m (Figure 10). Additionally, the 'Décourt caisson' possesses wall inclination and top diameters approximately 0.40 m larger than the base ones. The foundation installation is presented in Figure 11. This construction technique creates a wedge effect, enhancing side friction.

Another advancement in Brazilian foundation engineering is the integration of Expander Body Technology (EB) at the tip of conventional pile foundations (Monteiro et al., 2021). The EB consists of a bent steel tube inflated through an initial pressure-grouting process. The expansion is facilitated by discharging grout via a tube that extends through the reinforcing cage. Various models of the EB allow for diameters to expand from 0.4 to 0.8 m. Grout pressure and volume are continuously monitored during the EB expansion. Figure 12 illustrates the stages of EB expansion during the pressure grouting process.

The EB models have lengths between 1 and 2 m and widths between 0.10 and 0.13 m in the stages before the expansion (initial stage). During EB expansion stage, the relationship between injection pressure and volume can be registered by a data acquisition system. The lateral expansion of the EB induces an EB tube length shortening by almost 0.2 m, displayed as a rising of the EB bottom tip. This expansion causes soil decompression beneath the EB, which is compensated by a second grouting stage of the soil at the pile tip. The second grouting stage is discharged to the pile tip over a distinct grout tube inside the grout tube



ϕ_b: Bottom diameter	2.00 m - 6.00 m
ϕ_t: Top diameter	$\phi_s = \phi_i + 0.40$ m
h: Caisson height	2.00 m - 4.00 m
e_{cp}: Thickness of the fiber-reinforced shotcrete layer	0.10 m

Figure 10. 'Décourt caisson' dimensions.

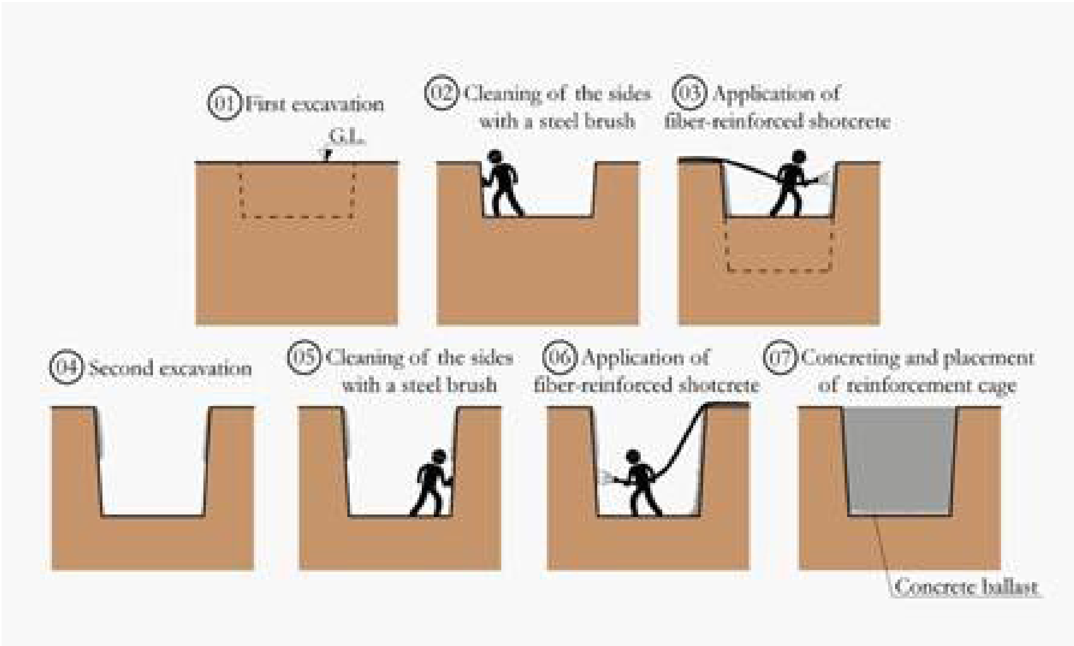


Figure 11. 'Décourt caisson' construction stages.

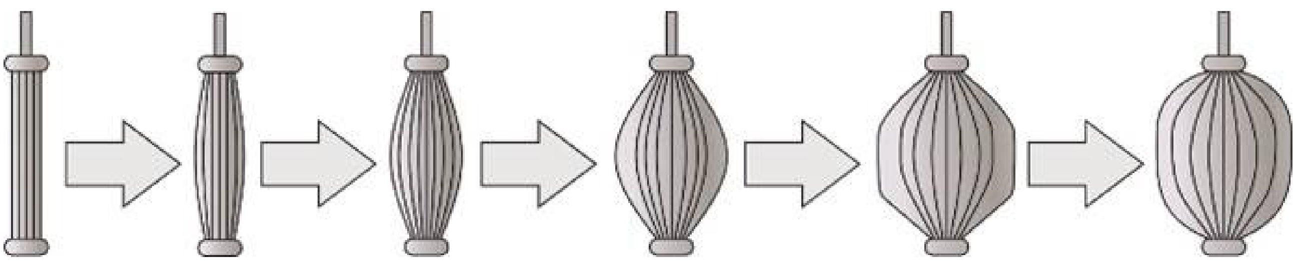


Figure 12. Expander body expansion stages.

(Figure 13) employed for the initial grouting stage (passing the EB inner section). Fellenius et al. (2018) describe the expansion of the EB as, in essence, a load test of the pile toe. This process ensures a stiff pile response, enhances pile bearing capacity, and substantiates the pile's performance, leading to fewer required piles and shorter construction time.

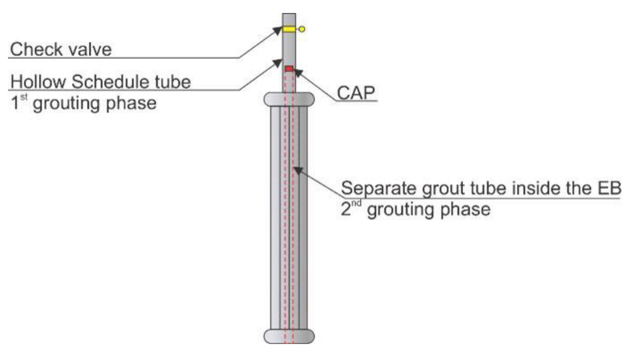


Figure 13. Grout tube passing the EB inner section.

3.2 Specialized foundation procedures

3.2.1 Pile group settlement behavior

Although soil is not a perfect continuous medium, its structure, formed by interlocking particles, gives the soil behavior similarity to continuous medium, especially at low deformation levels. The displacement of a soil particle resulting from the settlement of a foundation will also entail the movement of surrounding particles. This phenomenon can be observed in the case of a loaded pile, which will undergo a certain degree of settlement. This settlement will also occur in the surrounding area, though the values will decrease with increasing distance from the loaded pile. This phenomenon, whereby a loaded pile induces a displacement in a nearby pile, is referred to as pile interaction. The effect of the interaction is a direct consequence of the proximity of the piles and can occur between piles of the same block, but also between piles of different and nearby blocks and buildings.

Several factors can influence the degree of interaction between piles, either positively or negatively. These include the compactness of the soil (the interlocking of particles); the geometry of the piles (length, dia.); the pile driving process; and the number of driven piles. In their study, Sales & Curado (2018) observed that the position of a pile within a block, as well as the number of piles driven between this block and neighbors can influence the outcome of the interaction between two nearby piles. As observed by Sales et al. (2017), the driving or pressing of piles into the ground results in a modification of the particles present at the pile-soil interface. This alteration affects the characteristics of the interface soil, also known as the smear zone, which in turn influences the interlocking and, consequently, the settlement induced by lateral friction forces.

3. Methods for predicting pile interaction

Poulos (1968) undertook a numerical analysis based on the boundary element method, defining the "pile interaction factor - α" as the ratio between the increased settlement induced in a neighboring pile and the settlement of the pile under the original loading. This is represented by the following equation:

$$\alpha_{ji} = \frac{w_{ji}}{w_i} \tag{1}$$

where: α_{ji} is the interaction factor between loaded pile *"i"* and its neighboring pile *"j"*; w_{ji} is the induced settlement on the pile *"j"* due to the loaded pile *"i"*; w_i is the settlement of pile *"i"* due to its own load.

This method was more thoroughly delineated by Poulos & Davis (1980), wherein graphs were constructed that facilitate the calculation of interaction factors without the necessity for numerical analysis. Other studies have proposed estimating the interaction factor between two piles (Randolph & Wroth, 1979; El Sharnouby & Novak, 1990; Southcott & Small, 1996; Mylonakis & Gazetas, 1998; Cao & Chen, 2008). Aoki and Lopes (1975) solution for estimating stress and settlement due to a set of deep foundations by the theory of elasticity is also able to solve those interaction factors.

In order to extrapolate the meaning of the aforementioned concept, it is necessary to consider the settlement of a pile belonging to a pile group. This can be expressed as the sum of all the interactions, as demonstrated by the following equation:

$$w_j = \sum_i^n w_{ji} = \sum_i^n \alpha_{ji} w_i \tag{2}$$

where: w_j and w_i are the settlements of piles *j* and *i*, respectively; w_{ji} is the induced settlement in pile *j* due to the loaded pile *i*; α_{ji} is the interaction factor between piles *i* and *j*.

The result of the interaction between piles is that a group of piles or a block of piles will always settle more than a single pile would if it were subjected to the average load of the group. The settlement of each pile in the group can be predicted by setting up a system of equations derived from Equation 2. This system can be solved manually under extreme boundary conditions for blocks that are: perfectly flexible or perfectly rigid. An empirical prediction for the average settlement of the group, with a very good approximation for pile spacings within the range of 2.5 to 3.0 diameters, was presented by Fleming et al. (1992) in the form:

$$w_{group} = \sqrt{n}\ .\overline{w}_1 \tag{3}$$

where: w_{group} is the pile group settlement; $\overline{w_1}$ is single pile settlement, when the pile is supporting the average load of the group; n number of piles in the group.

4. Extrapolating limits for the interaction concept to large pile groups

The application of Equation 3 for the calculation of pile group settlement is effective for a limited number of piles, up to a maximum of 16. As demonstrated by Sales & Curado (2018), the discrepancy between the most accurate prediction obtained through FEM analysis and that derived from Equation 3 can exceed 15% in homogeneous soils, with even greater discrepancies observed in heterogeneous soils. One potential explanation is that the presence of other piles between the two piles under study acts as a form of enhancement (rigid inclusions) of the soil, thereby reducing the interaction. One possible solution to this issue would be to limit the maximum interaction distance between piles to 12 and 15 times the diameter of the loaded pile, as done by Bernardes et al. (2021).

It is also important to note that the rigidity of the block or raft that joins the piles will result in an uneven distribution of load between the piles. It is possible that some or several of the piles may receive loads that result in a settlement that is already affected by the plastic behavior of the soil-pile interface (nonlinear pile behavior). The plastic portion of the settlement occurs due to the movement of particles concentrated in the region very close to the pile shaft. Mandolini & Viggiani (1997) proposed that only the elastic portion of settlement should be considered when estimating pile interaction (Figure 14). It's the opinion of the present paper authors that this may be valid solely in cases in the elastic domain of the soil, where loads are far from the ultimate value.

5. Interaction on a piled raft - case study

A piled raft is defined as a mixed foundation in which both the raft and the piles play a significant role in determining the load capacity and settlement of the foundation. The way these interactions occur ultimately determines the final stiffness of the piled raft. In a piled raft, it is essential to consider the four forms of interaction, i.e., between piles, between piles and soil, between different regions of the soil under the raft, and finally between piles and raft (Hain & Lee, 1978; Poulos, 1994; Sales, 2000; Small & Poulos, 2007).

Figure 15 illustrates a piled raft comprising 241 continuous flight auger (CFA) piles (diameter of 0.7 m) that bears most of the load of a 172-meter-high building in the city of Goiânia (Bernardes, 2023; Bernardes et al., 2024). This project monitored the load on all columns and a large number of piles throughout the construction period between 2019 and 2022. It was observed that the piles were responsible for receiving approximately 93% of the applied load.

A comparison of the load-settlement curves derived from two static load tests and the average load curve measured on the piles is presented.

Figure 16 illustrates the effect of interactions. When subjected to an average load of 1123 kN, the piled raft settled approximately 11 times the values of the isolated pile test under the same load. Conversely, the interaction prediction from Equation 3 was not confirmed, indicating a reduction in interactions for a large number of piles exceeding distances of 12 to 15 times the diameter of the piles.

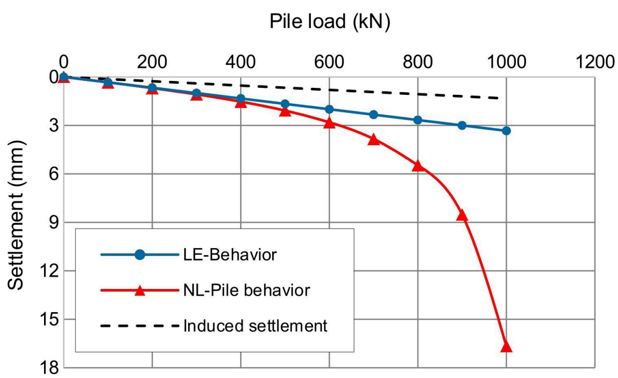


Figure 14. Nonlinear (NL) pile behavior and induced settlement proportional to linear elastic (LE) behavior.

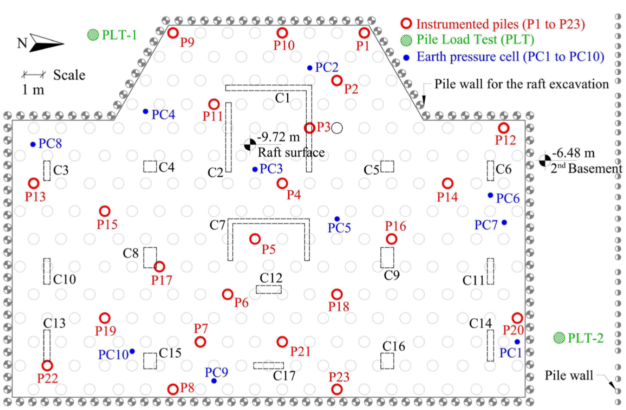


Figure 15. 241 Piled raft foundation with the position of the instrumented piles, columns, and earth pressure cells (Modified from Bernardes, 2023).

3.2.2 Soil-foundation-superstructure interaction

1. Group effect in a building

The performance of a single foundation element can be quite different from the performance of the overall building foundation, which depends on various mechanisms acting simultaneously, such as the soil-foundation-superstructure interaction. Average settlement for the same load increases as more foundation elements are considered, due to stress superposition effects, which leads to a reduction in foundation stiffness (the relationship between the average foundation load and the average settlement).

In the case of pile foundations, Poulos & Davis (1980) defined the parameter *Rs*, which is the ratio of the settlement of a pile in a group (w_{group}) compared to the settlement of the same pile when isolated (w_{is}) which represents the increase in pile settlement as a result of the interaction with neighboring piles.

$$R_s = \frac{w_{group}}{w_{is}} \quad (4)$$

2. Effect of the soil-structure interaction in the foundation settlement

The performance of a building is governed by the interaction between the superstructure, which corresponds to the part of the building that will be used after its construction, including the walls, slabs, beams, and columns; the infrastructure, which consists of the elements that transfer the superstructure's load to the foundation soil (footings, piles, and rafts); and the foundation soil, whose objective is to absorb the forces developed in the superstructure and transfer to the soil by the foundation elements. This is a complex mechanism known as soil-structure interaction (*SSI*).

Soil-structure interaction causes a redistribution of forces in the structural elements, particularly in the column loads, and induces settlement uniformization. This redistribution

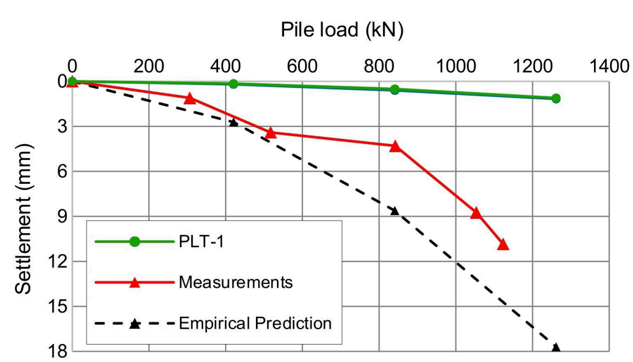


Figure 16. Pile-settlement behavior for the PLTs, for the piled raft (average of the instrumented piles), and the empirical prediction of Fleming et al. (1992).

depends, among other things, on the relative stiffness of the soil-structure system and the settlement pattern, or behavior, of the building.

Several studies have shown that total and maximum differential settlements decrease in magnitude with the increase in the relative soil-structure stiffness, with differential settlements being more influenced by this stiffness than the total settlements (Tang et al., 2013; Sheil & McCabe, 2015; Gusmão et al., 2020; Bernardes et al., 2024).

3. Load-settlement curve of a building – Case study

Santos (2020) presented a case study of a 41-story building, approximately 120 m high, constructed in Recife, Brazil. Its foundation consisted of pile caps on continuous flight auger (CFA) piles with diameters of 600 and 700 mm and a length of 24 meters, as shown in Figure 17.

The pile shafts were in contact with fine sand, and the pile bases were supported on a layer of stiff clay and silt, as indicated by the geotechnical soil profile in Figure 18. This Figure also indicates the water table level (WT), the blow count of the Standard Penetration Tests conducted on-site (SPT-1 to SPT-4), and the position of the piles within the referenced profile.

Settlement measurements of the columns were carried out throughout the construction of the building. Figure 19 shows the evolution of minimum, maximum, and average settlements. The building's load and column reactions were calculated using structural modelling software. The ratio of the total building load to the total number of piles gives the average load per pile. For example, in the last measurement, when the building was nearly complete, the total load acting on the building was 173.05 MN. Thus, the average load per pile was 173.05 / 121 = 1.430 MN = 1430 kN.

The average measured settlement of the building, which is equal to the average settlement of the piles, was also determined. In the last measurement, the settlement ranged between 6.99 mm and 13.69 mm, with an average value of 10.99 mm. Therefore, the average settlement of the piles was

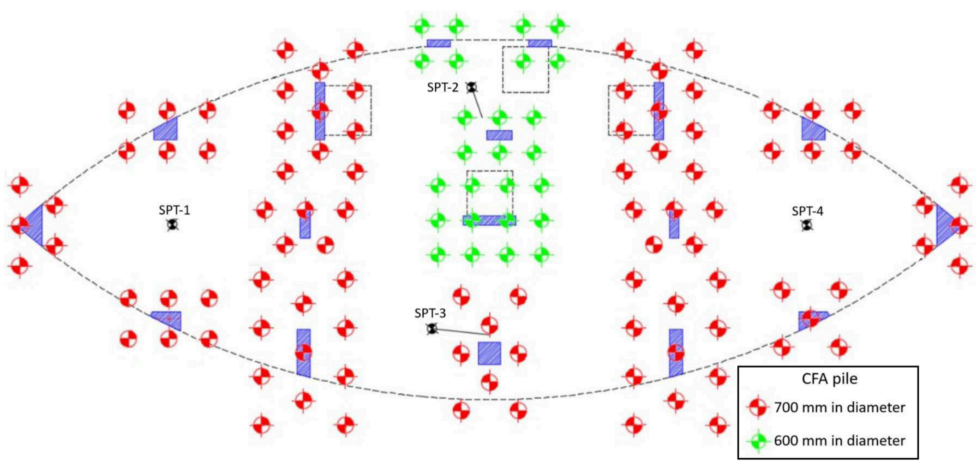


Figure 17. Arrangement of the CFA piles used in the building's foundation.

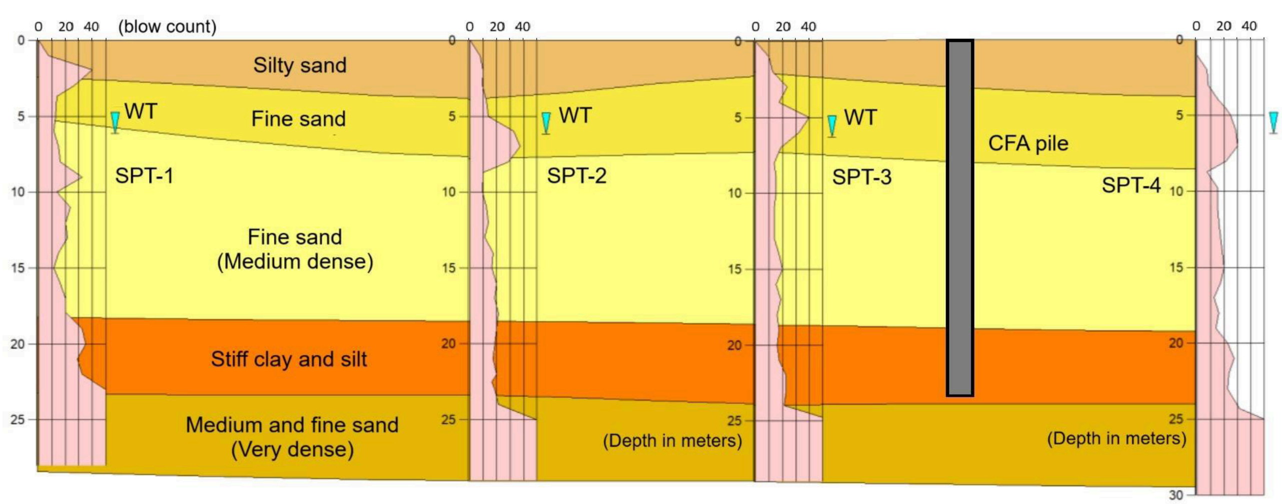


Figure 18. Geotechnical soil profile of the foundation building.

10.99 mm. Figure 20 compares the load-settlement curve from the static load test (SLT) with the average settlement of the piles of a corner (edge) column, a central column, and the average for the entire building, which implicitly includes the group effect. The SLT was conducted on a 700 mm diameter pile carried out on the profile shown in Figure 18, with no group effects. The interaction between the foundations is evident, resulting in the building's settlement significantly greater than that of an isolated pile.

3.3 Quality assessment and assurance of design

Urban development over the past 50 years has required the study of new materials and techniques to support the growing demands of construction in expanding cities in Brazil. According to Cunha & Albuquerque (2014), foundation engineering in Brazil made significant progress during the 1920s, particularly with the expansion of port infrastructure. However, it remained largely empirical until the following decade, when the first research was conducted by IPT and POLI/USP. Similarly, geotechnical engineering evolved as urbanization increased, and greater construction loads became usual due to the rising demand for residential and commercial spaces. The importance of investigating the subsoil and understanding the interaction between soil-structure became evident over time. Consequently, innovative techniques for site investigation and interpreting the soil-structure interaction have become prominent topics in foundation engineering in Brazil.

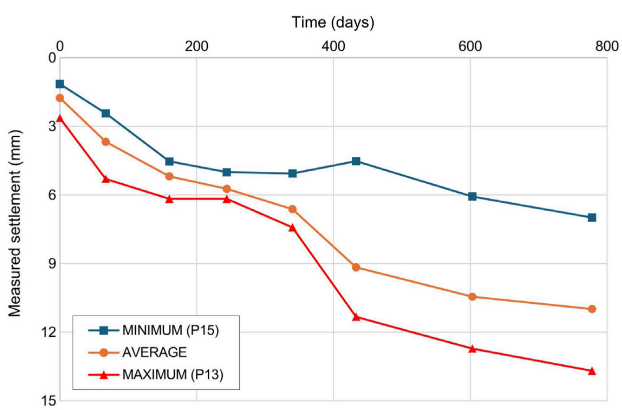


Figure 19. Foundation settlements throughout the construction.

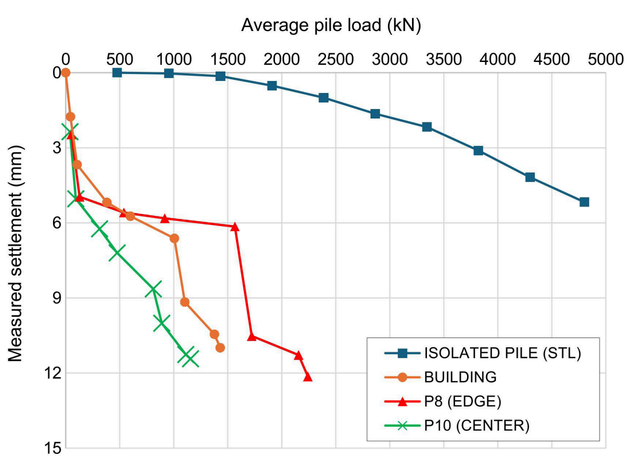


Figure 20. Load-settlement curves for the SLT and the building, with measurements taken at different locations.

It is essential to define the site stratigraphy during the investigation stage, by dividing the soil mass into homogeneous units, identifying the transition zones, classifying soil types, and assessing site variability. Subsequently, potential problematic layers can be identified, along with the position of the bedrock, groundwater table, and estimated design parameters. At this stage, correlations are calibrated to ensure accuracy in the design. Furthermore, data analysis using a reliability-based approach should also be considered to complement traditional safety factors, enabling a more comprehensive risk assessment for the project.

Since the 2010 revision of NBR 6122 (ABNT, 2022), load tests and structural monitoring have become mandatory in Brazilian foundation engineering. This revision marked a significant milestone, leading to a noticeable increase in the use of in-situ tests with a substantial enhancement of understanding of foundation behavior. Furthermore, the data obtained from these tests have contributed to the development of more reliable and cost-effective foundation designs.

3.3.1 Site investigation

The site investigation involves gathering geological, geotechnical, and other relevant data that may impact the construction and performance of civil works (Clayton et al., 1995). A reasonable characterization of foundation mass, with the necessary level of detail the project needs, together with the geological conditions of the site are relevant (Rocha et al., 2023). Understanding geological soil history is crucial when interpreting test data, as used to point out Terzaghi in the early stages of soil mechanics (Terzaghi & Peck, 1948).

Additionally, it is important to identify the position of the water table, locate the problematic layers, determine the depth of the bedrock and estimate the relevant design parameters. During this phase, empirical correlations should be validated or recalibrated. Geological and seasonal variability must also be considered, as they introduce uncertainties in the site profile definition, parameter estimation, and foundation-predicted behavior (Wickremesinghe, 1989). Consequently, variability plays a key role in the degree of uncertainty influencing parameter definition and project decisions (Giacheti et al., 2019; Camapum de Carvalho & Gitirana Junior, 2021).

The variation in soil parameters is typically represented through the evaluation of certain indexes, parameters, or properties that are measured and interpreted by experienced professionals, often relying on empirical methods and practical experience (De Mio, 2005). However, a rational analysis of uncertainties, based on Reliability Theory, offers a more robust framework for making engineering decisions in heterogeneous and variable environments. This approach is particularly suited for addressing uncertainties arising from the natural spatial and seasonal variability of the site (Silveira et al., 2024).

3.3.2 In-situ tests

In the site investigation, in-situ tests can be classified into indirect methods, such as geophysics, and direct methods, with the Standard Penetration Test (SPT) and Cone Penetration Test (CPT) being the most employed. Geophysical methods, particularly seismic techniques, are frequently used in foundation design, while electrical methods are more prevalent in geoenvironmental investigations (Juarez et al., 2023). These methods offer valuable insights into the spatial distribution of geological materials and their properties and assist in the identification of the water table, bedrock depth, and specific subsurface layers or buried objects (Giacheti et al., 2006). Crosshole tests, for example, have been used to determine dynamic soil parameters, which are critical for the design of vibrating machine foundations, wind turbine towers, and earthquake-resistant structures (Barros & Hachich, 1996; Gandolfo, 2022).

In Brazil, the site investigation for foundation design is predominantly conducted by the standard penetration test (SPT), as previously mentioned. Despite the existence of NBR 6484 (ABNT, 2020a), which standardizes SPT procedures, many companies still employ non-standardized methods and equipment (Schnaid & Odebrecht, 2012), potentially affecting test efficiency, i.e. the energy that is effectively transferred to the soil during sampling (Schmertmann & Palacios, 1979). Advances in the understanding of the SPT energy and its interpretation using a rational approach, based on energy conservation principles and wave equation theory (Aoki et al., 2007; Schnaid et al., 2017), represent significant progress, although these methods remain underused in practical foundation engineering.

As previously stated, Brazilian foundation design practice largely uses correlations between SPT results and (i) allowable stresses for shallow foundations and (ii) ultimate resistances for piles. In the second case, Brazil pioneered in publishing correlations between side friction and pile tip resistance with SPT results in the 1970s (Aoki & Velloso, 1975; Décourt & Quaresma, 1978). Attempts to extend prior correlations with CPT were proposed for sedimentary soils (Danziger & Velloso, 1995); Souza et al. (2012), for sands in different densities. Some correlations from international literature are also used after assessments/adjustments to local geological conditions. It should be noted that in the interior region of Brazil, tropical, unsaturated soils prevail.

Dynamic penetration (DP) tests are employed for site characterization, with the light dynamic penetrometer (DPL) being the most used, mainly due to its portability and compact design. This characteristic allows it to be utilized in areas where access to conventional equipment is limited (Cunha & Nilsson, 2003). Almeida (2023) analyzed DPL test data using the rational approach proposed by Lobo (2005). In addition, the author enhanced the test by integrating an accelerometer at the probe, conducting downhole tests and obtaining promising results. However, DPL test remains underutilized in foundation engineering, likely due to the inability to retrieve soil samples and limited practical experience in its application.

Cone penetration tests (CPT) and piezocone tests (CPTu) are valuable for identifying the stratigraphic profile and preliminarily assessing soil parameters (Lunne et al., 1997). Unlike the standard penetration test (SPT), which involves soil sampling, CPT and CPTu rely on classification charts to categorize soil behavior (e.g. Robertson et al., 1986; Robertson, 2016). These tests can be interpreted using an indirect approach to predict the behavior of sands and clays based on empirical correlations. Alternatively, the direct approach is commonly employed in foundation engineering correlating the tip resistance (q_c) and lateral friction (f_s) measured by the cone with pile behavior (Cintra et al., 2013). The direct approach is particularly prevalent in Brazil due to the presence of soils with unusual behavior (Rocha, 2018).

The flat dilatometer test (DMT) is conducted similarly to the cone penetration test (CPT). Three intermediate parameters are calculated based on correlations from the DMT data, which are then interpreted in terms of conventional soil parameters (Marchetti et al., 2001). Like the CPT, the DMT does not involve soil sampling. Instead, the Material Index (I_D) is used to identify soil behavior types, yielding reliable results in well-behaved soil profiles (Marchetti et al., 2001). A significant advantage of the DMT is its ability to estimate foundation settlements. This is achieved by determining the modulus of deformability under in-situ stress conditions, which provides accurate estimates of foundation settlements (Monaco et al., 2006; dos Santos et al. 2020), even considering the suction influence on the estimated settlements (Saab et al., 2023).

The pressuremeter (PMT) is a testing device installed in the ground and expanded under controlled conditions. The test results can be interpreted using two approaches. The direct approach employs correlations (Ménard, 1975), while the indirect approach uses models to represent the asymmetric expansion of an infinite cylindrical cavity, supported by well-established elastic and elasto-plastic solutions (Hughes et al., 1977). Despite its potential for defining design parameters, the PMT has limited use, particularly in Brazil (Cunha et al., 2004; Sampaio Junior & Sousa Pinto, 2004). But it is worth mentioning the work of Pinto and Abramento (1998) on the use of the Camkometer tests to provide parameters such as G_o, K_o and s_u for soils of São Paulo City.

Campanella & Robertson (1984) integrated a seismic wave acquisition system (SCPT) into the cone penetration test (CPT), and this feature was later incorporated into the dilatometer test (DMT) (Mayne et al., 1999). This advancement enables the performance of down-hole tests with either the CPT or DMT to determine shear wave velocity profiles (V_S) and, consequently, the shear modulus (G_0) without relying on correlations (Marchetti et al., 2008). Foundation settlement can then be predicted using G_0 and the modulus degradation curve. Amoroso et al. (2014) proposed estimating the degradation curve using the SDMT, as outlined by Marchetti et al. (2008). Fernandes et al. (2023) applied this approach to an unsaturated soil profile. The use of SCPT and SDMT provides new opportunities for foundation engineering by reducing the dependence on empirical correlations to define deformability parameters.

Therefore, there is interest in estimating the value of *G* (or Young's Modulus *E*) for settlement predictions, accounting for the strain level of the imposed actions. A classic indication of the *G* decay curve is Figure 21 (adapted from Seed & Idriss, 1970). Some evaluations show that average *G* values obtained in back-analyses, with solutions of the Theory of Elasticity, from load tests on piles and plates (or even measurements of footings settlements) are within the range indicated at the top of the figure. To the left of the range, the higher values correspond to single piles (under axial loads), and to the right, the lower values correspond to footings.

3.3.3 Foundation element testing and instrumentation

Load tests on foundation elements have been conducted for over a century. In Brazil, the first recorded test was performed in 1928 on the foundation footings of the Martinelli Building in São Paulo. A subsequent test on deep foundation piles, specifically Franki piles, was conducted in 1936 at Brazil's Northwest railroad station in Bauru, São Paulo (Carvalho & Albuquerque, 2023). With urban expansion and the construction of increasingly more significant buildings, there was a growing need for stringent control over construction processes, including foundations. In response, the standard ABNT NB20 (ABNT, 1951) was published, followed by the technical NB27 standard in the 1960s. These standards have since been revised and updated, with the current standards being NBR 6489 (ABNT, 2019) and NBR 16903 (ABNT, 2020b).

Instrumentation along the pile shaft can be employed to understand the distribution of loads at various depths, providing insights into the behavior of foundations and supporting the establishment of failure criteria for non-instrumented piles. This approach enables the measurement of the soil resistance mobilized at pile tip and skin friction at each loading stage. However, implementing this methodology demands a specialized team skilled in instrumentation and data acquisition techniques. The range of geotechnical instrumentation techniques available is extensive, and selecting the appropriate tool depends on the specific parameters required.

Hanna (1982) explored the role of instrumentation in foundation engineering, outlining its benefits, including monitoring construction, verifying design criteria, investigating geotechnical parameters and evaluating computational methods. Lindquist et al. (1988) reviewed various instrumentation techniques for measuring displacements, deformations, loads, total stresses, pore pressures, and vibrations, highlighting tools such as tell-tales, reinforcement extensometers, pressure cells, expansion cells, and electrical extensometers.

In Brazil, the first recorded instrumented load test was conducted in Rio de Janeiro in 1975 by Prof. Dirceu Velloso, who used tell-tales on a sheet pile. This was followed in 1979 by Prof. Costa Nunes, who performed the first instrumented load test with electrical strain gauges in Itaguaí/RJ (Albuquerque, 2001). Massad et al. (1981) reported the results of load tests in 3 root piles, also instrumented with electrical strain gauges in Guaraú Water Treatment Station in São Paulo city. Over recent decades, instrumentation techniques have advanced with the introduction of vibrating rope and fiber optic strain gauges, as well as removable strain gauges. As the production and use of electrical strain gauges (Figure 22) have become more globally widespread, costs have decreased, leading to their increased application in load tests at Brazilian construction sites. It is anticipated that future research will provide further insights into the use of these advanced techniques.

The load versus settlement curves and pile bearing capacity obtained from static load tests are typically used as a reference, being considered representative of the actual working conditions

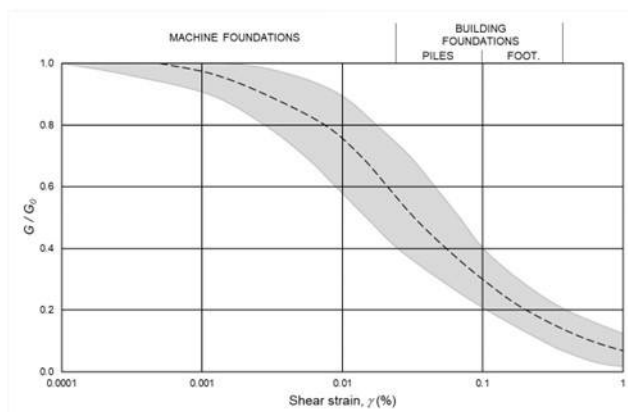


Figure 21. Shear modulus (*G*) decay curve, with the range of strains for different foundation types (modified after Seed & Idriss, 1970).

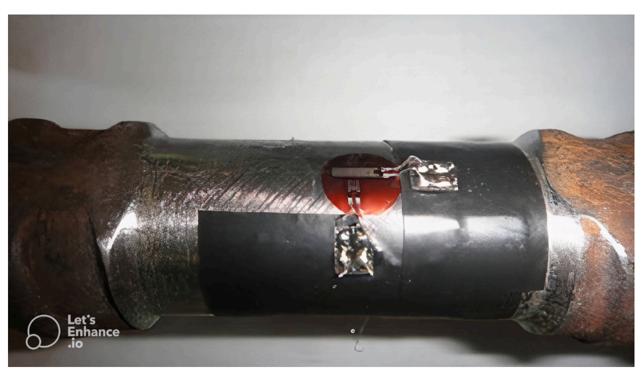


Figure 22. Strain gage (biaxial 2 mm) bonding configuration on a steel bar.

of foundations. However, conducting static load tests requires robust and complex reaction systems, as well as labor-intensive assembly and testing procedures. In contrast, dynamic methods enable the systematic testing of a broader range of piles.

In Brazil, high-strain dynamic loading tests have been employed since the 1980s, for instance with works carried out by IPT/SP for the design of offshore structures for Petrobras. These tests were initially standardized by NBR 13208 (ABNT, 2007). This technique involves the instrumentation of piles and interpretation involves the Wave Equation Method (Smith, 1960). Comprehensive information on dynamic loading tests, including the methodologies and their interpretation, is available in the works of Rausche et al. (1971, 1972), Goble et al. (1975), Rausche et al. (1985), Gonçalves et al. (1996) and Pile Dynamics (2000).

In dynamic tests, the impact generates a compression wave when the pile is struck by a hammer (Figure 23). This wave, which initially compresses the head of the pile, propagates through the shaft, reflecting to the top before and after reaching the tip. Strain transducers and accelerometers positioned near the pile top can measure the intensity of the wave caused by the hammer's impact and track how it changes as it interacts with the pile-soil system. The data collected by these sensors is monitored using specific equipment.

Figure 23. Hammer in PDA testing (Kormann, 2002).

To estimate the pile's load capacity, the force and velocity signals obtained from the instrumentation can be analyzed using numerical techniques, with CAPWAP analysis being the most well-known. This method was developed by Rausche et al. (1972) and it involves iteratively adjusting a numerically calculated signal (for example, of force) to closely match the dynamic signal measured in situ (of velocity). When this alignment is achieved, various parameters describing the behavior of the pile-soil system can be inferred. One important result of this analysis is the estimation of the static load capacity mobilized by the energy of the impact.

In Brazil, the use of dynamic loading tests with increasing drop heights has become widespread (Aoki et al., 2007). This procedure helps to determine whether the applied blows result in partial mobilization of the pile-soil system bearing capacity or if the dynamic load test fully mobilizes the available pile lateral friction and tip resistance.

Originally conceived for driven piles, dynamic loading tests have also been applied to cast-in-place piles. A system capable of applying blows to the foundation is required for these applications. The literature includes numerous studies on the use of dynamic loading tests to assess the performance of cast-in-place piles (e.g. Mello & Paraíso, 1998; Niyama et al., 2000a, b; Paraíso et al., 2000; Kormann et al., 2000; Debas et al., 2008; Andraos et al., 2009; Paraíso & Santos, 2020).

The principles of dynamic testing are also employed to assess the structural integrity of deep foundations. Techniques such as the Pile Integrity Test (PIT) and Cross Hole Sonic Logging (CSL) are commonly used. The PIT involves placing an accelerometer at the top of the pile and applying a few blows with a hand hammer. A portable unit then records and visualizes the signals captured by the accelerometer. The resulting compression pulse from the hammer impact propagates along the pile. When this wave reaches the pile tip, it generates a reflection that travels back to the top. Additional reflections occur when the pulse encounters variations in cross-sectional dimensions or material properties (e.g., modulus of elasticity, specific weight), which can be analyzed using the concept of impedance. The accelerometer records the responses to the hammer blows until the energy is fully dissipated. By knowing the propagation speed of the wave in the pile material, the location of any damage can be calculated based on the time between the hammer impact and the arrival of the reflected waves.

In recent years, bidirectional tests have become increasingly popular in Brazil due to the rising loads imposed on foundations and the test's simplicity and favorable cost-benefit ratio. The concept was developed in the 1980s by a Brazilian engineer, Pedro Elisio Silva (Silva, 1983), concurrently with the American engineer J. Osterberg. The latter published and patented the expansive cell (Osterberg, 1989), which became known as O-cell, gaining international recognition.

Numerous studies have been conducted in Brazil, with notable contributions from Alonso & Silva (2000), Massad (2015), Sestrem (2018), Dada & Massad (2021), and Barbosa et al. (2024). It has the advantage in terms of cost because it does not require a reaction system; however, to be successful – in revealing the full resistance of both tip and lateral resistances – an adequate choice of cell position depth is needed. The interpretation of the test must include the load-settlement curve of an equal pile but loaded from the top, the so-called equivalent load-settlement curve.

3.4 Prospective future use for the foundations: geothermal energy piles

Piled foundations can eventually be used in the future, for instance, as part of superficial geothermal energy systems (SGES) to provide sustainable "green" energy to superstructures.

To enhance understanding of this subsection, it is essential to describe the operation of a closed geothermal system and its main components. Figure 24 illustrates a simplified diagram of a closed geothermal heat exchanger, consisting of two closed, independent hydraulic circuits: the primary and secondary circuits. These circuits exchange heat via a geothermal heat pump (GHP). The primary circuit connects to the geotechnical infrastructure, while the secondary circuit links to the superstructure. This thermal exchange regulates and conditions the superstructure, transferring heat to or from the ground as needed, ensuring efficient temperature control.

The primary circuit is in direct contact with the geological medium, while the secondary circuit is in direct contact with the superstructure, where thermal exchange occurs with the conditioned environment. Between the two circuits is the heat pump, responsible for the thermal exchange between them, consisting of a compressor and an expansion valve that circulates the refrigerant gas. The efficiency of the system depends on achieving the highest thermal differential between the circuits with the lowest energy consumption (Laloui & Loria, 2020).

The advantage of embedding the primary circuit in the ground is to harness the seasonal thermal stability of the subsurface, which is absent in conventional air conditioning systems that use air as the thermal exchange medium.

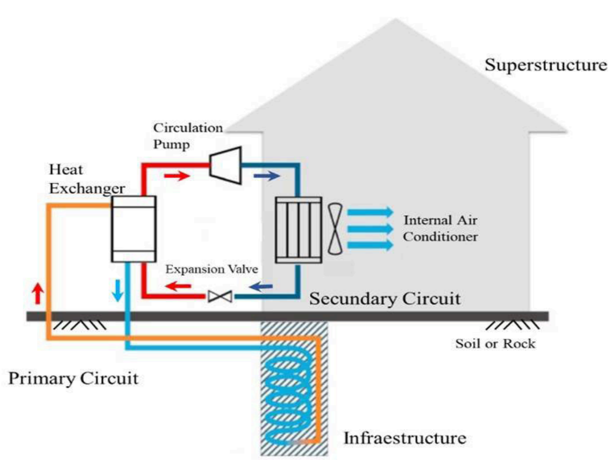


Figure 24. Diagram of a geothermal energy plant with heat exchanger piles (Chaves, 2023).

3.4.1 System components and overall characteristics

The performance and quality of the heat exchanger system depend on the geometric variables of the exchangers (depth, length, pipe diameter), the energy required to pump the fluid (fluid velocity in the piping), and the geotechnical medium where the primary circuit is embedded (soil type, degree of saturation, and dry apparent unit weight) (Brandl, 2006). Some of such characteristics are discussed next.

1. Pile types

Different conventional types of pile foundations can be used for thermal utilization. According to the construction method, geothermal energy piles (GEP) can be classified into non-displacement and displacement piles (Sadeghi & Singh, 2023).

Heat exchanger piles can be constructed from conventional concrete, reinforced concrete or steel. Concrete has good thermal conductivity and thermal storage capacity, being an ideal medium as a heat exchanger. High-Density Polyethylene (HDPE) is placed within the concrete pile to form closed coils or loops, which circulate a heat carrier fluid of water, or water with antifreeze or a saline solution (Brandl, 2006).

Precast concrete and steel pipe piles with central voids can be installed into the soil before incorporating the geothermal pipe loops in the hollow spacing (Sani et al. 2019). Driven precast concrete energy piles can be grouped into hollow cylindrical (concrete pipe pile) and square-shaped energy piles (Alberdi-Pagola, 2018). Precast concrete energy pile segments can also be constructed at a concrete factory (Sadeghi & Singh, 2023). In this case, the construction procedure comprises installing a cage in a formwork, embedding HDPE pipe inside the cage, and then pouring concrete into the formwork. Steel piles filled with different materials were tested as heat exchangers by Murari et al. (2022).

2. Heat exchanger pipes

Before pile installation into the ground, loops or closed coils of pipes are fixed to the reinforcement cage of the energy foundation using different configurations: U-shape pipe (single double, triple, etc.), W-shape pipe, and spiral form. The heat exchanger pipes are usually 27 or 34 mm in diameter (Abuel-Naga et al., 2015). Figure 25 presents examples of reinforcement cages with heat exchanger pipes installed at the campus of the University of São Paulo (CICS Living Lab), tested in Pessin & Tsuha (2023).

Park et al. (2019) tested cast-in-place energy piles constructed with various configurations of heat exchange pipe, and concluded that larger pipe volume in the same pile led to higher thermal performance due to a higher contact area with the ground for heat exchange; however, the thermal performance was not proportional to the pipe length, because a small distance between heat exchange pipes induces thermal interference that reduced heat exchange efficiency.

Figure 25. Examples of reinforcement cages with heat exchanger pipes of energy piles installed at the campus of the University of São Paulo (CICS Living Lab): (a) spiral configuration; (b) triple U-loops.

3.4.2 Installation procedure and design

1. Energy pile installation

The installation technique of energy piles is generally either hammer-driven or auger bored method depending on the pile type and geology (Sani et al. 2019). Driven precast heat exchanger piles with central voids can be installed into the ground before installation of the heat exchanger pipes, and after that filled with cement mortar to ensure contact between loops and the pile. The precast concrete pile segments constructed with heat transfer pipes inside are installed into the ground using pile-driving machines to push the pile into the ground (Sadeghi & Singh, 2023).

For bored energy piles, HDPE loops are attached to the inside of the reinforcement cage of the pile, which is installed in the drilled hole. Concrete is then slowly poured using tremie pipes accommodated in steel guides welded onto the reinforcement cage (Faizal et al., 2022).

As described in Loveridge & Cecinato (2016), for the case of continuous flight auger (CFA) energy piles, one important difference is that the construction process affects how the heat exchange loops are introduced into the concrete. For bored piles, the reinforcing cage with the loops of pipes is placed inside the pile bore before the concrete; and for CFA energy piles, the reinforcing cage is installed into the drilled hole after the concreting procedure is completed. For CFA piles the steel cage is plunged into the wet concrete, therefore the pipes are limited to the length of the cage.

2. Design

The geometry (diameter and length) of energy piles is basically governed by the required mechanical load of the superstructure. The pile length is an important characteristic due to the high-temperature fluctuations in the ground at shallow depths (Sani et al. 2019). Similar to the energy pile lengths, the diameters are also limited by the building structural design (Faizal et al. 2016).

Variables like ground thermal properties, pile grout or concrete, pipe, fluid, temperature boundary conditions, energy pile configurations, distance between piles and length affect the optimal sizing of energy foundations (Fadejev et al., 2017). Additionally, the hydrogeological characteristics influence the long-term efficiency of energy pile systems (Vieira et al., 2022).

Energy piles act as load-bearing foundations while also providing for heat exchange with the ground (Bourne-Webb et al. 2022). Therefore, the effect of cyclic thermal loading on pile foundations should be analyzed systematically. The pile-soil interaction is another critical aspect in energy pile design, currently treated with different levels of complexity (Arzanfudi et al. 2020).

3. Soil × structure interaction

The use of low-enthalpy geothermal energy, that is, shallow depth (<100m) extracted from typical SGES, has been primarily used in Europe for several decades through heat exchanger tubes inserted into the ground. However, the concept of heat exchanger piles dates back to the early 1980s (Laloui & Di Donna, 2011) and quickly spread to European, Asian, and North American countries. The efficiency of using heat exchanger piles, notably concrete and steel piles, has required various studies, with particular attention to the impact of additional stress induced by thermal loads.

Several factors must be considered when designing thermally activated deep foundations, among which can be highlighted: the stratigraphy crossed by the foundation, the degree of restraint at both the base and the head of the GEP, the distribution of friction with depth, the seasonality of thermal loads (heating and cooling cycles), and the interaction between piles in the case of pile groups. In general, these designs are based on field tests where the behavior of the pile is compared to a free pile, that is, one that deforms without restriction. Thus, the loads are measured by the deformations experienced by the pile in comparison to "free" piles.

Therefore, the design and sizing of thermo-active foundations must include the effects of specific heat exchange operations with the ground, as summarized in the following Figure 26.

The load transfer mechanism in piles has been already explained elsewhere (Bourne-Webb et al., 2016). If the pile heats or cools uniformly and both ends are unrestricted, the pile will expand or contract with its mid-height acting as the neutral plane. In the case of compressive loading without temperature variation, the pile will mobilize friction as it moves vertically downward.

In the case of simple cooling, the pile will contract if there is no restriction at the top. The restriction will cause tensile stresses, and the soil-pile interface will generate shear stresses in the opposite direction of the movement. If the pile is loaded and subsequently cooled, tensile stresses may appear in the lower half of the pile, and the mobilized lateral resistance increases in the upper part and decreases in the lower part.

4. Effect of temperature on soil and consequences for the pile performance

Considering thermally activated piles with heat rejection into the ground, there will be, in the medium and long term, a heating of the pile and consequently a heating of the adjacent soil layers traversed by the foundation element. Several studies show the implications of heating on the soil, with results varying according to soil type, thermal gradient, stress history, among other factors.

Particularly in the case of heated clay soils, there will be a volume change in response to heating or, in undrained conditions, the generation of pore pressure, which can be positive or negative depending on the soil's stress history.

In the case of normally or slightly over-consolidated clay soils, heating causes, in drained conditions, a volume decrease and an increase in the rate of secondary compression (Akrouch et al., 2014). In undrained conditions, an excess of positive pore pressure takes place and its subsequent dissipation may lead to additional efforts from negative skin friction that must be considered during the design phase.

As mentioned in Brandl (2013), a seasonal operation with an energy balance of cooling and heating loads has shown to be most economical compared to cases of unbalanced demand. For a case of cold load in summer larger than heat load in winter, the underground heat accumulation will gradually affect the efficiency of the GSHP system (Zhang &Wei, 2012). However, the use of energy foundations can be efficient even in cases of unbalanced demand.

Recently, ten Bosch et al. (2024) conducted a numerical study to evaluate the feasibility of energy piles in a hot-dominated climate (a case study in Dubai), and the results showed that for the analyzed building 40% of the cooling demand can be provided by energy foundations over at least

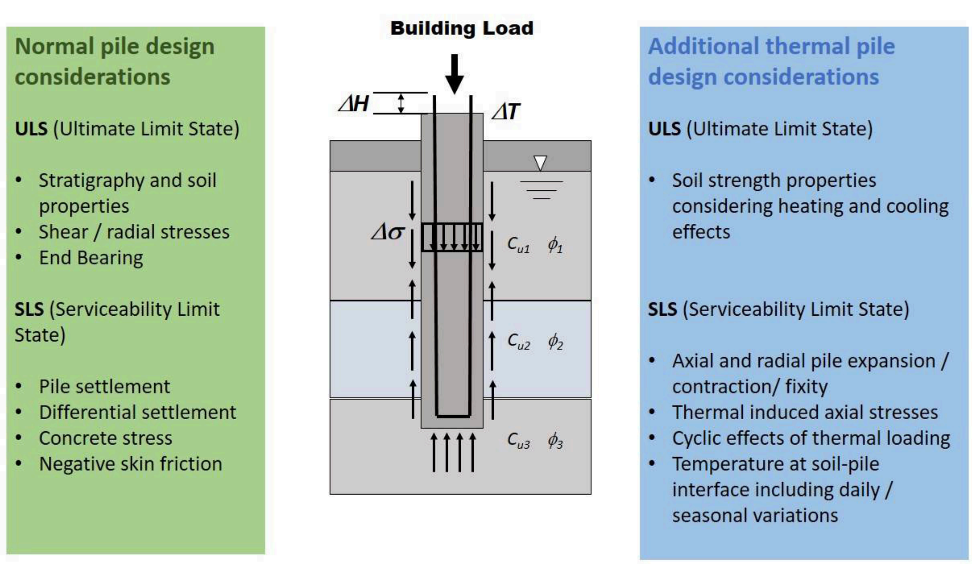


Figure 26. Modified after GSHP (GSHP Association, 2012).

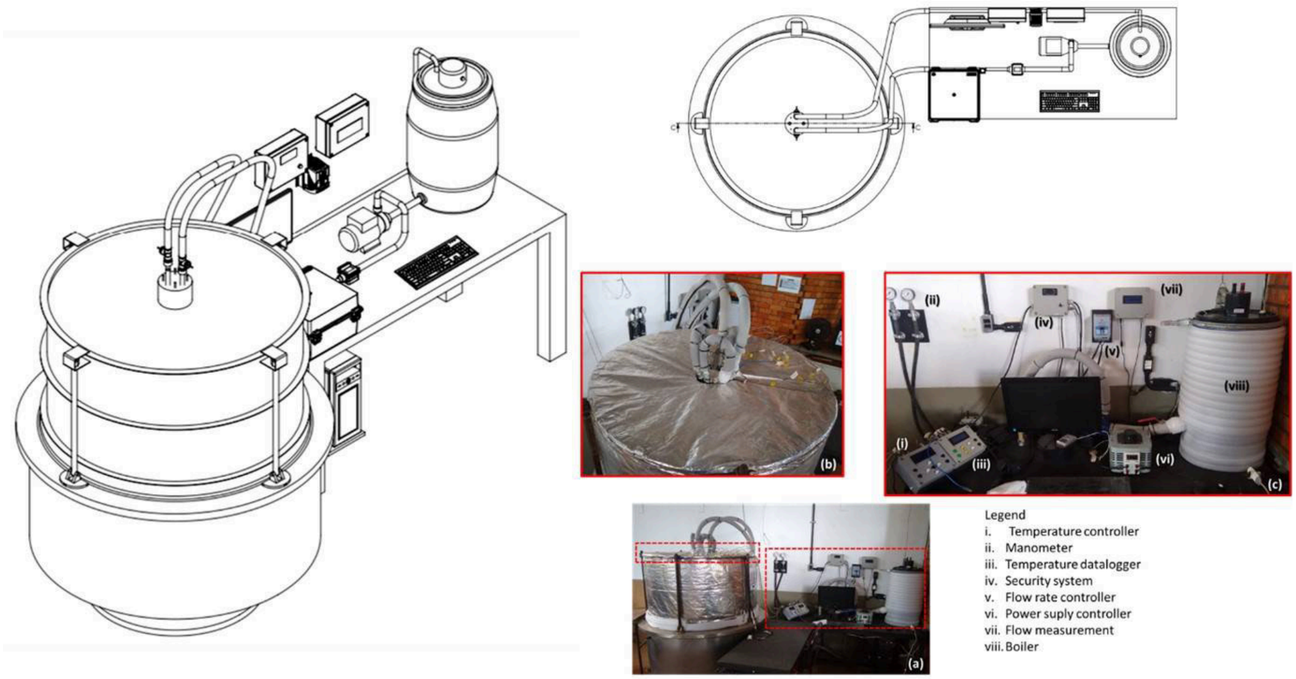


Figure 27. Electric details of the thermal response test machine and the calibration chamber for prototype piles (Chaves et al., 2022).

50 years. This result is encouraging for future implementations of this technology in Brazil.

Finally, in the case of tropical soils, several site-specific, laboratory or numerical results are under development in several Brazilian universities, as, for instance, the assessment of thermal piles prototypes in compacted and lateralized material (typical) from the Federal District of Brazil (Chaves et al., 2022), as depicted in Figure 27.

The latter authors have concluded that given scale limitations, an initial assessment was achieved regarding some of the critical parameters to design heat exchanger pipes and piles immersed in the tropical unsaturated soil of the Federal District of Brazil. Such preliminary results and experience can surely be of importance to start designing SGES to exchange heat loads with local superstructures, taking into account the specific local conditions of the region. Of course, more research is required, but the subsequent development of the whole technology, involving heat pumps, secondary superstructure refrigeration systems, and an integrated design, will be facilitated after these initial steps in Brasília, and elsewhere.

According to Cunha & Bourne-Webb (2022) in an extensive and critical review of geothermal energy pile systems, monitoring of existing structures designed with SGES is crucial to fine-tuning models and broadening the knowledge frontier. It should be encouraged or even forced by national codes. A more documented set of well-regulated and instrumented GEP structures either in the field or in the laboratory is therefore required to advance further the knowledge in the various technical fronts of this (“new”) technology.

4. Conclusions

4.1 On the foundation practice and design

The survey of this subsection reveals a concentration of foundation engineering projects in Brazil’s southeastern and northeastern regions. This geographical disparity underscores regional trends that may influence future resource allocation and industry focus. On site investigation, the survey revealed a predominant use of SPT, with other tests such as CPT and geophysical methods, beginning to gain space. The relatively limited use of DMT and PMT may present opportunities for further development in the future. The survey also underscores a strong use of conventional quality control methods, such as the static load test, but also a considerable use of both high-strain and low-strain (PIT) tests. There is a relatively lower adoption of the bidirectional static load test, which requires more attention in the selection of the O-cell depth and in the interpretation (construction of the ‘equivalent top-loading curve’). Additionally, the survey reflects diverse practices in settlement monitoring and a significant impact of the national standard requirements on foundation quality control. The advancement of new technologies in foundation engineering is crucial for addressing the evolving demands of the industry. Innovations such as the Expander Body (EB) and the ‘Décourt caisson' are a few examples. Continued development and integration of such technologies are essential for advancing foundation engineering practices and improving project results.

4.2 On the specialized foundation procedures

The subsection has discussed the settlement behavior of pile groups, focusing on how soil interactions influence this phenomenon. It highlighted that while soil behaves like a continuous medium under low strain levels, the settlement of a loaded pile causes movement in nearby piles, a phenomenon known as pile interaction. Empirical predictions for pile group settlement were discussed, with a focus on limitations when extending these predictions to larger groups. A case study of a piled raft foundation for a high-rise building illustrated the complexities of soil-structure interaction, revealing that the behavior of multiple foundation elements differs significantly from isolated scenarios. Measurements from this case show that group effects lead to significantly higher settlements than predicted by static tests.

4.3 On the quality assessment and assurance of design

This subsection has shown that in-situ tests are critical for characterizing the site conditions, defining design parameters, and assessing pile bearing capacity. The selection of the most suitable test depends on soil characteristics, foundation dimensions, and the objectives of the project. Advances in technology have led to the development of new equipment and testing techniques, such as dynamic tests and advanced instrumentation, which provide more accurate and reliable results. Integrating theoretical models with experimental data from in-situ tests enhances the understanding of soil behavior and soil-structure interaction, leading to safer and more cost-effective designs. Despite these advancements, challenges remain, including the standardization of test procedures, data interpretation, and the consideration of site variability, spatial and seasonal. Research is therefore needed to develop techniques and ways of interpreting tests to improve geotechnical engineering.

4.4 On the prospective future use of the foundations

The importance of this theme is quite high nowadays, and ongoing research is being carried out in many international institutions regarding several aspects of SGES and GEP systems, from laboratory experiments to field case studies. A more interconnected definition of objectives and sharing of individual material and personnel resources seem essential to amplify the outcomes. Academy, private companies and governmental agents have the responsibility to finance and foster this technology so that it becomes easily available to society in a widespread manner (Cunha & Bourne-Webb, 2022). Public awareness is particularly important and efficient to politically drive the technology, especially in emergent countries like Brazil. Without brainwork in this area, the application of this technology will continue to be impaired by narrowed simulation schemes.

4.5 On overall aforementioned terms

The article summarized some aspects of past foundation practice in Brazil and discussed the main topics, their relevance, developments in the last 75 years and the new outcomes. History, tendencies, practices and scientific/technical procedures have been briefly reviewed. In general terms, much knowledge has been developed by many talented Brazilian or foreign professionals, nevertheless new challenges in this field lay ahead.

It is finally important to mention that some unexplained results in field tests and foundation behavior were commonly attributed so far to instrument reading faults. However, at least some phenomena yet not clearly understood may be tentatively justified in the light of a more complete model of soil behavior. The extension of Terzaghi´s principle of effective stress encompassing strain rate and time effect, as developed and discussed by Martins (2023) allows a better comprehension of creep, stress relaxation, loading rate effects and is expected to broaden the understanding of foundation behavior in the following decades in Brazil and elsewhere.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest in reporting.

Authors' contributions

Renato Pinto da Cunha: conceptualization, project administration, supervision, validation, data curation, visualization, writing – review & editing. Alessander Christopher Morales Kormann: conceptualization, methodology, supervision, validation, visualization, writing – original draft. Alexandre

Duarte Gusmão: conceptualization, data curation, methodology, supervision, validation, visualization, writing – original draft, writing – review & editing. Bernadete Ragoni Danziger: writing, review & editing. Charles Pereira Chaves: conceptualization, methodology, supervision, visualization, writing – original draft. Cristina Hollanda Cavalcanti Tsuha: conceptualization, methodology, supervision, validation, visualization, writing – original draft. Fernando Feitosa Monteiro: conceptualization, data curation, methodology, supervision, validation, visualization, writing – original draft, writing – review & editing. Fernando Saboya Jr.: conceptualization, methodology, supervision, validation, visualization, writing – original draft. Francisco de Rezende Lopes: conceptualization, data curation, methodology, supervision, validation, visualization, writing – original draft, writing – review & editing. Heitor Cardoso Bernardes: conceptualization, data curation, methodology, supervision, validation, visualization, writing – original draft, writing – review & editing. Heraldo Luiz Giacheti: conceptualization, methodology, supervision, validation, visualization, writing – original draft. Marcos Fábio Porto de Aguiar: conceptualization, data curation, methodology, supervision, validation, visualization, writing – original draft, writing – review & editing. Maurício Martines Sales: conceptualization, data curation, methodology, supervision, validation, visualization, writing – original draft, writing – review & editing . Paulo José Rocha de Albuquerque: conceptualization, methodology, supervision, validation, visualization, writing – original draft.

Data availability

Subsection 3.1. The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request. Subsection 3.2. The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request and available in the University of Brasilia repository, [https://repositorio.unb.br/jspui/handle/10482/48816]. Subsection 3.3. The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request. Subsection 3.4. The datasets generated and analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of Generative Artificial Intelligence

This work was prepared with the assistance of Generative Artificial Intelligence (GenAI), specifically ChatGPT-4, with the aim of evaluating the written English of the manuscript, focusing primarily on grammar checking. The entire process of using this tool was supervised, reviewed, and, when necessary, edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols and abbreviations

ABMS	Brazilian Association of Soil Mechanics.
ABNT	Brazilian Association of Technical Standards.
ASTM	American Society for Testing and Materials.
C	Column.
CAPES	Brazilian Federal Agency for Support and Evaluation of Graduate Education.
CAPWAP	Case Pile Wave Analysis Program.
CFA	Continuous Flight Auger.
CNPq	National Council for Scientific and Technological Development.
COBRAMSEG	Brazilian Conference on Soil Mechanics and Geotechnical Engineering.
CPT	Cone Penetration Test.
CPTu	Cone Penetration Test with Pore Pressure Measurement.
CSL	Crosshole Sonic Logging.
DMT	Flat Dilatometer Test.
DP	Dynamic Penetration.
DPL	Dynamic Penetrometer Light.
EB	Expander Body Technology.
FAP-DF	Federal District Research Support Foundation.
FAPERJ	Foundation for Research Support of the State of Rio de Janeiro.
FAPESP	São Paulo Research Foundation.
FEM	Finite Element Method.
Finep	Brazilian Funding Authority for Studies and Projects.
GEP	Geothermal Energy Pile.
GHP	Geothermal Heat Pump.
G_0	Shear Modulus / Soil Stiffness at Very Small Strains.
GPR	Ground Penetrating Radar.
GSHP	Ground Source Heat Pump.
ID	Material Index.
IPT	Technological Research of São Paulo.
K_0	At-Rest Earth Pressure Coefficient.
LE	Linear Elastic.
N	Blow Count (Standard Penetration Test).
NB	Brazilian Standard.
NL	Nonlinear.
P	Pile.
PC	Earth Pressure Cell.
PIT	Pile Integrity Test.
PLT	Pile load test
POLI/USP	Polytechnic School of the University of São Paulo.
PMT	Pressuremeter test
Q	Question Number.
R_s	Ratio of the Settlement of a Pile in a Group Compared to the Settlement of the Same Pile when Isolated.
SCPT	Seismic Cone Penetration Test.
SDMT	Seismic Flat Dilatometer Test.

SGES	Shallow Geothermal Energy Systems.
SLS	Serviceability Limit State.
SLT	Static Load Tests.
SPT	Standard Penetration Test.
SSI	Soil–Structure Interaction.
s_u	Undrained Shear Strength
ULS	Ultimate Limit State.
Unicamp	University of Campinas.
USP	University of São Paulo.
WT	Water Table Level.
V_s	Shear Wave Velocity.
c_u	Undrained Shear Strength
f_s	Sleeve Friction
n	Number of piles in the group.
q_c	Cone Tip Resistance.
w_{ji}	Induced settlement in pile *j* due to the loaded pile *i*;
w_{group}	Settlement of Pile Group.
w_{is}	Settlement of Isolated Pile.
w_i	Settlement of pile *"i"* due to its own load.
w_j	Settlement of pile *"j"* due to its own load.
w_{ji}	Induced settlement on the pile *"j"* due to the loaded pile *"i"*;
$\overline{w_1}$	Single pile settlement, when the pile is supporting the average load of the group;
α_{ji}	Interaction factor between piles *i* and *j*.
ΔH	Settlement
ΔT	Temperature variation
$\Delta\sigma$	Applied stress
ϕ	Soil friction angle

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