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Execution energy of continuous flight auger piles as an assessment tool to evaluate the mechanical response of the soil mass

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Article

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Abstract

Allying technology, theory and engineering practice is one of the main challenges of modern foundation engineering. Current foundation and retaining walls designs may lead to oversizing or undersizing due to the spatial variability of the stratigraphic profile. As the design procedure of piled foundations involves defining the setting depth of the tip, sometimes the piles may not behave as expected, as the soil mass may change significantly even in a small region. In this paper, a study was conducted on the geoenergetic behavior of the soil mass and of the piles of a construction site located in Brasília, DF, Brazil. Previous studies showed that the energy needed to drill a continuous flight auger pile (CFAP) can be related to the strength of the drilled strata. Therefore, a methodological framework was built to further discuss how the geomechanical behavior of CFAPs foundations could be assessed by analyzing the energy needed to drill such piles. Statistical methods, in special the Bootstrap method, were used to assess the possible influences of construction procedures on pile behavior. It was studied how the execution energies of piles vary with initial depth and relative position in the terrain, as well as the influences that they suffer because of the order of execution within a same foundation group and due to the proximity to surrounding retaining walls. The proposed methodology can be used to improve the energy control procedure and performance evaluation of CFAPs, allowing a complementary reliability assessment for the foundation and retaining walls designs and implementations.

1. Introduction

Piles are deep foundation elements which are also useful in retaining wall structures. For their implementation, there are several execution techniques, among which the continuous flight auger piles (CFAPs) are very popular. Currently, due to the tight schedules of engineering works, which may come together with a non-rare planning deficiency, the complete control of the construction site is not observed, making it hard to propose adaptations to current standards and even to enable a proper real-time monitoring of the foundation implementation.

When it comes geotechnical designs, safety analyses are usually based on deterministic methods, treating the calculated parameters as absolute truths. Thus, it is common to neglect some of the peculiarities of each construction site, which are known to be prone to geological-geotechnical and even geomorphological variability in the soil-foundation system. Thus, understanding the drilling environment contributes significantly to engineering practice. In this sense, there have been some previous works by Silva (2011) and Ozelim et al. (2018, 2019), where it was investigated and verified that strength parameters can be estimated from the drilling data of geomaterials.

The problem that was sought to be solved with this paper is to further investigate how the drilling energy of CFAPs can be used to assess the geomechanical behavior of foundations constituted by this type of pile. Therefore, the goal is to enhance execution control methods that provide greater safety, executive quality, economy and reliability for the implementation of CFAPs' designs. Based on two survey campaigns, one with two mixed survey type (MS) and another with four Standard Penetration Tests (SPT), and CFAPs execution data from a construction site located in Brasília (porous red clay soil), capital of Brazil, a methodological framework is proposed, based on statistical analyses, to establish relations between the mechanical response of the soil mass and the execution energy of the piles drilled in

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it. In short, the foundation piles had 0.5 m of diameter and the retaining wall consisted of juxtaposed piles of 0.4 m of diameter. The lengths of the piles ranged from 8-14 m and 10-14 m, respectively.

For this purpose, the SCCAP methodology (Silva, 2011) will be used as basis for this framework to calculate the execution energies of the CFAPs. Also, statistical analyses will be performed on the spatialization of the SPT results and on the execution energy of the piles at different locations in the construction site and its boundaries (retaining walls). In special, it will be studied how the execution energy of the piles is influenced by the pile position inside the site and by the order of execution of the foundation blocks.

2. Continuous flight auger piles

Using CFAPs as a foundation solution dates back to the 50s in the United States, being later spread throughout Europe and Japan in the 1980s, and was first performed in Brazil in 1987. Due to the increasing evolution of the technology and types of equipment, the monitoring control tools tend to become more reliable and the diversity of diameters and depths options tends to grow (Antunes & Tarozzo, 1996).

The execution process consists, basically, of the following steps cited by Caputo et al. (1997): positioning of the equipment according to the location of the pile predicted in the design, drilling and concreting simultaneous to the auger extraction of the ground and, finally, placing the steel reinforcement inside the recently concreted shaft. In technological terms, there is an electronic monitoring during all these phases, generating a large amount of excavation data. For example, it is possible to gather data regarding depth, tower inclination, penetration and extraction velocities of the auger, torque, work on drilling the pile, execution time, pressure of concrete injection, volume of pumped concrete and overconsumption of concrete.

According to Antunes & Tarozzo (1996) and Rajapakse (2016), the CFAPs are greatly adequate as a foundation solution in constructions executed in large urban centers, becoming attractive due to reliability, productivity and low frequency of vibrations and noises. In Brazil, it is the preferred technique of the builders when it comes to deep foundations, especially for foundations lying below the water level combined with retaining wall structures of juxtaposed piles, as is the case hereby analyzed.

3. Execution energies

Determining the properties and behavior of soils are very complex issues since one must deal with the geotechnical uncertainties coming from the natural variability of their constituent materials as well as with the errors of measurement during the tests performed. About 65% of the Brazilian territory consists of tropical soils, which are most highly weathered due to the influence of high temperatures, rainfall distribution, fauna and flora (Toledo et al., 2000).

During the installation of a pile in a certain type of soil, it is possible to obtain several useful drilling information by means of monitoring sensors. Thus, it would be interesting to associate this data with a scalar metric, such as the energy consumed to drill each pile shaft, which could be correlated to the pile bearing capacity. This would allow one to have real-time feedback on the suitability of the initial pile design and to understand the behavior and mechanical response of the soil mass.

In order to quantify the energy required to install a pile, Silva & Camapum de Carvalho (2010) evaluated formulations based on the principle of conservation of energy. They further proposed a methodology of execution control based on statistical elements, which was later incorporated into a monitoring software of excavated piles, especially CFAPs. This methodology, called SCCAP, represents an automated real-time control routine that records the energy or work performed by the forces applied to the helicoid during the execution of each pile. According to Silva et al. (2012), the forces acting on the machine are presented in Figure 1 and the energy required to install a pile can be calculated as in Equation 1.

$$W_R = \int_0^{Zb} mhc.g.dZ + \int_0^{Zb} F_{di}.dZ + \int_0^{m2\pi} F_i.r.d\theta \qquad (1)$$

in which: W_R = work done or execution energy [M][L]^2[T]$^{-2}$; Zb = pile total length [L]; mhc = mass of drilling system [M];

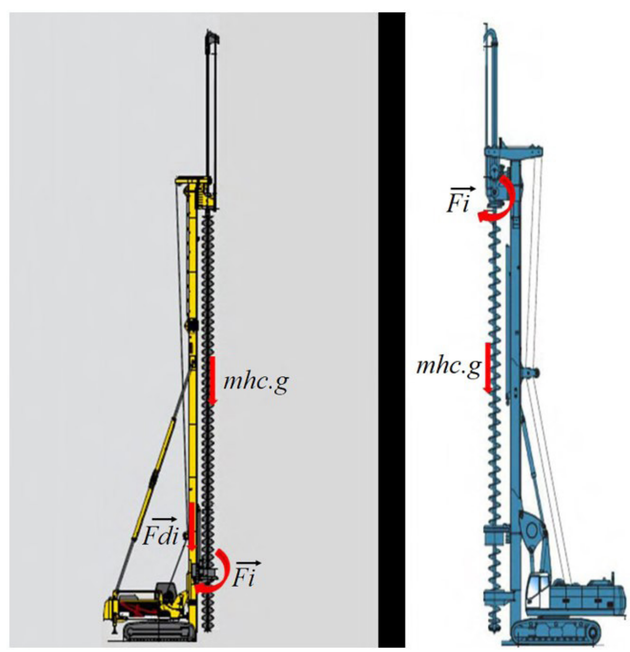

Figure 1. Drilling system and forces: (a) bottom drive CFA; (b) standard CFA (Silva, 2011).

g = gravity acceleration $[L][T]^{-2}$; F_{di} = downward force applied to the drill $[M][L][T]^{-2}$; F_i = force applied for drill revolution $[M][L][T]^{-2}$; m = number of drill revolutions; r = helical drill radius [L].

From the value of the execution energy and from the geometry of the drilled shaft, it is possible to calculate the specific energy in a given region of the site, which simply indicates the amount of energy spent per unit volume of drilled material. Visualizing the spatial distribution of specific energy allows one to compare different piles performances in the intervention site, as not necessarily the piles in a given design have the same diameter and depth.

For the execution energy analysis, the stress state is fundamentally important because the evolution of the construction from the beginning of the constructive procedures until the end of the consolidation period can affect the stresses transmitted to the drilling machine during the installation of the piles. The understanding of these changes in stress state enable a comparison between energetic measurements throughout the execution process. Following this reasoning, there are in the literature a series of studies that discusses the evolution of the stress state during construction, highlighting the change of horizontal stress during the various stages of construction. It is worth mentioning two studies, from a numerical and an experimental point of view.

According to Costa (2005), the use of advanced numerical methods represents a useful tool for estimating the behavior of geotechnical interventions. On the other hand, the study published by Richards et al. (2007) indicates the need for experimental evaluations as well. For both, even though in slightly different contexts, the stress states were analyzed during excavations of clay soils, discussing the behavior of a retaining wall structure along all of its constructive stages.

At all stages, a general decrease of the total horizontal stresses on both sides of the walls was observed, either due to the removal of the soil weight or due to the movement of the walls towards the cut. This is a consequence of the stress redistribution in the vicinity of these walls, making it clear that the farther from the wall, the lower the stress disturbances are observed. It is undeniable that soil matrices have different chemical and mechanical characteristics, but when it comes to physical behavior, the phenomena involved in the mobilization of stresses in the massif are similar.

In order to assess how the drilling energy is affected by the stress changes in the construction site, probabilistic tools will be considered, as the variability of the properties involved does not allow a deterministic approach on this matter. Some tools will be used to compare energy measurements throughout the terrain, as well as to check if particular groups of data can be considered equal from a statistical point of view. In the next section, the methods used will be discussed.

4. Probabilistic tools in foundation analysis

When comparing two values, instead of considering only point estimates, confidence intervals (CI) can be taken into account. This comes from the fact that when point estimates are considered, it is not possible to get a clear idea of the dispersion of the data and how the sample estimates differ from the population ones. CIs, on the other hand, enable one to have a better notion of the real population parameters.

Literature reveals a great variety of methodologies to determine the confidence intervals of a given measure. In special, the so-called z and t approaches are widely known as alternatives to evaluate the CI of means of a population (Moore et al., 2013). Both approaches rely on considering normality at some stage of the theoretical development of the method. In general, determining the distribution of the statistics which characterizes the hypothesis test behind the confidence interval evaluation is highly complex, being in most cases analytically unviable. This way, more general methods have been built.

Even though the determination of the confidence interval is deeply related to hypothesis testing, a specific test will also be considered in the present paper. The test whose null hypothesis is the equality of distribution between two samples is needed to check if different drilling energy samples are statistically equal or not.

With respect to building confidence intervals, the Bootstrap method shall be applied. This latter method also performs well when the equality of distribution test is considered. Thus such method is also applied in that case.

In order to familiarize the reader with respect to the Bootstrap method, one may refer to the works of Efron (1979, 1982) and Efron & Tibshirani (1993).

5. Materials and methods

In order to better exemplify the use of the methodological framework hereby presented, a construction site, with a porous clay soil, was selected, for which the entire executive procedure of the CFAPs of the retaining wall and foundation structures were controlled by the same machine-operator setup. In short, the foundation piles had 0.5 m of diameter and the retaining wall consisted of juxtaposed piles of 0.4 m of diameter. The lengths of the piles ranged from 8-14 m and 10-14 m, respectively. In addition, besides the CFAPs data, this specific site has been characterized by field tests. The characteristic subsoil of the region is composed of a porous red clay with low resistance in the first meters. As one goes deeper, the presence of more resistant silty materials is identified. More detailed information will be described in the next topic.

Subsequently, all data from the original geotechnical designs and drilling sensors were collected, as well as reports about the excavation of the site and the execution of each pile. The dataset was collected during the whole construction period.

To enhance data visualization, RockWorks® software was used to spatialize field survey data, generating 3D models and cross-sections of the stratigraphy and bearing capacity of the natural and excavated terrain. Such spatializations are achieved primarily by performing interpolations. In the present paper, the *Inverse-Distance Anisotropic* weighted distance method was used with the aid of the *Smooth Grid* data filter. With this method, to estimate the value of the spatialized property at a reference point, the weighted mean of the property values at the nearest points is considered, where the weights are the inverse of the distance between each surrounding point and the reference one.

In the case of data from the execution reports of the piles, an automated code was implemented in Mathematica® software, allowing the calculation of the execution energy, both accumulated in a meter-by-meter of depth manner and, finally, its normalized value by the volume of excavated material (specific energy). It is important to note that for the two-dimensional spatialization of the data, the idea of separating the data in similar groups was used. This process, known as *clustering*, applies a series of algorithms that group data according to common characteristics. Such a procedure is necessary to indicate which are the typical values of the execution energy around which the other values are grouped. To perform this procedure, the *ClusteringComponents* function of the Mathematica® software was used. All the calculated energy values have also been incorporated into RockWorks® in order to create three-dimensional energy profiles.

Finally, the general analyzes of the geotechnical behavior of the soil and the piles of the construction studied were carried out. At first, the stratigraphy of the site and its strength were assessed by means of regular soil survey techniques. Since such surveys were carried out at different moments throughout the years, it was relevant to carry out a brief climatic overview to characterize the conditions at which data was collected. Secondly, it was spatially analyzed how the energy and the specific energy are distributed along the whole construction site. Also, the Bootstrap statistical method was used to investigate the influence on the execution energy of both the horizontal and vertical distances of the foundation piles with respect to the retaining walls and the order of pile execution per foundation block.

6. Analysis and results

6.1 A brief characterization of the site and the piles studied

In order to carry out the analysis, a local residential ongoing construction site was chosen. The site is characterized by large flat/gently undulating surfaces. According to the planialtimetric analysis, the mean inclination of the terrain is about 5.5% with an average altitude of 1034.5 m above sea level. The geotechnical design prescribed the execution of 320 juxtaposed CFAPs for the retaining wall structure with 0.4 m of diameter and varying the length between 10 and 14 m. For the foundation, 316 piles were drilled after soil excavation, all of them with 0.5 m of diameter and with lengths varying between 8 and 14 m. The next analyses topics will complement and bring more site information and features needed for the present paper.

Previously to the piles execution, two survey campaigns were carried out for the investigation of the subsoil. The location of the two investigations is illustrated in. Figure 2. It should be noted that both campaigns were executed in different years, but coincidentally operated at the same time of year. Both campaigns were carried out in the rainy season in March of 2014 and of 2016, respectively.

The first campaign was a MS type and consisted of two sampling sites, encompassing both percussion and rotary sampling methodologies. This MS was executed two years before the construction and its results are illustrated in Figure 3.

After executing the retaining wall and performing the excavation to reach the quota to drill the foundation piles,

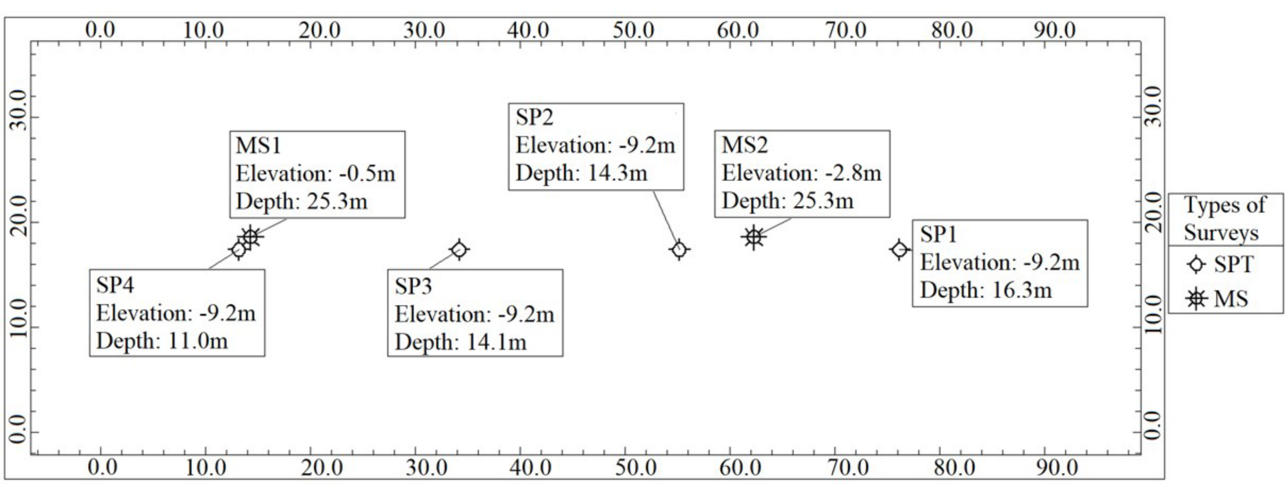

Figure 2. Location of the two survey campaigns (MS and SPT).

the second survey campaign began, but this time only with percussion sampling techniques. Thus, Figure 4 presents the results of four SPTs.

Making a parallel between these two survey campaigns and the superficial morphology of the soil, a certain parallelism is verified between the weathered mantles when considering the impenetrable quota (NSPT = 50 blows/30 cm) of the MS and the geomorphology of the soil (Figure 3). The same parallelism is not observed with respect to the SPT borehole results shown in Figure 4. A priori, this would point to the unsatisfactory quality of this second survey campaign, however, if one considers the SP4 result and the first peak corresponding to 50 blows/30 cm in the SP1, the same parallelism trend is verified. The most important, however, seems to be the verification of the expected deepening for this impenetrable limit established when drilling SP2 and SP3, indicating a possible stress relief in the central region of the site, which is compatible with one of the motivating purposes of this paper, i.e., the influence of the boundary conditions on the pile bearing capacity evaluated through the energy control in the pile execution phase.

6.2 Stratigraphic profile and NSPT spatializations

In previous works, the stratigraphy and number of SPT blows (NSPT) of both the undisturbed and excavated sites were spatialized (Ferrari de Campos et al., 2019). Two three-dimensional models were created, as shown in Figure 5, for the complete construction site. To better illustrate a representative cross section of the terrain, two transverse sections were strategically located in between the locations of the survey campaigns (Figure 6).

6.3 Execution energy

6.3.1 Cumulative; meter-by-meter and total energy

The accumulated energy was calculated to analyze the total energy of execution, investigating if this metric can be used to assess the mechanical behavior of the stratigraphic

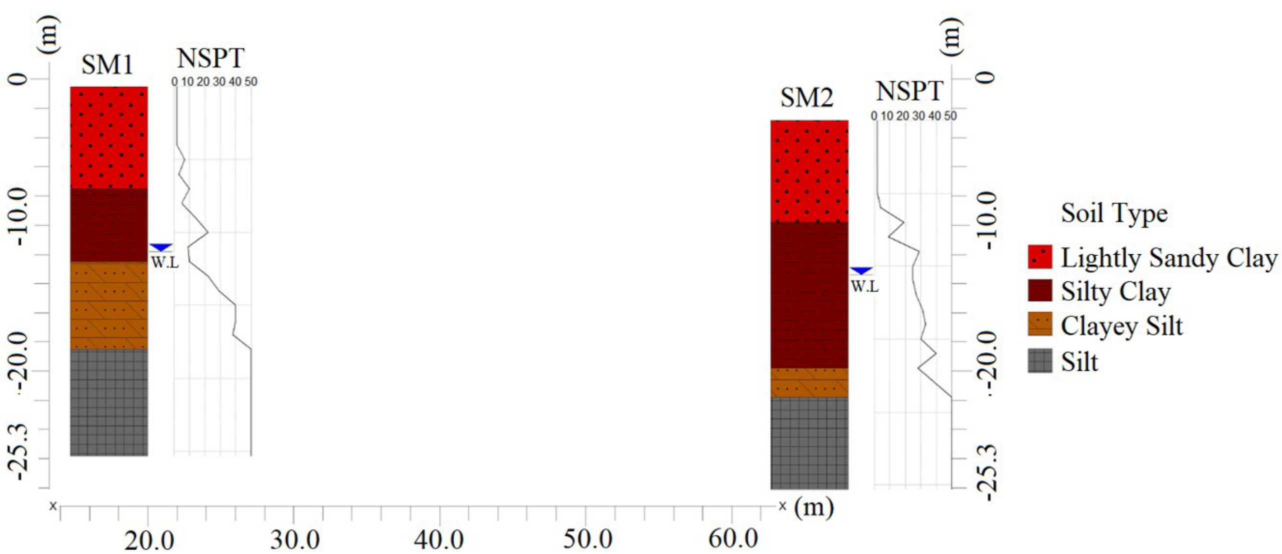

Figure 3. Section with the results of the first survey campaign.

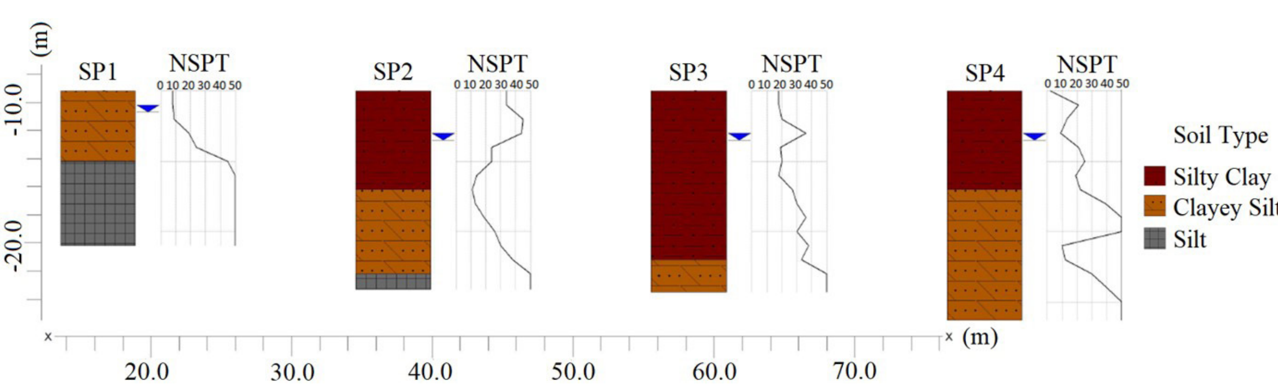

Figure 4. Section with the results of the second survey campaign.

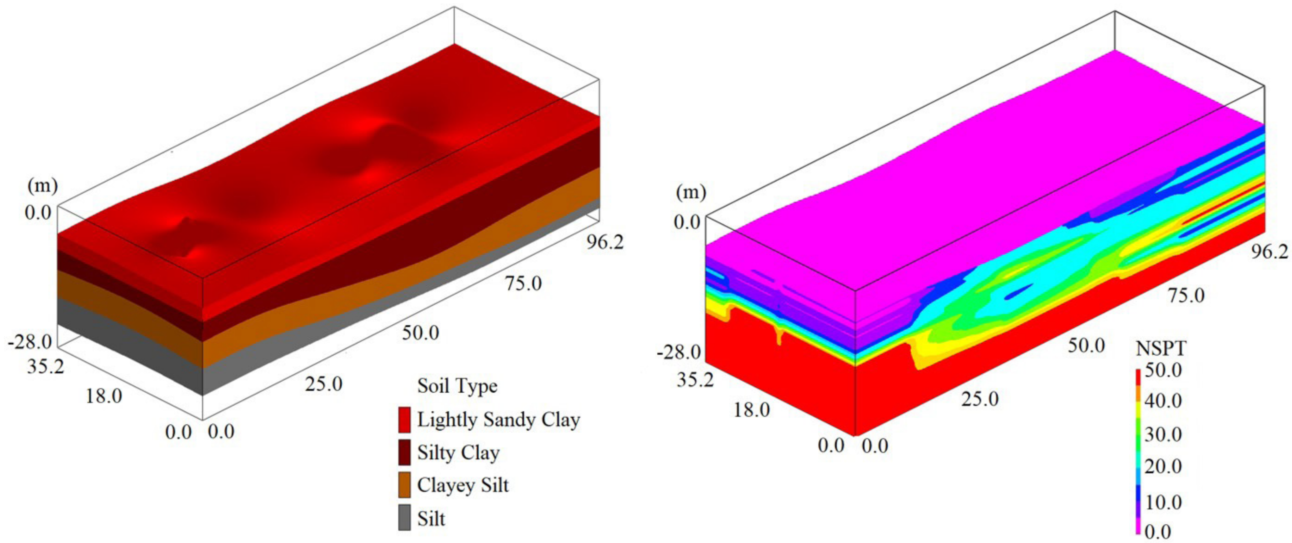

Figure 5. 3D models for stratigraphy and NSPT of the two survey campaigns.

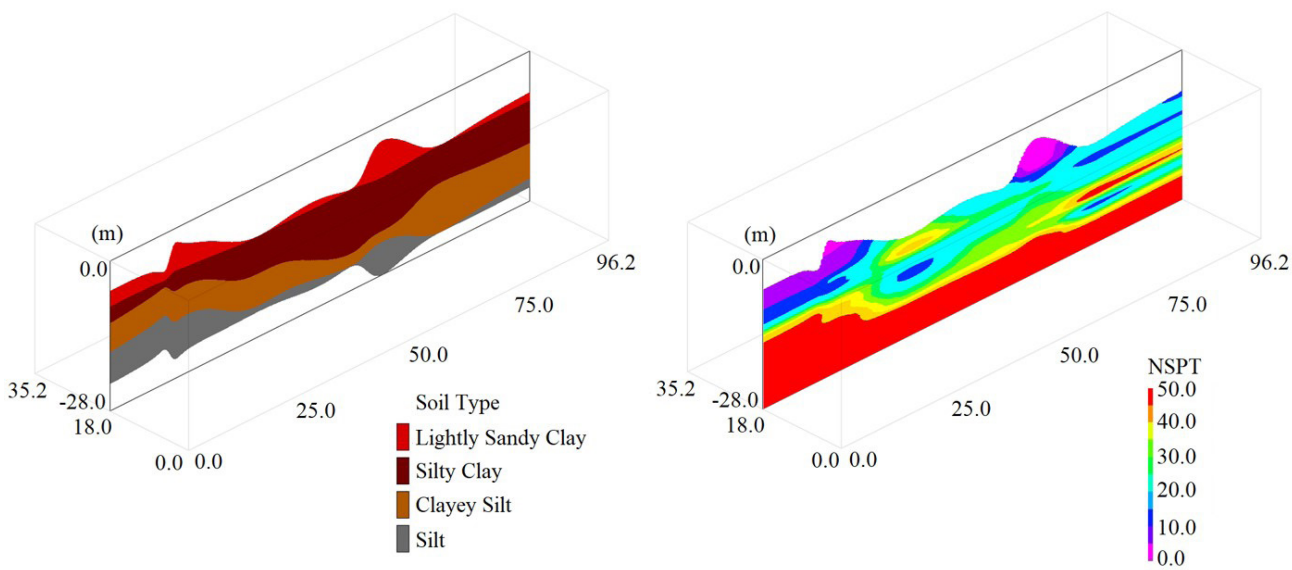

Figure 6. 3D cuts for stratigraphy and NSPT of the two survey campaigns.

profile in terms of resistance. Since the piles cover almost all the site area, it was possible to obtain a highly dense interpolation domain. Also, the energy needed to excavate each meter of soil (meter by meter) was calculated in order to verify the changes among soil layers. Thus, the graphs plotted in Figure 7 and Figure 8 show two examples of energy report results generated by the code developed. Figure 7 refers to a retaining wall pile, while Figure 8 refers to a foundation pile.

Figure 9 shows the histograms of the sampled total energies of execution for the piles of the retaining wall (left) and foundation structures (right).

When visualizing the histograms above, multimodal graphs are illustrated, where several peaks are observed, representing some typical total energy values. The physical interpretation of these peaks can account for several factors such as the length of the pile, the drilling of layers of different types of soils and the effect of stresses in the soil mass. The presence of three typical values of total energy is highlighted in the second histogram, which refers to foundation piles, and shall be discussed later.

6.3.2 Spatializations

A spatialized map was created from the interpolated total energy values in every area of the site. Figure 10 shows the behavior of the total energies of the foundation piles. It was observed that for the retaining wall piles, it was not

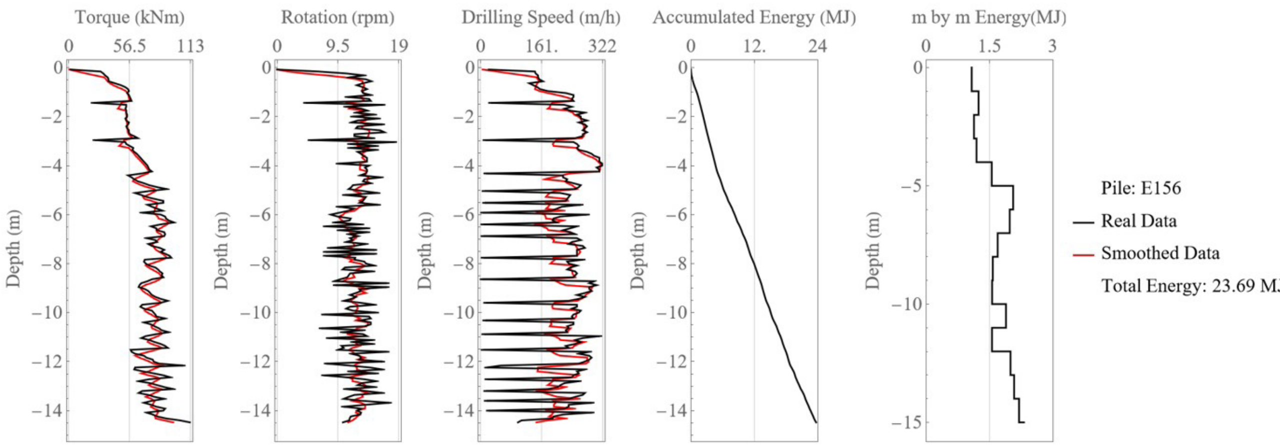

Figure 7. Calculated execution energy: E156 retaining wall pile (0.4 m of diameter).

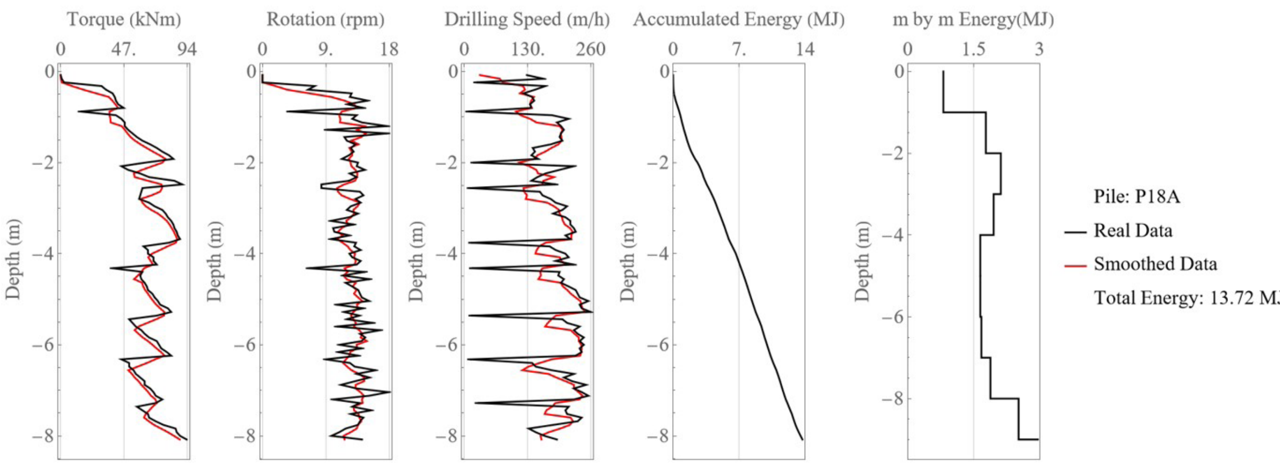

Figure 8. Calculated execution energy: P18A foundation pile (0.5 m of diameter).

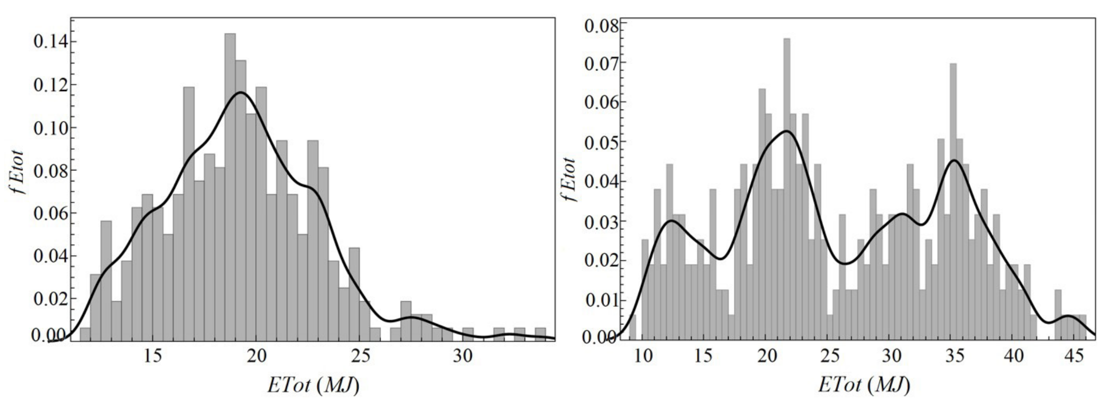

Figure 9. Total energy frequency curve of the retaining wall (left) and foundation piles (right).

possible to perform a spatial interpolation of the surface in a significant and coherent manner, since it was a perimetric data.

Individually, each pile has a certain volume (m^3). Also, during the drilling process, each slice excavated also has a given volume, which is related to the slice height and to the diameter of the pile. With such information, the total energy per excavated volume of soil was normalized and the spatialized results are presented in Figure 11. This normalization neutralizes the effect of the length and diameter of the pile, allowing a more accurate statistical analysis of the data collected.

In the case of the meter by meter energy, the results were spatialized similarly to the NSPT and stratigraphy

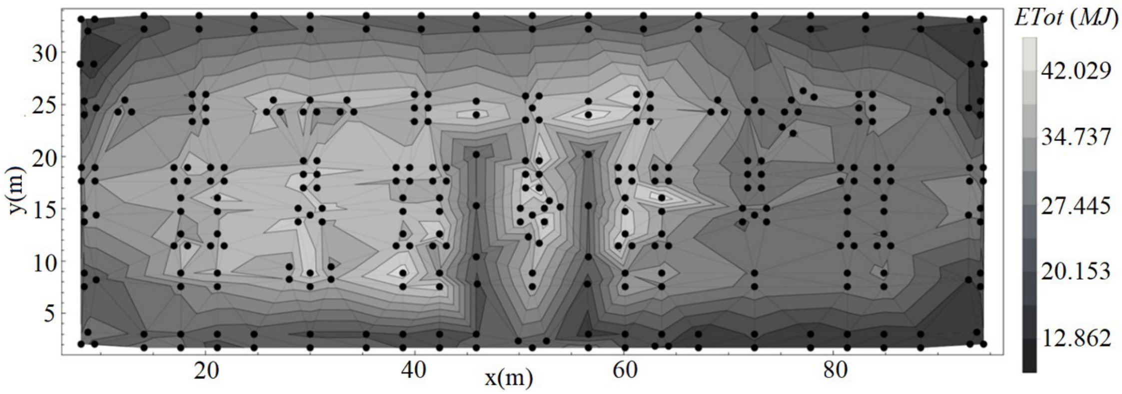

Figure 10. Total energy frequency curve of the foundation piles.

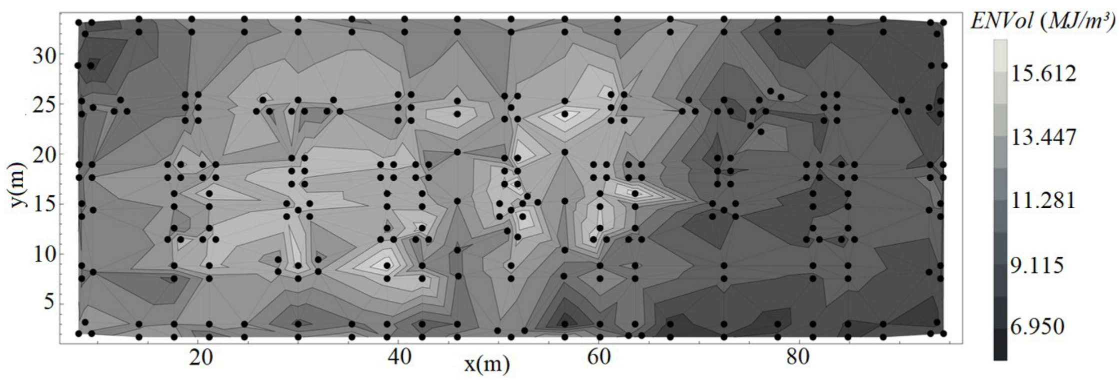

Figure 11. Spatialization of the energy density of execution of the foundation piles.

profiles. Two different sections, as indicated in Table 1, were chosen to illustrate the energy spatialization and are shown in Figure 12.

7. Discussions

7.1 Survey campaigns and their spatializations

Although the spatial distribution of the stratigraphic profile of the site is not frequently considered in everyday designs, this information may be of great interest, especially to obtain a better understanding of the soil mass in points other than the ones actually sampled during the preliminary surveys.

NSPT surveys may be subject to criticism because of the possibility of observing some dispersion between the results of different campaigns. Even though they have been done in very near places, the results from the two survey campaigns studied in the present paper showed significant variations. Ferrari de Campos et al. (2019) carried out an exhaustive analysis of the procedures needed to make the results of both the campaigns compatible. Such differences are due, on the one hand, to the variation in tactile-visual typification of the samples collected by the two survey teams responsible for the studies and, on the other hand, to the variations in the number of blows recorded by each survey campaigns as a consequence of the stress relief imposed by the excavation of the terrain.

Also, besides the factors discussed by Ferrari de Campos et al. (2019), any climatic variability during the periods between the execution of the two surveys can also impact the survey´s results. Analyzing the rainfall distribution, relative humidity and air temperature, according to data from the National Institute of Meteorology (INMET, 2021) in Brasilia, a comparison is made between the dates of the survey campaigns studied, as seen in Figure 13.

Although both campaigns were executed in March, a higher concentration of rainfall, higher relative humidity and lower temperature were observed in the first survey campaign, which would lead to a worse behavior of the soil, as the analysis of Figure 3 and Figure 4 suggest. Another influencing factor is that the executive process of the surveys was different, as there was water circulation during the first campaign.

It is worth mentioning that Ferrari de Campos et al. (2021) carried out a discussion about the bearing capacity of continuous flight auger piles in terms of their execution energy and of rainfall data. In that study, those authors showed

Table 1. Coordinates of the cutting steps for the retaining wall and foundation structure.

3D Energy cuts – Retaining wall and foundation structure	Coordinates (m)					
	Xi	Yi	Zi	Xf	Yf	Zf
3D Representation 1	0.0	0.0	0.0	0.0	35.20	-23.2
	0.0	0.0	0.0	96.20	0.0	-23.2
	96.20	0.0	0.0	96.20	35.20	-23.2
	0.0	35.20	0.0	96.20	35.20	-23.2
	24.05	0.0	0.0	24.05	35.20	-23.2
	48.10	0.0	0.0	48.10	35.20	-23.2
	72.15	0.0	0.0	72.15	35.20	-23.2
	0.0	18.0	0.0	96.20	18.0	-23.2
3D Representation 2	0.0	18.0	0.0	96.20	18.0	-23.2

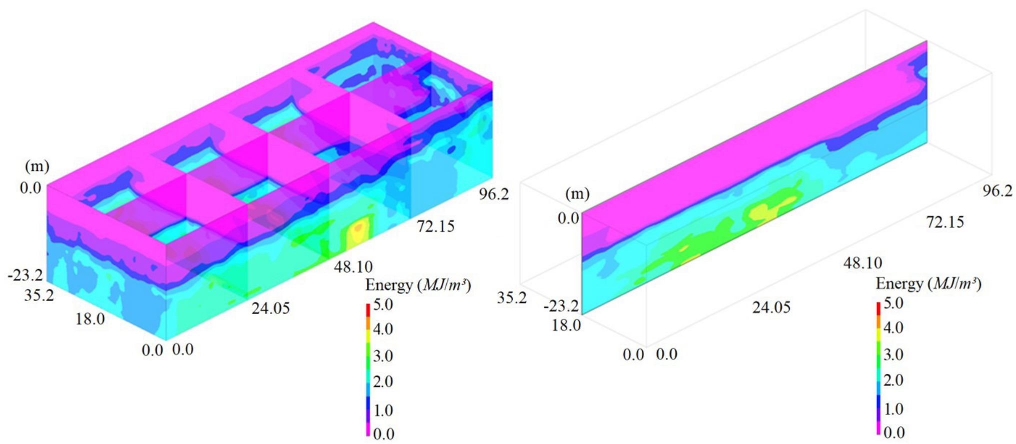

Figure 12. 3D Representation 1 and 2: Execution energy density (MJ/m³) of all piles.

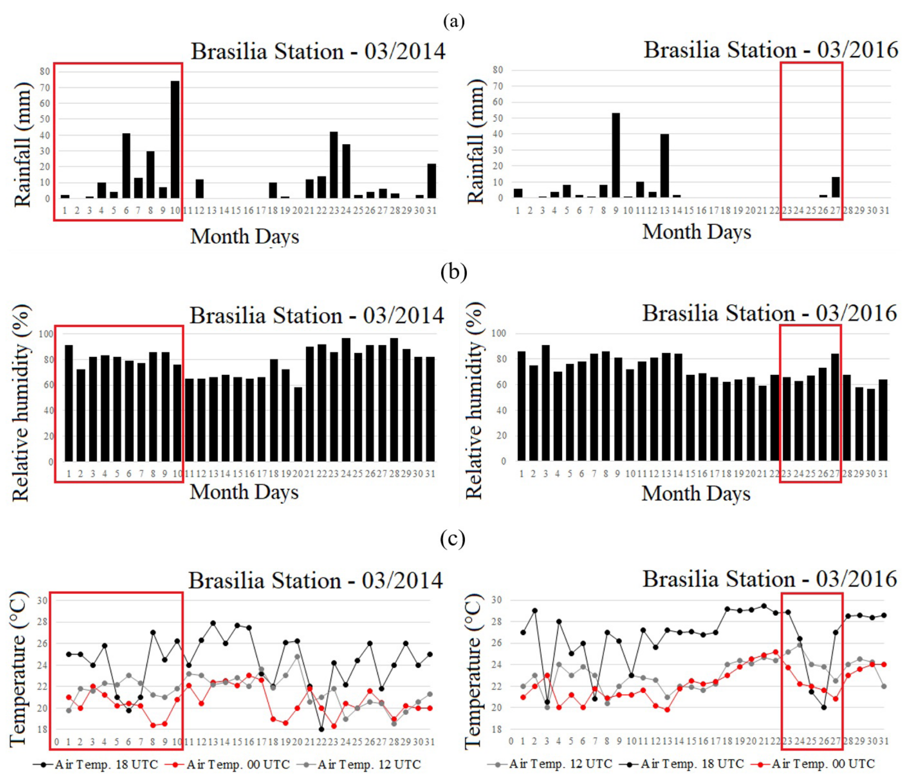

Figure 13. (a) Daily Rain; (b) Relative air humidity; (c) Air temperature.

that pluviometry events impact the energy needed to execute this type of pile and, therefore, also impact its mechanical behavior up to three meters of its depth. Wetting/drying cycles and resulting stresses imposed on the soil mass while performing excavations also alter the mechanical response of piles when loaded.

This need for compatibilization between survey teams and campaigns, as well as time of execution may not be ideal. Therefore, in the next subsection, it will be discussed how the execution energy can be used as a powerful and simple tool to evaluate the support capabilities of the terrain.

7.2 Execution energy

7.2.1 Evolution of the stress state

As discussed by Ferrari de Campos et al. (2019), most of the procedure carried out to make the survey results compatible was related to correcting the stress state in the site before and after the excavation of the site. It is important to highlight that the actual stress state the foundations will be subjected to during their lifecycle is the one after excavation.

While analyzing the execution energy, the stress state is also fundamental since the construction steps, especially excavations, affect the stresses transmitted to the drill during the execution of the piles. In particular, the horizontal stresses impact the energy needed to drill a given pile because, in general terms, an increase in the horizontal stresses tends to increase the frictional force that counterposes the rotation of the helical drill, thus increasing the work of this dissipative force and consequently the execution energy as a whole.

7.2.2 Spatial assessment of site resistance

Observing the plots in Figure 10 and Figure 11, using the execution energy to evaluate the behavior of the piles can be considered an interesting tool, allowing the designers to have a visual understanding of the energetic expenditure (and, therefore, bearing capacity) of the terrain as a whole.

To make the visualization even clearer, it is possible to cluster similar energetic expenditures instead of directly interpolation the drilling energy of each pile. These clustered results for total energy and volumetric energy density can be seen in Figure 14 and Figure 15, respectively. This construct was performed by applying the *ClusteringComponents* function to the *ListDensityPlot* function of the Mathematica® software for the data in question.

Figure 14 shows four characteristic regions. In special, low and medium energy expenditures are observed at the extremities of the site, possibly due to the loosening effect

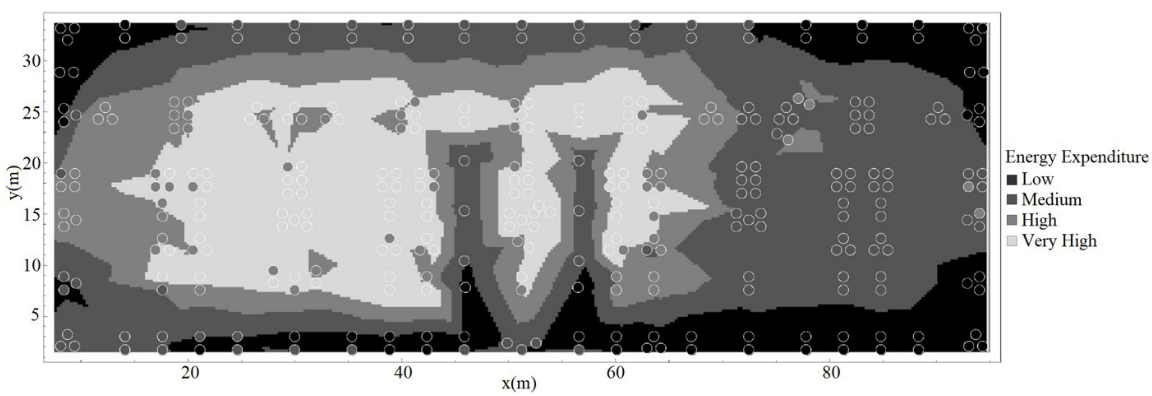

Figure 14. Spatialization of total energy expenditure demanded for the foundation structure.

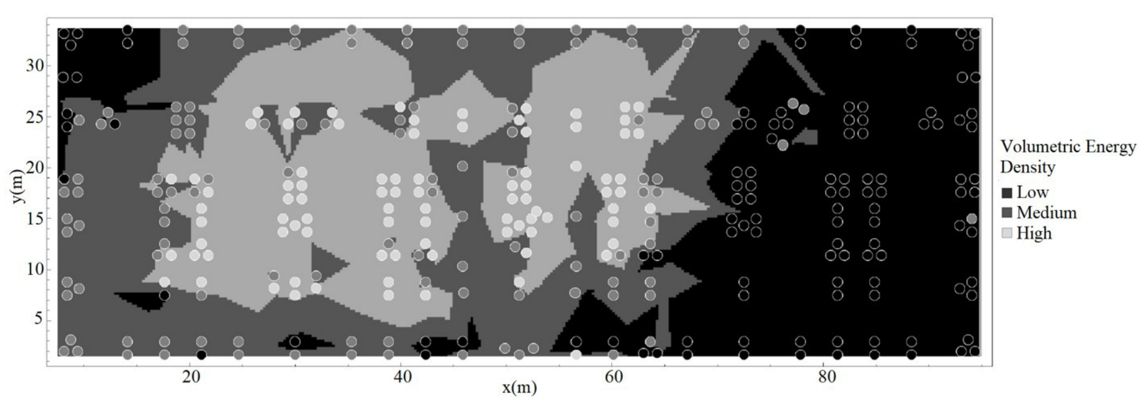

Figure 15. Spatial volumetric energy density for foundation piles.

of horizontal stresses caused by the unloading of soil by the excavation and by the retaining wall construction. On the other hand, high and very high energy expenditures are seen in the central-west part of the site, being directly correlated to the existence of the more competent soil layers when compared to the stratigraphy of the surveys located in this region.

Looking closely at Figure 15, a certain similarity to Figure 14 is perceived. This fact is expected because the influence of the stress state in the soil and the resistant soil layers remains the same, only changing the impact of the length of the pile, which has been neutralized in Figure 15. Another difference is observed that, in terms of energy expenditure, there were three characteristic regions. The characteristic values observed above are in accordance with the peaks observed in the histogram presented in Figure 9.

7.2.3 Assessments of site´s bearing capacity by using execution energies and bootstrap statistical simulations

In order to validate the usage of execution energies as metrics for estimating the potential bearing capacity of piles drilled in a given type of soil, it is imperative to first understand which external and internal factors impact these energetic measurements. In the following topics, several factors that would impact the values of the execution energy densities (specific energy) were considered. Both the measured values and the Bootstrap resampling method were combined to present a robust statistical framework for the analysis.

Bootstrap is a non-parametric estimation method introduced by Efron (1979, 1982), which allows one to estimate the confidence interval of a given statistic of interest. In short, the Bootstrap method is a statistical inference method based solely on the available data (sample). One of the greatest advantages of the method is that the latter does not rely on any consideration of the random variables involved (Ozelim & Cavalcante, 2018).

The core of the Bootstrap method is that it assumes that the sample collected is representative of the population from which the former has been drawn and that the observations are independent and identically distributed. Thus, the Bootstrap method is capable of estimating the sampling distribution of a given statistic (for example, the mean and variance of the population) (Ozelim & Cavalcante, 2018).

Such methods were used to understand the possible impact of different factors on the execution energy measurements. In special, it was considered the influence of morphological factors such as the pile positioning with respect to the retaining wall, the execution order of the pile inside a foundation block, the influence of the retaining walls at the edges of the excavated terrain and the impact that the retaining walls have on the execution of piles which go below the wall´s setting depth.

In general, by selecting subgroups of the measured energy values, a resampling random Bootstrap algorithm was used to calculate the mean values, coefficients of variation and confidence interval for some parameters of interest. For this, 10.000 replicates or resamplings were performed in all statistical procedures.

It is interesting to notice that the calculation of confidence intervals with the Bootstrap method may outcome asymmetric intervals, i.e., not centered around the mean value of the parameter of interest. In addition, this method always maintains the physical meaning of the variables involved (strictly positive, for example) since the values of the statistics are always calculated from the sampled data. It should be emphasized that the confidence interval that will be shown in the analyzes have a 95% confidence level, considering the trend correction and BCa acceleration. Also, the hypothesis test of the equality of distribution of two different samples will be evaluated.

7.2.3.1 Influence of pile positioning

One of the main precautions that must be taken during the execution of a foundation refers to the control of the positioning of the piles in relation to the geomorphology of the site. In addition, in order to understand how the execution energies can be used as metrics to assess the competency of a given terrain, one must investigate if the piles arrangement can influence other piles in terms of execution energy. According to Figure 16, all foundation piles were divided into three groups.

The idea is to test whether or not the execution energy of foundation piles is affected by their positions with respect to the retaining wall. The following hypothesis test was considered:

- H0: The energy samples from any two groups being compared belong to the same distribution;
- H1: Reject H0.

Table 2 shows the p values for the hypothesis tests and in the sequence, in Figure 17, the histogram of specific energy values and the 95% confidence interval of the respective

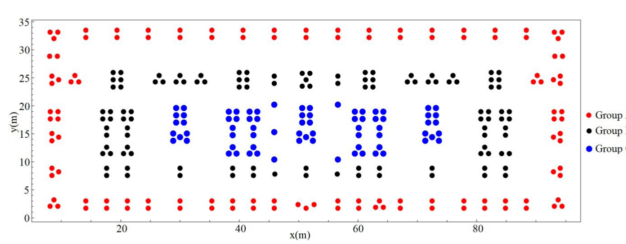

Figure 16. Division of the groups related to the foundation piles.

Table 2. Hypothesis test results (p value): piles positioning.

Piles Positioning	Group A	Group B	Group C
Group A	**1**	0	0
Group B	0	**1**	0.0007
Group C	0	0.0006	**1**

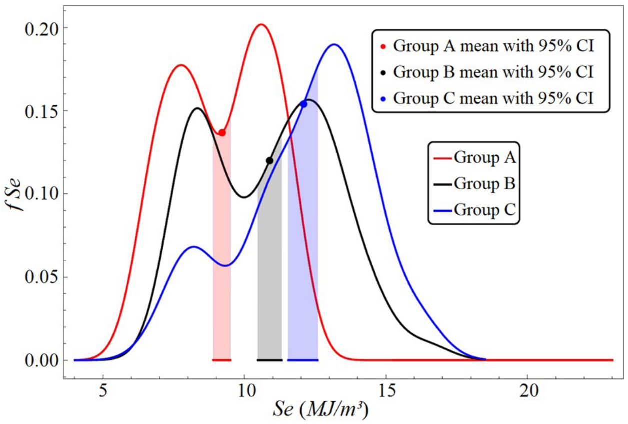

Figure 17. Histogram with 95% confidence interval for groups A, B and C.

mean of each group were presented. In such table, bold cells indicate that the null hypothesis is accepted and the other cells indicate that the alternative hypothesis is accepted, which represents the rejection of the null hypothesis with a 5% tolerance.

It is evident that the groups A, B and C do not come from the same distribution, and cannot be considered statistically equal. This conclusion makes complete sense, since it shows that physically each group represents regions with different characteristics. This way, it can be seen that the positioning of the piles with respect to the retaining wall is an important factor.

7.2.3.2 Influence of execution order per foundation block

According to the current Brazilian standard ABNT NBR 6122 (ABNT, 2019), 5D-distance and 12 h lag are requirements to execute neighboring piles, precisely to prevent the sectioning of shafts. In order to investigate if the executive order of piles impacts their execution energies, a statistical analysis for each of the three groups previously defined will be performed. The order of execution of each pile with respect to its foundation block is illustrated in Figure 18.

Groups A, B and C are still considered for this type of analysis because a statistical difference between the specific energy values between them was previously observed. Thus, for each group, the same hypothesis test previously enunciated was carried out. On the other hand, instead of comparing all the piles inside a given group, the piles which were executed in the same sequence were compared (first piles to be executed for each foundation block with other piles in the sequence and so on). The p values are presented from Table 3 to Table 5.

Each group will be analyzed separately. Group A fits the null hypothesis for most of the cases, indicating that all the specific energies of first piles executed in each foundation block have the same distribution like the ones executed secondly and thirdly. This indicates that executive order is

Table 3. Hypothesis tests results (p value): execution sequence of Group A.

Execution sequence	1st	2nd	3rd	4th
1st	**1**	**0.1321**	**0.4913**	0.001
2nd	**0.1298**	**1**	**0.6165**	0.0312
3rd	**0.4868**	**0.6183**	**1**	0.0162
4th	0.0009	0.0292	0.0139	**1**

not important. By observing in Table 3, the sub-group of the fourth piles in the sequence was neglected in the analyses. The reason for the exclusion is that the sample considered is too small, consisting of only two blocks which had four piles. Small samples as these invalidate any statistical analysis.

Group B results were similar to group A, making it clear that the specific energies are not influenced by executive order of the piles in each foundation block. For the cells that are not in bold, the hypothesis test failure can be attributed to two factors: number of piles in the sample (there are only four blocks with four and six piles) and variations in the foundation's executive procedure. Note that for the sub-group of fifthly executed piles, the expected behavior occurred.

As in the cases of groups A and B, for group C the expected behavior was verified. It is noted, however, that for the third and sixth piles executed, the null hypothesis was rejected. These rejections can be attributed to the same factors discussed for group B (sample size and executive procedures).

7.2.3.3 Edge Influence in the Group A

The first analysis showed that the position of the piles with respect to the retaining walls is an important factor. For the closest group to the wall, Group A, it is also important to understand if the edges of the wall impact the specific energy values differently when compared to the other regions. This way, it was decided to divide Group A into eight regions for this analysis, as observed in Figure 19.

The intention of this analysis was to investigate the existence of characteristic regions in terms of execution energy between each sub-region, mostly considering the position with regard to the retaining wall. Analogously, the p values results for the equality of distribution hypothesis test for the eight regions are shown in Table 6 and the complete histogram with all 95% confidence intervals for the mean specific energy values is illustrated in Figure 20.

Table 6 reveals that several of the sub-regions can be considered statistically equivalent. Observing each relation, it is possible to compare the position of each sub-region and the spatialization of the volumetric energy density for the foundation piles, located in Figure 15. Certain regions tend to present similar characteristics in terms of execution energy, depending on the positioning in relation to their stratigraphy and the effect of the stress state.

Table 4. Hypothesis tests results (p value): execution sequence of Group B.

Execution sequence	1st	2nd	3rd	4th	5th	6th
1st	**1**	**0.6883**	**0.3584**	0.0012	**0.106**	0.0075
2nd	**0.6924**	**1**	**0.7753**	**0.6322**	**0.7657**	**0.3294**
3rd	**0.3484**	**0.7788**	**1**	**0.8073**	**0.8925**	**0.4125**
4th	0.0145	**0.6378**	**0.8006**	**1**	**0.9519**	**0.3872**
5th	**0.0988**	**0.763**	**0.9853**	**0.9498**	**1**	**0.5152**
6th	0.007	**0.32**	**0.4135**	**0.3959**	**0.514**	**1**

Table 5. Hypothesis tests results (p value): execution sequence of Group C.

Execution sequence	1st	2nd	3rd	4th	5th	6th
1st	**1**	**0.5411**	0.0005	**0.6005**	**0.3691**	0.0405
2nd	**0.5329**	**1**	**0.0518**	**0.8831**	**0.5821**	**0.1914**
3rd	0.0002	**0.0544**	**1**	0.0275	0.0348	0.018
4th	**0.5857**	**0.8831**	0.0304	**1**	**0.6041**	**0.1487**
5th	**0.3647**	**0.5705**	0.0365	**0.5993**	**1**	**0.3867**
6th	0.0445	**0.194**	0.0203	**0.1511**	**0.4002**	**1**

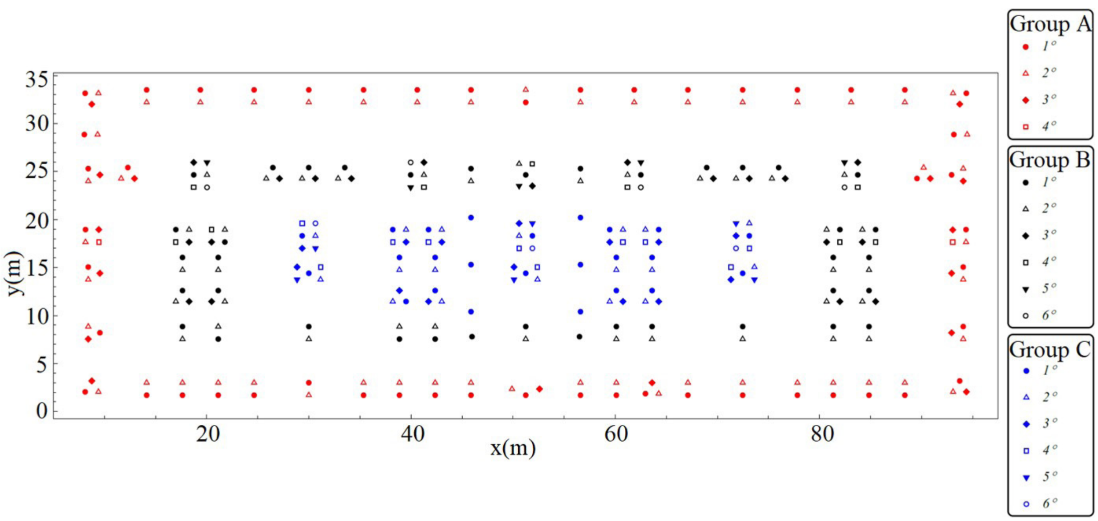

Figure 18. Execution order per foundation block.

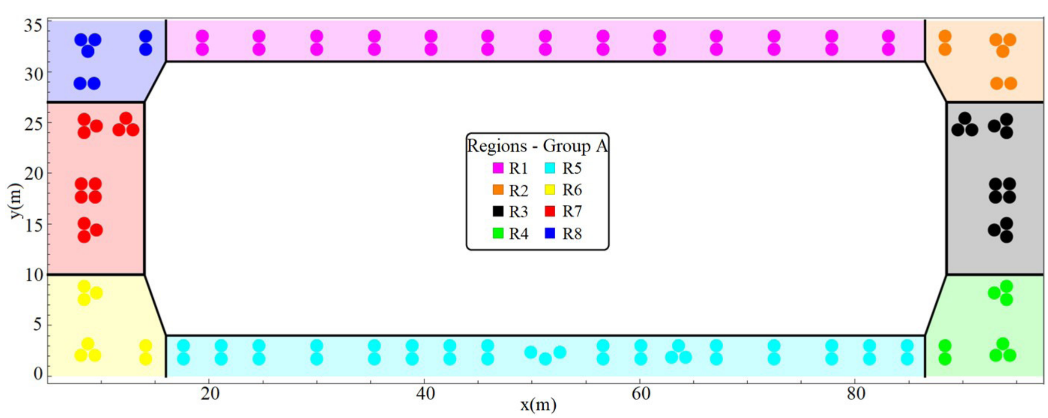

Figure 19. Regions belonging to group A.

The main focus of this section analysis is to understand whether the piles in the corners suffer significantly more influence from the piles executed along the sides of the polygon delimited by the retaining wall. It is noted that for

Table 6. Hypothesis tests results (p value): execution sequence of Group C.

Group A zones	R1	R2	R3	R4	R5	R6	R7	R8
R1	**1**	0	0	0	0.0045	**0.369**	**0.1619**	0
R2	0	**1**	**0.3051**	**0.237**	0.0371	0.0001	0	**0.4387**
R3	0	**0.2927**	**1**	**0.0648**	0.0418	0	0	**0.7514**
R4	0	**0.2358**	**0.0599**	**1**	0.0092	0	0	**0.0874**
R5	0.0041	0.0363	0.0432	0.0096	**1**	0.0142	**0.1703**	**0.0907**
R6	**0.3693**	0	0	0.0001	0.0144	**1**	0.0097	0.0005
R7	**0.1656**	0	0.0002	0	**0.1755**	0.0094	**1**	0.0006
R8	0	**0.4442**	**0.7536**	**0.0929**	**0.0888**	0.0004	0.0003	**1**

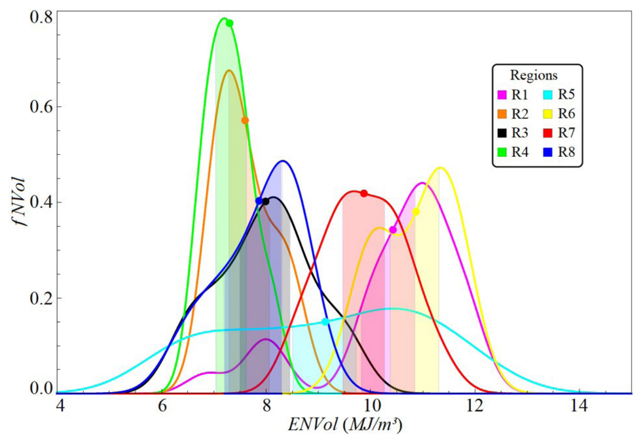

Figure 20. Histogram with 95% confidence interval for the regions of group A.

region 1, regions 6 and 7 can be considered statistically equivalent. In this case, this similarity is more related to the predominant soil layer than the position in relation to the wall.

On the other hand, for region 2, there is correspondence with regions 3, 4 and 8. The correspondence with the piles of region 3 is mainly due to the predominant soil layer being the same. Another point is that for regions 4 and 8, the correspondence by influence of the stresses (corners) is clear. It is important to note that region 6 (lower left corner) is not related to the other edge regions (2, 4 and 8) because it does not suffer from the same effects. For region 6, the garage ramp pushed the retaining wall further away from the foundations, changing the effect of stresses on the piles of that region.

Region 3 has the same type of correspondence described in relation to regions 2, 4 and 8. The same holds for region 4 in relation to the regions 2, 3 and 8.

Region 5 has correspondence in relation to the regions 7 and 8. This relationship stems mainly from the predominant soil type in the excavated profile.

Region 6 is only related to region 1. This relation comes from the similarity of stresses for both groups (horizontal neighborhood effect) and the most common type of soil in the profile.

Region 7 shows similarity to the regions 1 and 5. This correspondence stems mainly from the similarity of the stress state between these regions (neighborhood from the sides of the polygon defined by the retaining wall).

Finally, for region 8, similarities with regions 2, 3, 4 and 5 were found.

7.2.3.4 Influence area of retaining wall structure on foundations

During the executive procedure of a retaining wall structure or, depending on the case, only after its execution, excavation is carried out to implement the foundations. This process of excavation provokes a stress relief in the soil mass, implying in redistributions of stresses until the re-establishment of the equilibrium.

The construction under consideration had its foundation executed 30 days after the implementation of the retaining wall. According to Figure 21, there is a section in profile in which both structures´ piles coexist. The probable influence of the wall on the energy spent in the execution of the foundations will be analyzed. For this, a representative area of interest was selected within the site. The specific energy spent to drill the overlapping area (from -9.2 m to -15 m) between foundation and retaining wall piles will be analyzed.

This area was selected because the foundation and retaining walls are close to each other and the total number of piles is sufficient to carry out statistical analyses. Figure 22 shows the histogram of specific energies and the confidence intervals for their mean values for the foundation piles, named R3-A, and the retaining wall piles, R3-B.

The results showed that, in comparative terms, the energies used to excavate the same material in the overlapping region (from -9.2 m to -15 m) in both structures are not equivalent. Physically, this result demonstrates that these distinct characteristics may be related to the effect of the total horizontal stress state, which is severely impacted by the process of unloading the soil. Also, the movement of the walls after being submitted to the horizontal load is another important factor which can be considered, indicating that there is a great influence on the behavior of foundation piles while compared to nearby piles in the retaining wall. In addition, this result also indicates that tests performed before and after the excavation, such as SPT, are strongly influenced by stress relief.

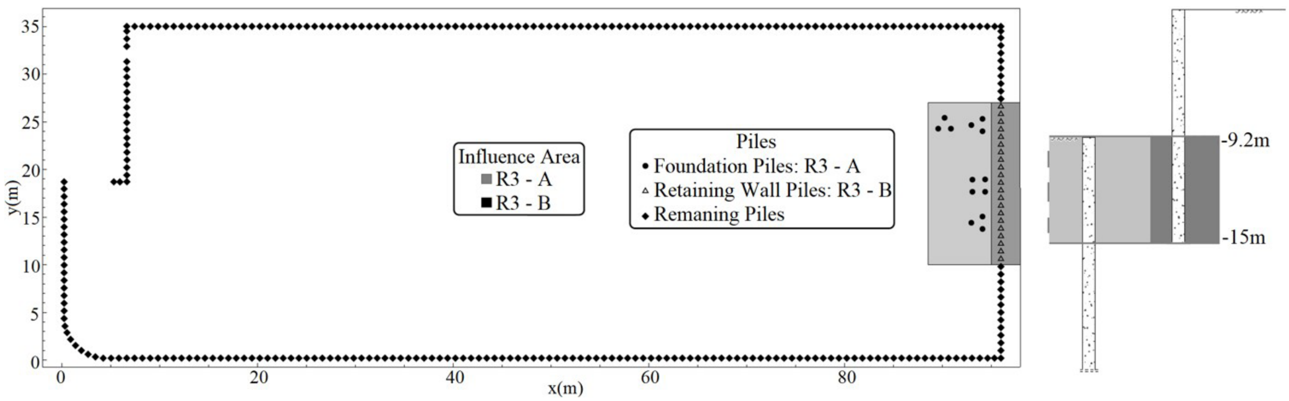

Figure 21. Stretch corresponding to the influence area.

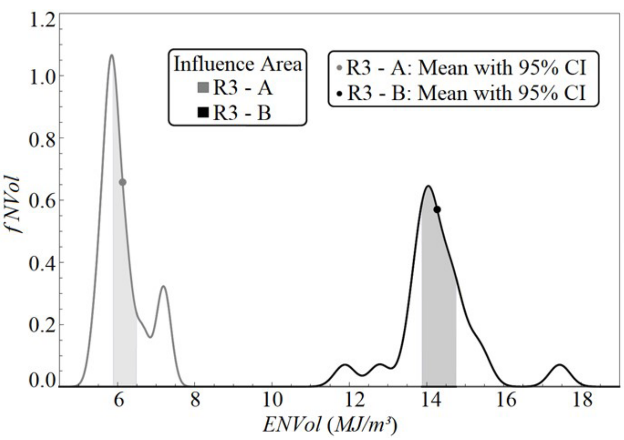

Figure 22. Histogram with 95% confidence interval of piles belonging to influence area.

8. Conclusion

Prior knowledge of local geology and geomorphology is important to perform any type of modeling, be it three-dimensional or two-dimensional. By combining this knowledge with the professional experience, the uncertainties arising from natural soil variability can be considerably mitigated.

Allying the results of the measured execution energies with the Bootstrap resampling method, it was possible to study how the positioning of the piles in the site, as well as the proximity to the retaining wall piles, impact these energetic metrics. The analysis carried out also revealed that the executive order per foundation block does not impact the execution energy when the piles are in the same region.

Regarding the pile execution, it is possible to say that the energy demanded is influenced by the type and competence of the soil being drilled. In the regions where the foundation piles are close to the retaining wall, a general decrease in the execution energy has been observed, which has been attributed to the changes in the horizontal stresses due to stress redistribution. Moving away from the wall, the reductions are less significant, and energy values are mostly impacted by the competence of the stratigraphic profile being drilled.

In accordance to the previous work by Ozelim & Ferrari de Campos (2016), where a new mathematical model was built to correlate the cumulative execution energy to the cumulative blows of SPT, the spatializations presented in the present paper confirm that there is a good correlation between the accumulated execution energy density and the accumulated NSPT values. Following this reasoning, as the NSPT is used to verify the bearing capacity of the piles, the use of the execution energy represents a promising tool for the actual verification of the performance of the foundation piles.

Not only the bearing capacity itself, but stress-strength constitutive parameters such as Young's Moduli (Ozelim et al., 2018) and Unconfined Compressive Strength (Ozelim et al., 2019) have shown to be related to the execution energy of CFAPs. This reinforces the importance of the present paper, as understanding how the execution energy behaves in real applications is crucial to use this metric as a proxy for the mechanical behavior of the pile during its lifetime. This physical/engineering understanding of the execution energy can be combined to the previous mathematical and statistical correlations and build a powerful estimator of CFAPs response to real-world scenarios.

Geotechnical Engineering, especially the branch dedicated to foundations, has evolved in a substantial way in recent years. This evolution is due in large part to the advent of technologies that allow to simulate and test more precise models of soil´s behavior. However, the advances which are currently used in foundation engineering practice are more related to enhanced executive procedures than to a broader understanding of the phenomena involved during the foundations execution. In this sense, the present paper sought not only to list but also to discuss a number of fundamental issues which may show up during the energetic control of the execution of CFAPs.

In summary, foundation designers must analyze the construction site in an integrated way, trying to understand how the stratigraphy, the stress history and the quality of execution procedures can be integrated in order to ensure reliable solutions.

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Declaration of interest

The authors have no conflicts of interest to declare. All coauthors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Darym Júnior Ferrari de Campos: conceptualization, data curation, visualization, software, writing – original draft. Luan Carlos de Sena Monteiro Ozelim: methodology, supervision, validation, software, writing – review & editing. André Luís Brasil Cavalcante: formal analysis, investigation, writing – review & editing. Carlos Medeiros Silva: data curation, conceptualization. José Camapum de Carvalho: supervision, conceptualization, formal analysis.

List of symbols

2D	Two-dimensional
3D	Three-dimensional
p	p value
t	Time
Φ	Diameter

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