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Semi-empirical method for the bearing capacity of continuous flight auger piles based on installation energy

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Article

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Continuous Flight Auger (CFA)
Energy
Load capacity
SCCAP methodology

Abstract

The prediction of load capacity and the control of the execution of the Continuous Flight Auger (CFA) piles are often exercised with components of empiricism and intuition. This fact is often added to the uncertainties arising from the formation of the soils and the limitations of preliminary studies that support the project design. In this context, aiming to aid the executive control of CFA, a semi-empirical method is proposed based on the soil type, geometric dimensions of the piles, and the installation energy obtained during the pile excavation. The method makes it possible to determine the CFA pile load capacity during the execution process of each pile of pilling. As a consequence of the proposed method, the settlement of each pile can be controlled through the quantification of the energy required or the work carried out to excavate each pile through a specific software installed in the machinery monitoring system that increases the safety and reliability of the piling.

1. Introduction

Safety and reliability in foundation engineering should be the subject of attention because only the current practice of using the safety coefficient does not guarantee the proper assessment of the risks associated with the design and execution of the project. The major source of variability in foundation engineering is the geological-geotechnical formation, affecting the performance of the soil-foundation system that is strongly influenced by stratigraphic variability along the profile and the soil as a whole. Other factors such as climate and geomorphology can also assume great relevance and their dynamics must be observed in each case.

Pile driving seeks to ensure that the design assumptions, in terms of load capacity and deformability, are met during execution. The aim is then to define in the design and execution, among the various possibilities, a resistant surface for the pile foundation's settlement levels that meets the technical, economic, and legal requirements.

In this context, Silva (2011) presented the SCCAP methodology for the control and standardization of excavated piles, specifically of the CFA type, which is based on the interpretation of the energy required or the work performed during the excavation of a pile. The methodology was developed from the understanding of the drilling rig force system and the application of the universal principle of energy conservation, which when applied to the process of excavating a pile, allows for the quantification of the energy required or needed to excavate a pile.

The theoretical basis of the methodology was presented in detail by Silva (2011) and according to the author, it can be extended to any type of excavated or displacement pile as well as to other rotary excavations, as long as it is possible to identify the force system to quantify the energy that is demanded in the process.

But even though the execution of a CFA pile involves advanced technology and controls during execution, the pile settlement quota is almost always defined by empirical and practical criteria with no theoretical or scientific basis, making the process lacking in proven effective methods and methodologies.

2. Energy at the basis of pile foundations

Fundamentally, the performance of a foundation depends on the process adopted during its execution and on the geological-geotechnical characteristics of the soil. Therefore, determining the load-bearing capacity of a foundation, a practical problem present in the daily life of geotechnical engineering, becomes a problem of difficult solution, especially in places with great geotechnical variability, because generally there are insufficient field investigations and little accuracy.

The geotechnical engineer has in most of the projects only deterministic, empirical, and semi-empirical methodologies or limited theoretical methods. Consequently, the geotechnical engineer will never obtain or be certain of the exact value,

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obtaining only the order of magnitude of the bearing capacity and deformability.

In driven piles, the uniformity of the pile foundations is accomplished using energy control, in this case, represented by the set and rebound, and are indispensable in the reliability of this type of pile cap. It enables, from dynamic and static formulations, the comparison of results obtained in the field with those of the project and the results of load tests, if any.

Generally, in some CFA foundation designs, the pile settlement is conditioned to a minimum depth and the attainment of a certain value of torque or oil pressure at the end section of the pile. But the torque obtained during the monitoring of the execution of the flight auger pile is thrust-dependent, consequently, the criterion may be satisfied before the design load capacity is reached.

It is worth remembering that the magnitude of the torque is conditioned to the angular velocity and the feedrate imposed on the helix. For example, a force or torque of small magnitude, applied to the helix during a long time interval, can generate the same displacement (final elevation of the pile) caused by a force or torque of high magnitude applied in a short time interval as described by the impulse-momentum theorem (Silva, 2011).

However, in this case, the sum of the helicoid rotations and, consequently, the path of the force applied to the helicoid will be greater for the force of lesser magnitude, compensating for the existing differences between the forces, which perform equivalent work at the end of the excavation. As an example, a machine of greater power generates a torque of great magnitude and performs the work required to excavate a pile in less time, when compared to a machine of less power that will need more time to excavate this same pile, a fact demonstrated by Silva (2011).

To replace the maximum torque criterion, Silva (2011) presented and validated the SCCAP Methodology, Silva & Camapum de Carvalho (2010). This methodology is based on the thesis that the control of mechanized excavations, of CFA piles, through the determination of the energy required in the execution of the drilling, constitutes an element of technological control capable of offering greater safety and less risk to the works that use it. The SCCAP was based on the law of conservation of energy, one of the fundamentals of classical physics, and quantifies the energy required or the work done to excavate each pile of the foundation.

From this quantification Silva (2011) developed routines and proposed statistical criteria for the acceptance of the piles, based on the statistical characteristics of the population or on an energy sample taken from the pile itself and incorporated the routines to the software for monitoring the execution of CFA piles. Silva (2011) presented the methodological framework that supports the thesis that the control of the excavated piles, in particular the CFA piles, through the determination of the energy demanded during the pile excavation, constitutes an element of technological control capable of offering greater safety and less risk to the works that use them.

2.1 Energy and pile foundation control

An important concept that is directly related to energy is the work done, a scalar quantity and therefore without associated direction. The universality of the concept of energy makes it possible, for example, to understand how the mechanical energy produced by a motor is transformed into kinetic energy and in turn dissipated by work, in the case of a pile, by friction (heat), so that even with these energy transformations, the total energy is a constant.

Physically, work describes what is accomplished by the action of a force, being defined by Young & Freedman (2008), as the product of displacement by the force parallel to the displacement. If a body, moving from the initial pile elevation (c_i) to the final one (c_f) along any trajectory (x), is under the action of a variable force (F), work (W) can be defined in Equation 1.

$$W = \lim_{\Delta x_i \to 0} \sum_{i}^{n} F_i . \Delta x_i = \int_{c_i}^{c_f} F.dx \quad (1)$$

Another form of energy associated with an object is potential energy, which depends on the position and configuration of the system. For example, to lift the auger of a continuous propeller machine, work must be done and, consequently, energy will be consumed to move it from one point to another (Young & Freedman, 2008).

If energy is conserved, how is this energy stored? We can say that this energy is accumulated in terms of gravitational potential energy, which depends only on the position of the object relative to the Earth's center and its mass. Therefore, the work done by the gravitational force (w) when a mass (m) changes its elevation (y) relative to the Earth's surface is given by Equation 2.

$$W = F\Delta y = mg\left(y_1 - y_2\right) \quad (2)$$

where "g" is the gravity acceleration.

Another important principle is Hamilton's, which starts from the concept of conservative energy, in which energy cannot be created or destroyed, only transformed. In the case of structural system dynamics, the concept can be summarized by Equation 3, according to Clough & Penzien (1975):

$$\int_{t_1}^{t_2} \delta\left(T - V\right) dt + \int_{t_1}^{t_2} \delta\left(W_{nc}\right) dt = 0 \quad (3)$$

where T is the total kinetic energy; V is the potential energy, including the strain energy and the potential energy of any external conservatively acting forces; W_{nc} is the work done by the nonconservative forces acting on the system, including damping, friction, and external forces.

This principle in variational form, applied to a system in equilibrium, states that the variation occurring within the system, of kinetic and potential energy, added to the variation in work done by nonconservative forces acting during any time interval (t_2 - t_1) is equal to zero.

Therefore, it is evident that Hamilton's principle can be applied to the case of loading of any system, in static or dynamic equilibrium, and particularly to the pile-soil system. One should also remember the first law of thermodynamics: in any transformation of energy, its absolute value is conserved. That is, energy cannot be created or destroyed, only transformed, a principle applied by Aoki et al. (2007) to calculate the work, energy, and efficiency of the dynamic SPT test.

Foundation engineering is based on field tests, which are energy measurements, a fact studied by Odebrecht et al. (2007), who realized the need to standardize the measurement of the number of blows of the SPT test in terms of energy. They suggested a new approach and an analytical solution to calculate the delivered energy and the efficiency of the system. Schnaid et al. (2009) warn that interpretations of dynamic penetration testing (SPT) results are traditionally interpreted based on empirical correlations, and this is a frequent criticism of these tests.

Thus, they proposed an interpretation method based on the system energy measurement, because, from this value, one can calculate the dynamic force that represents the soil reaction to the sampler penetration, enabling the interpretation of soil properties such as the angle of internal friction and undrained shear strength.

Knowing this force, Lobo et al. (2009) presented a new method for predicting pile load capacity developed based on the interpretation of SPT test results. Unlike other methodologies established in the engineering practice, of essentially empirical nature, the new approach was based on concepts of dynamics and makes use of the principles of energy conservation involved in the driving of the SPT sampler. The energy absorbed by the soil was calculated from the number of blows N_{SPT} (or directly from the corresponding measure of penetration of the sampler) and analytically converted into a dynamic reaction force to penetration.

This force allowed determining the unit resistances mobilized in the SPT sampler and estimating the unit resistances mobilized in the pile. According to the authors, the methodology is simple and presents advantages over empirical methods, because the use of different equipment and procedures, resulting from local factors and the degree of regional technological development, do not interfere with the method if the efficiency of each SPT system is properly gauged, since the energy transmitted by the hammer-rod-sampler system is a function of the soil type. Therefore, the method captures the influence of the soil in predicting the pile load capacity.

In practice, the geotechnical engineer defines the test campaign, and consequently the soil-bearing capacity, essentially based on his experience and knowledge of the region, leaving the control and reliability that should be associated with the project in second place.

It is observed that only piling made of precast piles and Frank types are, for the most part, controlled through energy measurement, through elastic rebound, final set, and dynamic or static load tests.

Tsuha & Aoki (2010), through the results of physical modeling tests in a centrifuge, verified a theoretical relationship between installation torque during driving and the tensile load capacity of flight auger-driven piles in sandy soils, indicating that there is a relationship between the accumulated torque, the energy required to excavate a CFA pile and its load capacity. However, it is warned that torque, being dependent on thrust, can only be adopted as a control measure if angular and drilling speeds are controlled during excavation.

3. Energy required to excavate a pile

van Impe (1998) proposed Equation 4 to calculate the energy required to excavate a pile per unit volume.

$$E_s = \frac{N_d.v_i + n_i.M_i}{\Omega.v_i} \quad (4)$$

where: E_s = installation energy per unit volume [J/m^3]; N_d = vertical thrust force [N]; v_i = auger vertical velocity [m/s]; n_i = angular velocity [Hz]; M_i = applied torque [N.m]; Ω = area of the plane projection of the auger [m^2].

Therefore, the total energy (E_{sT}), Equation 5, necessary to execute a pile with radius (r), excavated in a certain amount of helicoid rotations (θ) in any time (t), must be multiplied by the volume of the pile (Ω.L), as shown.

$$E_s.(\Omega.\mathrm{L}) = \left(\frac{N_d.v_i}{\Omega.v_i} + \frac{n_i.M_i}{v_i.\Omega}\right).(\Omega.\mathrm{L})$$

$$E_{sT} = N_d.L + \frac{\frac{2.\pi}{t}\theta.(F_T.r).L}{\left(\frac{L}{t}\right)}$$

$$E_{sT} = N_d.L + F_T.2.\pi.\mathrm{r}.\theta \quad (5)$$

According to Silva (2011), the total work done by external forces, Figure 1, is the sum of the work done by the tangent force to the helicoid, plus the work done by the gravitational force and the work done by the downward force that is equal to the mechanical energy applied to the helicoid. Therefore, the work is a scalar quantity represented and defined by Equation 6. Knowing that the vertical thrust force (N_d) is the sum of the weight force ($m_{hc}.g$) of the system with the downward force applied to the helicoid (Fd_i), it can be verified that Equation 5, proposed by van Impe (1998) is an approximation of Equation 6, proposed by Silva & Camapum de Carvalho (2010) that is presented in integral form and without approximations:

$$W_R = \int_0^{z_b} m_{hc}.g.dz + \int_0^{z_b} Fd_i.dz + \int_0^{m2\pi} F_i.r.d\theta \quad (6)$$

where, WR = work done or energy required to excavate a pile [J]; F_i= force applied to the helicoid [N]; m_{hc} = mass of the excavation system [kg]; r = radius of the auger pile [m];

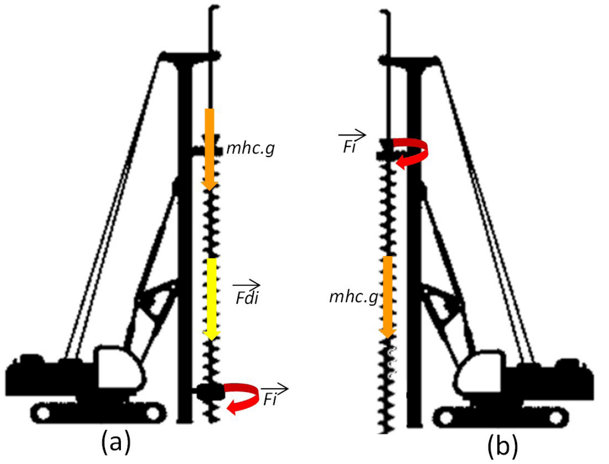

Figure 1. Drilling system and forces, (a) CFA bottom drive and (b) CFA system (Silva, 2011).

g = acceleration of gravity [m/s^2]; z_b = length of the pile [m]; Fd_i = downward force applied to the helicoid [N]; m= number of turns of the helicoid during excavation.

The proposed formulation, Equation 6, can be implemented in any monitoring system. For example, they can and were implemented in the monitoring system that is used by most of the continuous propeller auger-type machines existing in Brazil. The system described by Silva (2011), basically consists of a computer and sensors, whose data acquisition, treatment, and control of the execution are performed in specific software.

An analytical model to estimate the load capacity of a CFA pile as a function of the torque applied by the machinery was proposed by Hortegal & Cavalcante (2016). The model can be easily rewritten as a function of force or energy, since the lever arm and the force-displacement are known and monitored, consequently proving, once again, that the load capacity is also a function of the energy required in the executive process.

The proposed model considers that the installation energy of the CFA pile is defined by the sum of the penetration energy and the energy lost by the system. It is assumed that the installation energy is a function of the drilling torque and the downward force. On the other hand, the downward force is associated with the installation of the CFA and involves the rotation of the auger within the soil. Based on these hypotheses, a model was proposed and solved to find an analytical solution to evaluate the load capacity of the CFA piles, C, per meter, as a function of the execution torque, Equation 7.

$$C(T) = \frac{6\delta\left(2\pi T + F_{di}p\right)\left[r^2 + \sum_{i=1}^{n}\left(R_i^2 - r^2\right)\right]}{3\delta^2\left[r^2 + \sum_{i=1}^{n}\left(R_i^2 - r^2\right)\right] + 8\pi\alpha\left[3r^3\lambda + \sum_{i=1}^{n}\left(R_i^3 - r^3\right)t_i\right]} \quad (7)$$

where, d = pile deflection at ultimate load capacity [m]; T = execution torque [kN. m]; F_{di} = downward force, or pull down force [kN]; p = blade pitch [mm/rev]; r = radius of the propeller auger [m]; t_i = thickness of the propeller [m]; n = total number of propellers; R_i = helicoid radius, approximately equal to the radius of the EHC [m]; l = effective length of the tube penetrating the soil, approximately equal to the length of the EHC [m]; a = constant of proportionality between the torque due to shear along the tube and the penetration stress [dimensionless].

Thus, the admissible load, C_{adm} [kN], of the CFA piles, per meter, is presented in Equation 8:

$$C_{adm} = \frac{C(T)}{FS} \quad (8)$$

4. Semi-empirical method based on pile installation energy

Given the proof that the bearing capacity of the pile is related to the installation energy of the pile, Silva (2011), 12 load tests were analyzed in order to balance, propose and validate the semi-empirical method presented.

The piles tested were installed in the Federal District soil, whose geomorphological context was described by Cardoso (2002), who disserted on the genetic, geological, and mineralogical aspects of the region. The soil of the region is predominantly composed of a porous clay that is collapsible on its surface, but due to excavations imposed by the existence of at least two subsoils in the studied works and the presence of water table, the piles, in their majority, were deployed in less weathered soils with low collapse potential, transition soils and saprolitic soils texturally characterized as clays and silts.

In summary, the studied piles were installed in horizon classified as silt, the soil found until approximately 10.0 m depth in the analyzed areas is the collapsible porous clay of the Federal District, as a result of the weathering associated with the leaching process and laterization and, from this point on, there is the transition soil, layer generally not very thick, followed by the saprolitic soil, a layer that ends in the saprolite. Mineralogically, the soil profile is generally rich in kaolinite and iron and aluminum oxyhydroxides in the deeply weathered mantle and progresses to 2:1 clay minerals as they lose in weathering until they reach the primary minerals in the rocks.

Quartz, being a mineral that is difficult to weather, is generally found throughout the profile, and according to the hypothesis presented by Senaha (2019) it can also be neoformed. Texturally, the composition of these soils is linked to the source rock, for example, in slates it consists of silts and clays. These materials generally exhibit increasing compactness to the parent rock.

To evaluate the ultimate load, it was adopted the criteria proposed by Vesic (1977), which is defined as the load corresponding to a deformation of 10% of the pile diameter, deformation that was defined as conventional rupture by

Décourt (2008). The load versus settlement curves that did not reach conventional failure were extrapolated by van der Veen (1953), the methodology showed adequate load prediction when tested on the curves obtained in the load tests that reached conventional failure.

In the studied works, the pile settlement depths were controlled by the SCCAP methodology, through the control of the installation energy, described in Silva (2011). Consequently, in each work, soil type, and for each type of pile there was a minimum depth and reference energy that should be reached, similar to what happens during the control of driven piles that are also controlled by energy, represented by the rebound and the set.

It is noteworthy that, in dozens of works, controlled by the SCCAP methodology, it was observed that there was a pattern, in terms of installation energy, for a given load, soil type and pile type, suggesting that the pile load capacity was directly related to the installation energy required during execution. It was also observed that the installation energy for a given diameter and pile load capacity fluctuated within a narrow range in terms of energy and that its variation was directly related to soil type and soil condition and pile depth.

Table 1 presents the geometric characteristics of the 12 tested piles that were used to validate the proposed formulation by means of load tests. Also presented are the results in terms of ultimate load, the energies required during installation, and the soil type defined in the SPT borings. All the piles studied were executed with machinery and tools manufactured by CZM Equipment (bottom drive CFA) whose characteristics are described by Silva (2011).

Figure 2 shows the variability in terms of load *vs* displacement behavior of the tested piles. Probably, three

Table 1. Characteristics of the tested piles, installation energy and soil type.

Analyse cases (pile load test)	*D* [m]	*L* [m]	Q_r [kN]	E_i [MJ]	Soil type
E184	0,6	20.0	1900	42	silt
E202	0,6	12.0	1673	25	silt
E206	0,6	12.0	1897	31	silt
E277	0,6	20.0	1900	45	silt
E1	0,6	13.0	1900	31	silt
E2	0,6	12.0	1899	30	silt
E3	0,6	12.0	1900	30	silt
E4	0,6	13.0	1900	32	silt
APB-31	0,5	14.0	1819	32	clay
BPA-23	0,6	14.0	1833	35	clay
BPC-24	0,6	14.0	1839	40	clay
CPD-36	0,6	14.0	1698	27	clay

Where, *D* is the diameter; *L* is the length; Q_r is the conventional failure load; E_i is the installation energy.

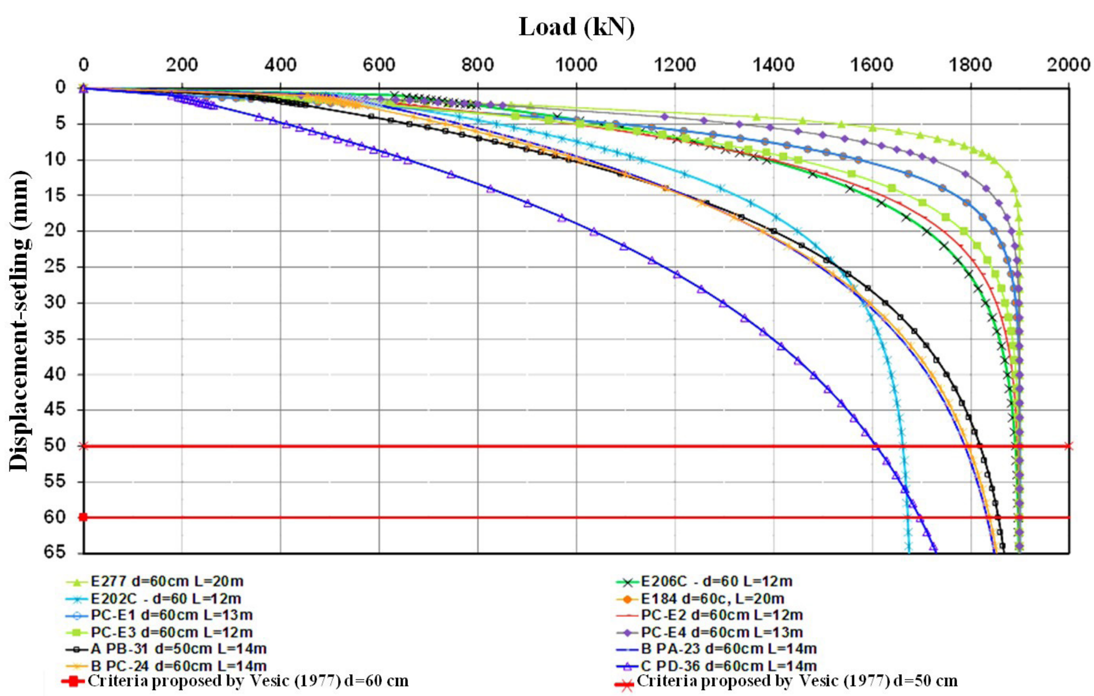

Figure 2. Load *vs* displacement (settling).

factors impacted the performance of the piles, in terms of load capacity and deformability, and were determinants for the dispersion of the results, they are: soil type; settlement elevation of the pile, longer the length of the pile the more material will be transported to the surface and more energy will be required; and the load capacity at the tip of the pile which is influenced by its state of cleanliness. Silva (2011) instrumented the tip of 11 CFA piles and concluded that the tip's cleanliness condition is determinant in the performance of the tip and consequently of the pile itself, in terms of load capacity and deformability. Other factors such as pile location, soil morphology, and moisture along the soil profile, when not saturated, can also impact the results.

The proposed method has as dependent variables the diameter, depth, and soil type, variables studied by Silva (2011), who observed that the magnitude of the measured energy is dependent on the type and strength of the soil, the efficiency of the machinery, the depth of pile excavated, the geometry of the drilling tools and the procedures adopted during excavation.

Also warned that the behavior of the CFA piles, in terms of load capacity and deformability, depends not only on the installation process but also on the procedures adopted during concreting, particularly the injection pressure used during concreting, especially when it takes place in the deeply weathered and collapsible mantle.

Added to this intricate matrix is another variable difficult to solve, the system of nonconservative forces involved in the process of excavation, destructuring, and soil transport during the execution of a propeller auger-type pile. The system is complex and difficult to solve, as it consumes and dissipates energy, for example, among other factors: - in the friction and adhesion between the helicoid and the soil; - in the friction and residual adhesion between the pile shaft and the helicoid/soil assembly.

However, the universal law of conservation of thermodynamic energy, synthesized in Hamilton's principle, allowed us to conclude that the energy or work done to excavate a pile is the sum of the work done by the system of external forces applied to the helicoid, Figure 1. This fact simplifies the resolution of the problem and was synthesized in Equation 6. Silva (2011) reminds us that in a set (machine and operator), the energy demanded or the work done during the excavation of the piles of a pile foundation presents acceptable variability, because the drill rig, the tool (helicoid) and the process adopted in the operation of the machinery during excavation and concreting tend to be repetitive and systematized, with hits and errors incorporated into the process, consequently the installation energy can be controlled and measured.

Equation 9 was proposed based on the results presented in Table 1 and in Figures 2 and 3, being valid for diameters greater or equal to 40 cm. For diameters smaller than 40 cm it was observed, in most cases, that the energy required was greater than that predicted by the proposed method. Probably due to the ratio between the diameter of the concrete injection tube, between 150 mm and 180 mm, and the diameter of the pile, transforming the process of pile excavation into a hybrid process of excavation and soil displacement, a process of semi-displacement, which demands more energy.

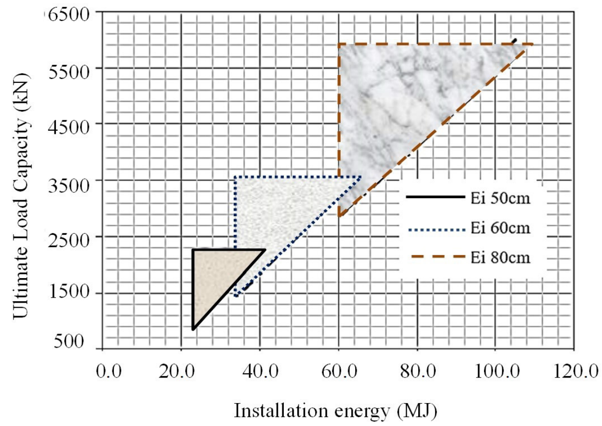

Figure 3. Ultimate Load Capacity versus Installation Energy - Silt.

The system of non-conservative forces involved in the process of excavating these piles, including soil compaction between the helicoids, soil transport to the surface, and even the compressive stresses of the excavated soil against the pile shaft, a process of semi-displacement, must be better studied and understood.

In any case that applies the proposed formulations, Equations 9, 10, and 11, the ultimate load capacity and the allowable must be predicted by the designer through empirical, semi-empirical or theoretical methods that are usually adopted in the practice of foundation engineering. From this prediction, the geometric characteristics of the pile and the geotechnical characteristics of the soil, the installation energy is estimated, which will serve as a reference for the control of pile driving during execution. Therefore, based on the observation of the behavior of energy-controlled piles in the Federal District, on the load tests performed in these works, on the geometric characteristics of the piles and soil geotechnical characteristics, the formulations for estimating the installation energy, Equations 10 and 11, are proposed.

$$E_i = \left[\left(\frac{C_{ult}}{70} \right) + D^2.L \right].\alpha.\beta \tag{9}$$

$$C_{ult} = \left[\left(\frac{E_i}{\alpha.\beta} \right) - D^2.L \right].70 \tag{10}$$

$$C_{adm} = \frac{C_{ult}}{\ } \tag{11}$$

where, E_i=installation energy [MJ]; C_{ult}= ultimate pile load capacity [kN]; C_{adm}= allowable load capacity [kN]; D=pile diameter [m]; L=pile length [m]; α=set factor for soil; β=set factor for machinery and its tools.

For the soils of the region and the machines studied, it is proposed: $\alpha = 1,00$ (silt and sand) and $\alpha = 1,20$ (clays); $\beta = 1.00$ (CZM, bottom drive CFA).

In Figure 3, the proposed formulation was used to determine regions where the pairs of ultimate load capacity versus installation energy are expected to be possible for piles of 50, 60 and 80 cm. For example, for the 60 cm piles it was considered the ultimate load ranging from 1500 to 3600 kN and lengths ranging between 10.0 and 30.0 m, similarly, it was determined the region for the 50 and 80 cm piles. It can be observed that all pairs of ultimate load capacity versus installation energy presented in Table 1 are within the regions delimited in Figure 3. It should be noted that for each case, there is only one possibility for the abscissa and ordinate, ultimate load versus installation energy.

5. Applicability of the semi-empirical method

The performance of a foundation depends, fundamentally, on the process adopted during its execution and on the geological-geotechnical characteristics of the soil. Therefore, determining the bearing capacity of a pile is a difficult problem to solve, especially in places with great geotechnical variability, because generally there are insufficient and inaccurate field investigations.

To this is added the difficulty, almost always of cultural order, in performing previous tests to verify performance, such as load tests in the design phase and drilling after the completion of embankments and/or excavations. Their realization in the execution phase only serves to adjust the part not executed and to subsidize eventual reinforcements in those already executed.

Consequently, the geotechnical engineer has, in most works, only empirical and semi-empirical deterministic methodologies or limited theoretical methods. But he should at least be aware of these restrictions, knowing that he will never obtain or be certain of the exact value, obtaining only the order of magnitude of the load capacity and deformability, Silva (2011).

One of these uncertainties, which was observed by Aoki & Cintra (1996) during the execution of pile foundations, is the existence of a resistant surface where the pile foundations are placed, a surface that should geotechnically and structurally meet the ultimate limit states and states of utilization. However, the location of the resistant surface depends on the geological-geotechnical formation of the soil, the driving or excavation process and the level of application of the foundation element, being difficult to determine during the execution of a pile foundation, particularly the excavated ones, because there are no control tools available, such as the control of the set or elastic rebound present in precast piles.

In the traditional executive method, the depth of excavation is previously fixed by the designer and is generally not changed during execution. However, in a profile with folded structural geology, such practice can lead to errors, especially when the unsampled soil, soil between boreholes, is in the depression zone of the fold (synclinal), leading to low resistances up to the settlement quota foreseen in the project. When the bend is reversed (anticlinal), many times the drill does not reach the desired depth, causing doubts about the pile's bearing capacity to persist. The proposed method, which adds to the SCCAP Methodology (Silva, 2011), will help the execution, because, in addition to the settlement level, predicted by empirical, semi-empirical, and theoretical methodologies, it will be possible to control each pile during execution, by means of the installation energy.

Consequently, it is verified if the pile meets the design assumption in terms of load capacity. The proposed formulation can be easily implemented in the monitoring system of the CFA piles employing specific software and will help the designer and the executioner in the decision-making process and, as a consequence, will increase the reliability of the piling. Figure 4 shows a resistant surface for a set of 40 and 50 cm piles after standardization presented by Silva (2011). It can be

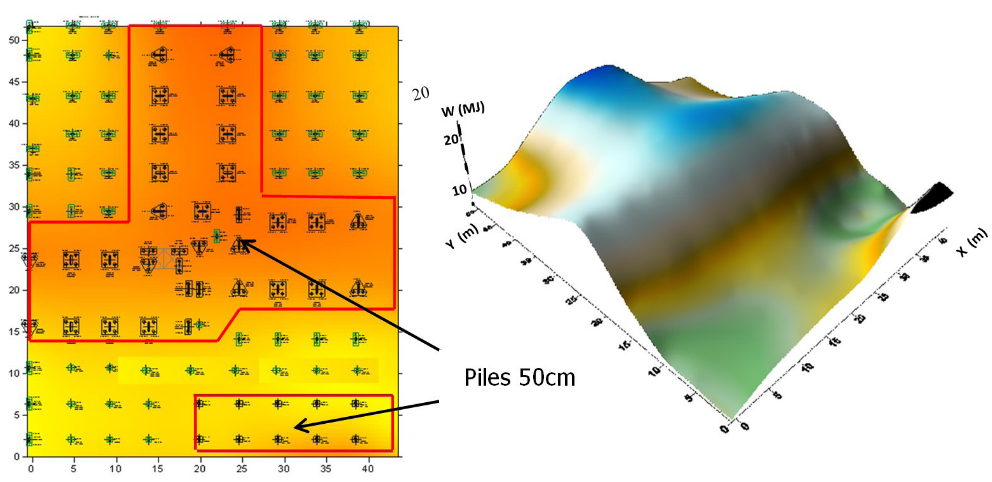

Figure 4. Energy resistant surface - piles 40 cm and 50 cm (Silva, 2011).

seen in this figure that the methodology uniformed the piling in terms of energy, clearly identifying through the energy level the regions where 50 cm piles and 40 cm piles predominate.

6. Conclusions

The proposed method has proven to be accurate and of great importance in the piles in the Federal District and Goiás that were controlled with the technique. The method conferred quality, reliability, and safety to these pile foundations. It ensured that the design precepts in terms of load capacity and deformability were met by reducing variability in terms of installation energy and performance. It is observed that the method provides an additional criterion to determine the pile settlement level, a complementary and corrective drilling stop criterion, contributing to the reduction of variability in pile load capacity and failure probability.

Undoubtedly, the method brings greater safety to foundation works without eliminating the valuable professional performance of the engineer, remembering that knowledge undergoes transformations and additions over time. The experience, although valuable, is only sporadically repeated in the geotechnical area, because the situations, the soils, the rocks, the stratigraphies, the drainage conditions, the equilibrium humidity, the water table when present, the hydrogeological flows, among others, present often spatial, temporal, and relative alterations to the execution of the pile. Particularities such as these, if on one hand highlight the relevance of the proposed technique, on the other, it shows the need for the engineer to be constantly observing, reflecting, and taking complementary decisions. Although apparently, the executed foundation is close to the reality of the work, there are temporal factors to be considered that can generate differences from the real situation. For simplicity, the soil shear strength equation can be considered, which is a function of cohesion, friction angle, and normal stress to the shear plane. Considering the more complex context, it would have to be considered, in this case, soils not saturated with matrix suction. Added to this is the fact that these are foundations concreted in situ, consequently one would have to consider the osmotic suction that will pass in the surroundings of the foundation due to alterations over time, something still little studied and generally not considered. But staying in the simplest situation, that of the shear strength of the saturated soil, the horizontal stresses that directly affect the lateral friction and the load capacity of a pile will change over time with the stiffening of the surrounding foundations that alter the propagation stresses and generate, for example, differences in the load capacity of the piles that make up a raft (Collantes, 2017). Influences like this, which are at the same time temporal and spatial, must be considered not only in the evaluation of the execution energy of the foundation but also in the results of tests such as the SPT and CPT and the load tests.

Regarding the execution of the pile, its load capacity, and the energy demanded and controlled during the execution, which is directly linked to its geometry and type of soil, other factors can interfere with the load capacity, among them, the process of execution and the concreting pressure. Concreting pressure may have some practical implications, for example, in non-saturated collapsible soils, it will induce an increase in the diameter of the pile and the collapse generated in the surrounding soil matrix may or may not be beneficial, depending on the constitution and composition of the soil. and how the chemistry derived from the concrete will act on this soil, stabilizing or destabilizing it as exemplified by Camapum de Carvalho & Gitirana Junior (2021).

Therefore, concluding these final considerations, the proposed methodology is undoubtedly of great value, but it does not put aside the importance of the engineer's performance, his sense of observation, and his capacity for reflection.

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 to report.

Authors' contributions

Carlos Medeiros Silva: conceptualization, methodology, validation, writing – original draft. José Camapum de Carvalho: data analysis, supervision, validation, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols

a	Constant of proportionality between the torque due to shear along the tube and the penetration stress [dimensionless]
d	Pile deflection at ultimate load capacity [m]
g	Gravity acceleration
l	Effective length of the tube penetrating the soil, approximately equal to the length of the EHC [m]
m	Number of turns of the helicoid during excavation
m_{hc}	Mass of the excavation system [kg]
n	Total number of propellers
n_i	Angular velocity [Hz]
p	Blade pitch [mm/rev]
r	Radius of the auger pile [m]
t_i	Thickness of the propeller [m]
v_i	Auger vertical velocity [m/s]
z_b	Length of the pile [m]
C_{adm}	Admissible load

C_{ult}	Ultimate pile load capacity [kN]
D	Pile diameter [m]
E_i	Installation energy [MJ]
E_s	Installation energy per unit volume [J/m^3]
FS	Safety factor
L	Pile length [m]
F	Force
F_i	Force applied to the helicoid [N]
Fd_i	Downward force applied to the helicoid [N]
M_i	Applied torque [N.m]
N_d	Vertical thrust force [N]
R_i	Helicoid radius, approximately equal to the radius of the EHC [m]
T	Total kinetic energy
T	Execution torque [kN. m]
V	Potential energy
W	Work
W_{nc}	Work done by the nonconservative forces acting on the system
WR	Work done or energy required to excavate a pile [J]
α	Set factor for soil
β	Set factor for machinery and its tools
Ω	Area of the plane projection of the auger [m^2]

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