Energy and Reliability Applied to Continuous Flight Augern Pilings - The SCCAP Methodology

Énergie et fiabilité appliquées à l'excavation des pieux forés en continu - La méthodologie SCCAP

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ABSTRACT: The SCCAP methodology was developed to control the execution of Continuous Flight Auger (CFA) type foundation works. The methodology SCCAP was based in the law of energy conservation, which is one of the basic fundaments from classical physics and quantifies the required energy, or developed work, to excavate each of the piles from any particular foundation site. It proposes formulations, routines and criteria for pile acceptance based on the statistical characteristics of the population or from an energy sample taken from this one. It has been incorporated into the monitoring and execution software from CFA piles machines, and it allows for local corrections on procedures and excavation depth at each executed pile from the site. Consequently it enhances the reliability and mitigates involved risks to the geotechnical job. The SCCAP methodology has been validated through the assessment that the necessary energy to excavate a particular pile is related to its bearing capacity, when the excavation process is monitored.

RÉSUMÉ : La méthodologie SCCAP a été développée pour contrôler l'exécution des pieux forés en continu (CFA). La méthode SCCAP est fondée sur la loi de conservation de l'énergie, qui est un des fondements de la physique classique et qui quantifie l'énergie requise - ou le travail à fournir - pour excaver chacun des pieux dans n'importe quel sol de fondation. Elle propose des formulations, des procédures et des critères pour définir la conformité des pieux, basés sur les caractéristiques statistiques de la population ou sur un échantillon d'énergie pris dans celle-ci. Cette méthode a été incorporée au logiciel de suivi et d'exécution des machines foreuses de pieux CFA et elle permet d'effectuer des corrections locales sur les procédures et la profondeur d'excavation de chaque pieu. Par conséquent, elle améliore la fiabilité et réduit les risques encourus lors du travail d'excavation. La méthode SCCAP a été validée par le fait que l'énergie nécessaire pour excaver un pieu particulier est en relation directe avec sa capacité portante, lorsque le processus d'excavation est contrôlé par monitoring.
KEYWORDS: Energy, Methodology SCCAP, Continuous Flight Auger (CFA) and Reliability.

1 INTRODUCTION

Safety analyses in Foundation Engineering when are done, are generally restricted to design and are deterministic, that is, in theory certainty of the parameters involved in dimensioning exists, accepting as precise the calculating methodology adopted. However, it is known that the greatest source of variability in Foundation Engineering is the geological-geotechnical formation., which affects the performance of the soil-foundation system that is strongly determined by the stratum variability through the soil profile as a whole.

In pilings the aim is to reach the design assumptions in terms of load capacity and deformability for them to be verified during execution. Consequentially, Foundation Engineering look for techniques that assure the good performance of the foundations concerning resistance and/or deformability. The ideal is to adopt procedures and routines during design phases especially during the quality control of the execution to identify the need of intervention during execution.

In this context, the SCCAP Methodology is presented for the control and uniformity of the bored pilings, especially for the continuous flight auger pile which is based on the interpretation of the necessary energy or the work done during the excavation of a pile. Such methodology was developed from the understanding of the force system of the boring equipment and the application of the universal energy conservation principle which when applied to the excavation process of a pile allows the enrgy quantification necessary for a pile. As a consequence of the confirmation that the bearing capacity is related to the necessary energy to excavate a pile, it was possible to incorporate the statistical concepts as SCCAP routines allowing to control the excavation process quality during the piling excavation.

For the confirmation of the SCCAP Methodology efficiency load tests and comparisons were used with predictions based on SPT tests. The developed methodology was presented in details in Silva (2011) and according to the author can be extended to any type of bored or other rotating excavations such as the ones for tunnels, only if it is possible to identify the force system to quantify the spent energy in the process.

The SCCAP proposed routines do not substitute the geotechnical engineer judgment but it can help him in the identification and mitigation of involved risks in any type of piling, especially for the ones that do don't have controls based on scientific concepts, as the excavated pilings.

1 ENERGY AS BASE FOR THE CONTROL OF PILINGS

Silva (2011) and Silva et al. (2012) presented the construction of the methodological structure that is the basis of a thesis which says that the control of mechanical excavations, especially for bored piles done by the determination of the required energy during the pile excavation consists of an element for technological control capable to offer a greater security and less risks to the constructions that use them. Coming from some hypothesis, Silva (2011) proposed an analytical formulation to quantify the total transferred energy by the system to the soil, which is obtained by the volumetric integration as a function of the soil temperature. Consequently the total energy of the system is obtained by:

$$E_{st} = \iiint_V \rho_s \, C_{ps} \, [T_s(r,z,t) - T_s(r,z,0)] dV \quad (1)$$

Where: E_{st} = total energy of the system [J]; ρ_s = soil density [kg m^{-3}]; C_{ps} = specific soil heat [J m^{-3} ^{0}C^{-1}]; V = refering to volume [m^3].

The problem which was showed concerning heat transient transference in the soil is bi-dimensional (2D) and aximetric and it can be solved analytically, for example, through finite differences. However, Silva (2011) and Silva et al. (2012) considering Hamilton's principle it is possible to determine the variation of mechanical energy produced by the system, assuming that the presented energy of the system is conservative, that is, such energy cannot be created or destroyed, simply transformed. Considering such principle, Silva (2011) and Silva et al. (2012) applied the concept of work done to the excavating process of a pile, achieving the conclusion that the system of variable forces (*Fi)* produced by the continuous flight auger equipment, showed in Figure 1, applies to the boring device a movement from the initial elevation (*ci*) to a final elevation (*cf*) through a path (Δxi). Accordingly, the work (*W*) done to excavate a pile is a pure number defined by Silva (2011) as the pure product of such two greatness, Fi e Δxi given by:

$$W = \lim_{\Delta x_i \to 0} \sum_{i}^{n} F_i . \Delta x_i = \int_{ci}^{cf} F_i . dx \qquad (2)$$

Where: W= Work [J]; F_i= Force applied to the body [N]; Δx_i= body path [m]; c_i= initial elevation of the body [m]; c_f= final elevation of the body [m].

Similarly, he defined the work done by the friction and adhesion present during the excavating process which represents parts done by the non-conservative forces through the same displacement, defined by:

$$W_c = -\lim_{\Delta x_i \to 0} \sum_{i} F_{ci} . \Delta x_i = -\int_{ci}^{cf} F_{ci} . dx \qquad (3)$$

Where: W_c=work done by non-conservative forces [J]; F_{ci}=non conservative forces applied to the body [N].

Figure 1. Boring system and forces.

Moreover according to Silva (2011), another type of energy associated to the excavation of a pile is the potential energy which basically depends on the position and system configuration, in the case, the position of the helical device or of the auger, is given by:

$$W_g = F_g \Delta y = m.g.(y_2 - y_1) \qquad (4)$$

where: Wg= work done by the gravity force [J]; Fg=*Gravity force or Weight Force* [N]; g = gravity acceleration [m/s^2]; m = system mass [kg]; $(y_2$-$y_1)$ = variation of the geo-reference position [m].

Silva (2011) also considered that the conservation energy principle summarized in Hamilton's principle is present in the excavation of a pile. Similarly to the structural system dynamics it can be simplified as mentioned by Clough and Penzien (1975):

$$\int_{t1}^{t2} \delta(T - V)dt + \int_{t1}^{t2} \delta(W_{nc})dt = 0 \qquad (5)$$

Where: T = total kinetic energy [J]; V = potential energy including the deformation energy of any external conservative force [J]; W_{nc} = work done by non-conservative forces that act in the system, including cushion, friction and external forces [J].

Silva (2011) solved the problem considering Hamilton's principle represented by Equation 4, assuming that the total thermal and sound energy of the system (ΔE_{st} is equal to the mechanical energy applied to the system or the work done by external forces applied to the system (W_R), in the case, forces applied to the helical device during the excavation of a pile represented in Figure 1.

Then, knowing the torque applied to the helical device and the lever arm, he measured the tangent force applied to the helical device and knowing the angular and boring speed of the helical device, the track can be determined and consequently, the work of the tangent, which is the pure product of such force by the displacement through depth. Finally, the total work done by the external forces is the sum of the work done by the tangent force to the helical device, plus the work done by the gravity force and the work done by the downward force which is equal to the mechanical energy applied to the helical device. Thereby, the work is a pure greatness represented and defined by Silva (2011) and Silva et al. (2012) as:

$$W_R = \int_{0}^{z_b} m_{hc}.g.dz + \int_{0}^{z_b} Fd_i.dz + \int_{0}^{m2\pi} F_i.r.d\theta \qquad (6)$$

Where: W_R = work done or required energy to excavate a pile [J]; Fi= force applied to the helical device [N]; m_{hc} = mass of the excating system [kg]; r = radius of the CFA pile [m]; g = acceleration of gravity [m/s^2]; z_b = pile length [m]; Fdi= downward force applied to the helical device [N]; m= number of turns of the helical device during excavation.

Silva (2011) and Silva et al. (2012) proved mathematically that Equation 6 is consistent in terms of the physical point of view and take to values close to the ones obtained by Van Impe (1998) proposal, that considers in its approach mean values to survey the required energy to excavate a pile type atlas.

3 SCCAP METHODOLOGY

In the traditional execution method, the pile depth is previously set by the designer and is generally not modified during the execution. However, in a profile with folded structural geology, the current practice can take to mistakes, mainly when the non-sampled soil, soil between boring tests appear in the depression zone of the synclines, achieving low resistance till the predicted design tip elevation.

To solve this problem, Silva (2011) proved that the work done in each pile of the foundation piling executed by a fixed process of the system machine/operator is proportional to the pile bearing capacity. When put together in a data file, these works make a population which fit in a normal probabilistic distribution that allow the authors to establish acceptance criteria related to the mean value and standard deviation of the population from an extracted soil sample of the piling. The methodology which is physically represented by Equation 6, was introduced in the monitoring system of CFA piles, allowing to quantify the work or required energy to excavate each pile of the piling and, consequently to control the piling based on on the required energy during the execution of the piling. Therefore, the SCCAP routines introduce to the execution monitoring software for CFA piles the excavation quality control in real time and assure to the execution piling process conditions for the piles to achieve individually the planed bearing capacity, assuring quality and the design assumptions. It is very clear that the final behavior of the pile will also depend, among other issues, for example, the concrete injection pressure which depending on the type of soil and its value will have a great influence on the pile behavior, such fact observed by Silva (2011).

Figure 2 presents the results obtained during the execution of seven load tests, construction on the Paranoá Lake shore in Brasília – Brazil and the total required energy to execute each pile. It can be seen in Figure 2 that the measured energy in each pile is proportional to its bearing capacity. In Table 1, the most important geometric and monitored data of the tested piles are shown. Moreover it's also observed in Picture 2 that the ultimate load is rampant with the required energy increase during the excavation, independently of the failure criteria adopted, the one from Brazilian norm criterion (NBR 6122, ABNT) or the conventional one which corresponds to 10% of the pile diameter. In this case, all piles were excavated by a same set machine/operator.

Table 1. geometric features of the piles (modified from silva, 2011).

Pile	Length (m)	Medium pressure of concrete (kPa)	Diameter (cm)	Total Energy (MJ)
E110BA	17,12	100	42	9,64
EPC1BB	15,12	100	42	10,60
TC2BB	12,80	0-75	53	13,18
E55AA	14,24	25-100	37	7,06
EPC1C	10,80	50	42	4,73
GE 24C	20,92	0-50	52	13,36
EE6B	20,08	100	54	14,27

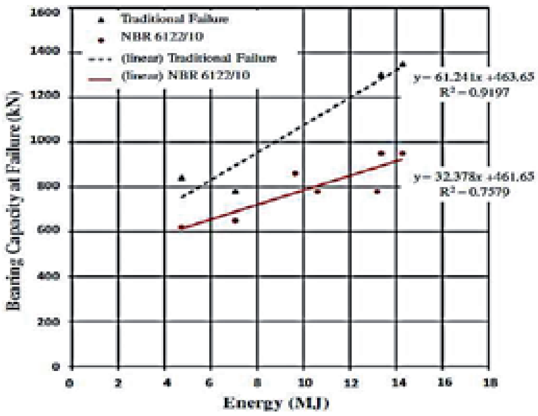

Figure 2. Ultimate bearing capacity versus work done (Silva, 2011).

By the confirmation that the bearing capacity of the pile is directly proportional to the work done and that the collected results in the piling (energy) when organized in frequency distribution conducted to a normal distribution, Silva (2011) proposed an acceptance for the piles based on Physics concepts (energy conservation) and on statistics characteristics of collected energy sample during the execution of the piling. Preferably they suggested that the population sample would be collected close to the load test once statistics properties of the sample could be associated to the real bearing capacity of a pile in the execution condition adopted in the construction. According to the authors, if the referred association is not possible, it is important that the sampling is done in a region with known geotechnical characteristics, for example, giving attention to regions where the field tests were executed and have little variability. Once the region to be sampled was chosen and its size, the results are put together by class fitting them to a normalized distribution. By that way, the mean (μ) and the standard deviation (σ), were calculated what made possible to establish reliability and acceptance criteria to applied in boring. From the beginning they proposed criteria tht should be chosen by geotechnical variability basis and the existing quality control in the construction, for example, it will be accepted the pile which when achieving the minimum design depth did during excavation a required and measured work (w) greater than the mean (μ) of the work measured from the sample (W≥μ).

Tabela 2. Caracterização Geotécnica – Ensaio SPT

Deep (m)	SPT by Layer				Type of Soil
	SPT 01	SPT 02	SPT 03	SPT 04	
1	7	6	6	6	Clay
2	4	4	5	5	
3	2	4	2	5	
4	2	4	4	7	
5	4	6	6	10	
6	4	6	8	15	
7	8	7	4	18	
8	7	7	13	13	
9	5	11	30	7	
10	14	24	30	5	
11	32	12	32	9	
12	58	31	56	14	Silt
13		52		18	
14				21	
15				19	
16				24	
17				27	
18				42	

In Table 3 the required energies to excavate each pile are presented. The tip elevations of the pile bases were defined based on the geotechnical characterization and its location in the construction site and three different depths were adopted, 10, 11 and 13 m. It is important to mention that the piles were executed from elevation -4,00m, which is related to the initial elevation of the borings because of the existence of an underground level.

Table 3. Energia demandada na escavação das estacas (Silva,2011)

Estaca	Prof. (m)	Energia (MJ)	Estaca	Prof. (m)	Energia (MJ)
E42A2C	13,12	6,0	E13A2D	13,12	4,7
E23A2F	13,12	6,4	E18A2A	13,12	4,8
E23A2B	13,12	3,9	E25A2C	13,12	4,9
E23A2D	13,36	6,3	E26A2C	13,12	4,3
E18A2E	13,12	5,8	E13A2C	13,12	6,1
E18A2D	13,12	3,6	E13A2B	13,12	8,2
E23A2E	13,12	4,0	E25A2A	13,12	7,5
E23A2C	13,12	4,9	E26A2A	13,12	6,6
E23A2A	13,12	5,8	E13A2A	13,12	5,1
E18A2F	13,60	5,1	E13GA	10,08	3,1
E18A2C	13,12	2,7	E20GB	10,08	3,6
E18A2B	13,12	3,5	E65DC	10,08	3,8
E25A2B	13,12	6,3	E19GB	10,08	5,1
E26A2B	13,12	6,8	E64DC	10,08	3,8
E10GB	10,08	5,1	E2B1E	11,12	8,5
E17GB	10,08	4,3	E11B1A	11,12	6,9
E23G	10,08	2,9	E17B1D	11,12	6,9
E63DB	10,08	2,8	E5B1A	11,12	7,8
E17GC	10,16	4,3	E2B1C	11,12	6,5
E10GC	10,16	4,9	E17B1B	11,12	6,1
E11B1E	13,04	5,6	E5B1B	11,12	5,4
E17B1E	12,96	8,8	E4B1B	11,12	6,7
E17B1A	13,04	6,6	E17B1C	11,12	6,5
E2B1A	11,12	7,6	E2B1D	11,12	6,6
E4B1A	11,12	7,1	E2B1B	11,12	7,2

For the 40 centimeter pile sample, the data of the works done, obtained during the excavation of 10,00 meter depth piles, once a load test was made on a pile with those characteristics, close to boring SPT 1 (Table 2), which results are marked with grey color in Table 2. Silva (2011) submited all the collected data to normality tests that evaluate if the frequency distribution of a data group adheres to the Normal Distribution and verified that the data adheres to the normal distribution. The central tendency measures, mean and median, the standard deviation and the variance are presented in Table 4.

Table 4– Características estatísticas da população e da amostra

Estacas	População	Amostra
Média (MJ)	5,56	3,97
Mediana (MJ)	5,70	3,80
Desvio Padrão (MJ)	1,56	0,84
Variância (%)	29	21

It is observed in this case that the mean and the variance of the sample was smaller than the population. Such fact was expected for the mean once it refers to a very folded profile, the load test was made on the pile with a small depth in favor of safety. The smaller value of variance is perfectly justified because in accordance with the methodology, a region with small variability must be chosen what was assured, in the case, by the sampling in a restricted area, on the contrary concerning the piling which was executed taking all the area and consequently all its variability. Then to assure that the bearing capacity could be achieved, the SCCAP methodology was applied during the piling execution, in the case, the first criteria by considering that the mean is a good representative of the population, the criterions are:

- It will be accepted the pile which when achieving the minimum design depth did during excavation a required and measured work (w) greater than the mean (μ) of the work measured from the sample ($W \geq \mu$);
- It will be accepted the pile which when achieving the minimum design depth did during excavation a required and measured work (w) greater than the mean (μ) plus the standard deviation (σ) of the work measured from the sample ($W \geq \mu + \sigma$);
- It will be accepted the pile which when achieving the minimum design depth did during excavation a required and measured work (w) greater than the mean (μ) plus two times the standard deviation (σ) of the work measured from the population sample where they belong ($W \geq \mu + 2.\sigma$).

For the analyses, hypothetical applications were done from the first and second criterion. Comparing the work done (W) in each pile during its excavation (Table 3) with the mean (μ) of the required work to execute the piles of the sample, first criterion ($W \geq \mu$), it is observed that it would be necessary to correct or increase the depth of 4 piles with a diameter of 40 cm for them to present a cumulative work smaller than the mean obtained for the sample. By using the second criterion, which is more conservative, it is noticed that eliminating the piles which have been excluded from the previous analysis, even though 8 piles with a diameter of 40 cm would be refused.

Once the results presented in Table 3 were set in the chronological execution sequence of the piling and knowing that the piling was executed sequentially till the total area of the construction was covered, it can be verified, for example, in Table 3, that the piles refused by criterions 1 and 2 are arranged in group, that is, those piles are neighbors and probably are founded in regions with NSPT mean value smaller than what was expected or they were founded on synclinal folds.

It is clear that the adoption of the SCCAP methodology gives more reliability to the piling in terms of bearing capacity.

4 RELIABILITY

Trying to measure the reliability of CFA pilings, Silva (2011) from a data file made with energy or wok done records to execute each pile of the piling, he evaluated the reliability in bored pilings. He considered the concept that the bearing capacity of each pile and its deformability are directly related with the measured energy or the required work to bore it, he used the proposal of Ang & Tang (1984), which defined the continuous random variables, in the case, their probability distributions that define the demanding forces and piling resistance: X= resistance or resistant capacity of the system; Y= demanding load acting in the system.

The goal was to assure that the event (X > Y) happens during the whole life of the foundation. This condition or warranty can be verified in terms of the which represents the piling reliability. On the contrary, the probability of failure is the measurement which corresponds to the completing event.

Once fixed to the shape of the demanding action curves (loads on foundations) and of resistances (bearing capacity of piles); and knowing their coefficients of variety and the global safety factor of the piling, the reliability index can be determined and the probability of failure of the piling, interpreted by Cardoso e Fernandes (2001). From that proposal, Silva (2011) showed that the reliability index (β) of the piling increased a great deal, going from 2,69 to 3,14.

4 CONCLUSIONS

The routines of quality control proposed by the SCCAP methodology are showing their great importance in constructions controlled by such technique, assuring quality for the whole process of excavation. Mainly because it can assure that all design assumptions in terms of bearing capacity and deformability are guaranteed through the decrease of the variability and the increase of reliability. Another important issue which was observed is that the SCCAP methodology offers stopping criteria for the boring which has a complementary and corrective role, contributing to risk reduction in the construction once it reduces the probability of failure and increasing the reliability..

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