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On Modelling Continuous Flight Auger Pilings by means of Energy

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Abstract- The necessary energy to install or excavate a pile can be achieved by the identification of the forces involved in the excavation and the application of the law of energy conservation. In the quantification it is considered that the whole energy generated in the excavation process is spent by the non-conservative forces present in the energy balance of Hamilton´s Principle. This paper aims to show how it is possible to model continuous flight auger pilings by means of energy.

Keywords- *piling; continuous flight auger; energy.*

I. INTRODUCTION

One important concept which is directly related with the energy is the work done by a pure greatness and then, with no associated direction. The universal power of the energy concept makes it possible, for example, to understand how the mechanical energy produced by an engine is transformed into kinetic energy and then dissipated by work, in the case of an excavation of a pile, mainly by friction and heat in such a way that at the end of the process, the total energy is constant.

Physically, the work describes the displacement which is done by the action of a force, as the product of the displacement by the parallel force to the displacement. Another important principle is the Hamilton´s one which is based on the concept f conservative energy, in which the energy cannot be created destroyed, simply transformed. According to Silva (2011) it is clear that the energy conservation law, summarized in Hamilton´s principle can be applied in the loading case of any system in static or dynamics and especially to the pile-soil system. He also recalled the first thermodynamics law, which in ay energy transformation, the absolute value is kept, that is, the energy can´t be created or destroyed, simply transformed.

II. MODEL FOR CONTINUOUS FLIGHT AUGER PILINGS

In the beginning it will be mentioned the concept of work done to excavate a pile. According to Silva (2011), during the execution of a bored pile, it is imposed by a system of variable forces (F_i) to the boring device, a displacement from the initial elevation of the pile (c_i) to the final elevation (c_f) through a path (Δx_i). Therefore, the work (W) done to excavate a pile is a pure greatness defined by the product of those two greatnesses, F_i e Δx_i given by:

$$\mathrm{W} = \lim_{\Delta x_i \to 0} \sum_i^n F_i.\Delta x_i = \int_{c_i}^{c_f} F_i.dx \qquad (1)$$

where, W is the work [J], F_i is the force applied to the body [N], Δx_i is the body path [m], c_i is the initial elevation of the body [m] and c_f is the final elevation of the body [m].

Similarly, he defined the work done by the friction and adhesion present in the excavation processes that represent parts of the non-conservative forces along the same displacement given by:

$$\mathrm{W_c} = -\lim_{\Delta x_i \to 0} \sum_i^n F_{ci}.\Delta x_i = -\int_{c_i}^{c_f} F_{ci}.dx \qquad (2)$$

where, W_c is the work done by the non-conservative forces [J] and F_{ci} corresponds to non-conservative forces applied to the body [N].

It is observed that the forces play a fundamental role in the description of the pile displacement. Such displacement can also be described as a function of another Physics concept, the energy, which is a greatness that is kept in any situation. Once the energy conservation law is especially worthy in terms of systems with many variables in which the precise understanding of the system of forces is a problem with a difficult solution, just as the case of the excavation of a pile. It was also considered that the potential energy depends basically on the position and configuration of the system, in the case, the position of the helical device or auger. For example, to lift the auger of a CFA equipment pile it is necessary to do a work and consequently, energy will be spent to move it from one point to another. Then, the work done when the auger changes its position relating to the Earth surface is given by:

$$\mathrm{W_g} = F_g.\Delta y = m.g.\left(y_2 - y_1\right) \qquad (3)$$

where W_g is the work done by the gravity force [J], F_g is the gravity force or weight force [N], g is the gravity acceleration [m/s^2], m is the system mass [kg] e $(y_2 - y_1)$ is the variation of the geo-reference position [m].

Finally, the principle of energy conservation was used, summarized by Hamilton´s principle and really present in the excavation of a pile. In a similar way to the case of structural system dynamics it can be simplified as mentioned by Clough and Penzien (1975), in the way of:

$$\int_{t_1}^{t_2} \delta(T - V)\,dt + \int_{t_1}^{t_2} \delta(W_{nc})\,dt = 0 \qquad (4)$$

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

Hamilton´s principle which is presented in a variable way, when it is applied to any system in equilibrium, establishes that the kinetic and potential energy variation (generated energies by the equipment during excavation) occurred inside the system, added to the work done by the non-conservative forces (friction, adhesion and heat) which act in any time interval $(t_2 - t_1)$ is equal to zero. According to Silva (2011), when the referred system is consisted by more than one particle, the internal energy variation of the system can be measured by the total external work done over the system, that is:

$$W_{total} = \Delta K \qquad (5)$$

where, ΔK is the internal energy variation [J] and W_{total} is the total external work done in the system [J].

Therefore, it is clear that Hamilton´s principle can be applied in the loading of any system in static or dynamics equilibrium, and especially in a pile-soil system. In such case, it is necessary to measure the work done by each force applies to the system. Those forces were identified and are showed in Figure 1.

Figure 1a shows the Bottom Drive CFA, a system installed in the lower part of the rig and present in most of the Brazilian equipment. That was the studied system of this research, which has three involved forces, the gravity (system weight), the rotation force and a third one exerted by a hydraulic piston, known as downward force. In Figure 1b, it is observed the Continuous Flight Auger (CFA) system in the upper part of the rig, where the gravity and rotation forces are identified. In this case, for the application of the downward force it is used an auxiliary cable system, which operation is hardly incorporated to foundation construction routine and then, not represented in Figure 1b.

The mechanical energies produced by the equipment presented in Figure 1 are transformed in kinetic and potential energies and are applied to the system through external forces. Energies that are dissipated by the work of the non-conservative forces, that is, in the end of the excavation process all the system energy is transformed into thermal and sound energy.

According to Silva (2011), observing the system showed in Figure 1, it is verified that the required energy to excavate a pile and spent by the non-conservative forces are dissipated:

i. in the energy spent during the excavation to destroy the soil structure, in the compaction or soil remolding among the flights and in the densification and remolding of the soil mass in the soil-pile interface;

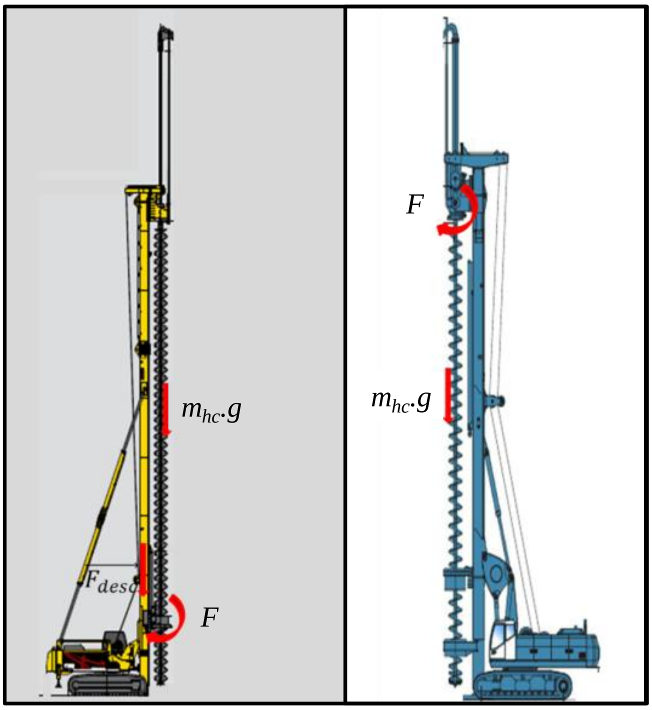
ii. in the friction and/or adhesion between the helical device and soil;

iii. in the residual friction and/or adhesion between the pile shaft and the set of the helical device/excavated soil;

iv. by the losses of the system, represented by the heat generated by the equipment.

Thereby, according to Silva (2011) to determine the sum of those works during the excavation of a pile, it would be necessary to know the stress in each point of the helical device with respect to the pile shaft and set of helical device/transported soil contact and the energy spent during an excavation.

Consequently, integrating those stresses by area unit and the energy by unit volume during the time spent in the boring, it could be obtained the spent energy by the non-conservative forces. That energy is equivalent to the work done by the system of forces applied to the helical device and is represented in Figure 1. However, those greatnesses are difficult to be obtained because of the complexity of the energy process which exists during the excavation of a pile.



(a) (b)

Figure 1. System of Forces, (a) Bottom Drive CFA e (b) Continuous Flight Auger CFA (Silva, 2011).

The system which is represented in Figure 1, is consisted of by variables which will hardly be isolated. But, taking into account the physics concept of energy conservation represented by Equation (5), which says that the internal energy variation of the system during the excavation of a pile is equal the sum of the external work done by the forces applied to the system, the energy can be quantified or the required work to excavate a pile.

Physically, the phenomenon is similar to the energy transference one, described by Rabin et al. (1991) and Rabin & Korin (1996). The authors proposed an analytical formulation to predict the transient in a semi-infinity mean (soil) and to describe the heat transfer in helical piles for energy transmission tower foundations heat conduction, considering the constant existence of a heat source produced by the energy transmission system, the soil temperature variation and the forces generated by those variations and neglecting the sound energy.

From the ideal assumed model, the equations that govern the problem are presented. Starting from the heat transference system present in the execution of a helical pile, this is briefly showed in Figure 2. The theoretical model is based on the following simplified assumptions, concerning the soil:

i. The heat transference model in the soil considers a multi-phase system 9solid, liquid and air). It also considers the present effects in the joining process of heat and of mass transference in soils.

ii. It is assumed as isotropic, with constant thermal properties.

iii. The temperature gradient in the tangential direction is neglected and the model is considered transient, with two dimensions (2D) and axial-symmetric.

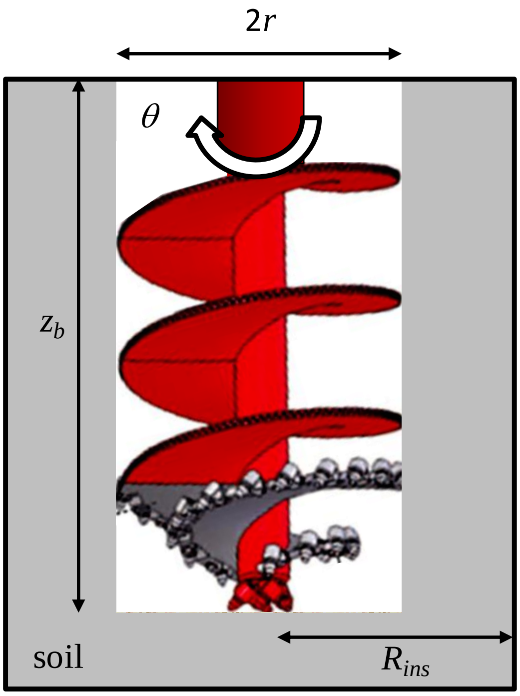


Figure 2. Description of the Helical System.

Based on the proposed hypothesis, the equation which governs the heat transference in the soil, in cylindrical coordinates is given by:

$$\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r} + \frac{\partial^2 T_s}{\partial z^2} = \frac{\partial T_s}{\partial t} \tag{6}$$

The initial condition of the system is:

$$T_s(z,r,0) = T_{s0}(z) \tag{7}$$

The boundary conditions of the system are:

$$\frac{\partial T_s}{\partial r}(z,0,t) = 0 \tag{8a}$$

$$\frac{\partial T_s}{\partial z}(z_0,r,t) = 0 \tag{8b}$$

$$\frac{\partial T_s}{\partial r}(z,R_{ins},t) = q_{\sup} \tag{8c}$$

$$k_s \frac{\partial T_s}{\partial r}(z_0,r,t) = q_{\sup} \tag{8d}$$

where T_s is temperature [^{o}C], t is time [s], R_{ins} is half of the distance between the axis of two sequential CFA piles, k_s is the thermal conductivity [W.m^{-1} ^{o}C^{-1}], q_{sup} is the heat flow on the system surface [W.m^{-2}], z is the depth [m].

Basically the energy system represented by Equation (6), considers the temperature variation through the depth and radius in a certain time. Equation (6), represented in cylindrical coordinates, is parabolic and transient with the term first order running transference heat processes associated to a temperature change as a function of thermal conductivity and the second terms run the diffusion processes associated to temperature gradients.

In standstill condition, the term that depends upon time tends to zero and by that way an equilibrium situation is achieved. Energy is obtained by the volumetric integration as a function of soil temperature variation. Consequently the total energy of the system is achieved by:

$$E_{st} = \iiint_V \rho_s C_{ps} \left[T_s(r,z,t) - T_s(r,z,0) \right] dV \tag{9}$$

where, E_{st} is total energy of the system [J], ρ_s is the specific soil mass [kg.m^{-3}], C_{ps} is the specific soil heat [J.m^{-3} ^{o}C^{-1}], V is the control volume.

The actual transient heat transference problem in the soil is bi-dimensional (2D) and axial-symmetric and can be solved, for example, numerically by finite difference.

However, Silva (2011) considered Hamilton's principle and determined the mechanical energy variation produced by the system from the principle that the presented system energy is conservative, that is, the energy cannot be created or destroyed, simply transformed, which concept is represented by Equations (4) e (5). Consequently, the total thermal energy variation of the system ΔE_{st} is equal to the mechanical energy applied to the system, that is, equal to the work done by the external forces applied to the system (W_R) in the case, the forces applied to the helical device during the excavation of a pile, given by:

$$\Delta E_{st} = W_R \tag{10}$$

But, to quantify the work, it is necessary to know the external forces that are applied to the system, forces which were identified in Figure 2. Therefore, knowing the applied torque to the helical device and the lever arm, the tangential force applied to such device is determined and knowing the angular velocity and the boring velocity of the helical device, the path can be determined and consequently the work of the tangential force as well, which is the product of such force by the displacement through the depth. Finally, the total work done by the external forces is the sum of the work done by the tangential 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. Then, the work is a natural greatness represented by Silva (2011) as:

$$W_R = \sum_i m_{hc}.g.z_i + \sum_i F_{di}.z_i + \sum_i F_i.r.\theta_i \tag{11}$$

or even by,

$$W_R = \int_0^{z_b} m_{hc}.g.dz + \int_0^{z_b} F_{di}.dz + \int_0^{m.2\pi} F_i.r.d\theta \tag{12}$$

where, W_R is the work done or the required energy to excavate a pile, F_i is the applied to the helical device [N], m_{hc} is the the mass of the excavating system [kg], r is the radius of the CFA pile [m], g is the gravity acceleration [m/s^2], z_b is the pile length [m], F_{di} is the downward force applied to the helical device [N], m is the helical device number of turns during the excavation.

Silva (2011) showed from Equation (12), that the required energy to excavate or install a pile can be estimated. He considered that the vertical motion force (N_{di}) is defined as the sum of the gravity force (weight of the system) with the downward force, and then it can be written as:

$$N_{di} = m_{hc}.g + F_{di} \tag{13}$$

In this case, Equation (12) can be written again as:

$$W_R = \int_0^{z_b} N_{di}.dz + \int_0^{m.2\pi} F_i.r.d\theta \tag{14}$$

By integrating Equation (14) and using average values for the variables, it follows:

$$W_R = N_d.z_b + m.2\pi r.F = \Delta E_{st} \tag{15}$$

Or even, for any displacement:

$$W_{Ri} = N_{di}.z_i + m_i.2\pi r.F_i = \Delta E_{st_i} \tag{16}$$

The term $m_i.2\pi r.F_i$, which appears in Equation (16) can be written again, in terms of angular velocity (n_i), vertical velocity of the auger (v_i) and the applied torque (M_i), during a given time (t_i) and a certain displacement (z_i) as:

$$m_i.2\pi r.F_i = \frac{n_i M_i}{v_i}.z_i \tag{17}$$

where,

$$n_i = \frac{m_i 2\pi}{t_i} \tag{18a}$$

$$M_i = r.F_i \tag{18b}$$

$$v_i = \frac{z_i}{t_i} \tag{18c}$$

Replacing Equation (17) in Equation (16), it follows:

$$W_{Ri} = N_{di}.z_i + \frac{n_i.M_i}{v_i}.z_i = \Delta E_{st_i} \tag{19}$$

By dividing all terms of Equation (19), by the excavated volume of the pile, that is, $\Omega.z_i$ and considering the constant motion force it comes that the installation energy by volume unit is given by:

$$E_s == \frac{\Delta E_{st_i}}{\Omega.z_i} = \frac{N_{di}.v_i + n_i.M_i}{\Omega.v_i} \tag{20}$$

where, E_s is the installation energy by volume unit [J/m³], N_d is the vertical motion force [N], v_i is the vertical velocity of the auger [m/s], n_i is the angular velocity [1/s], M_i is the torque applied [N.m], Ω is the area of planar projection of the auger [m²].

Equation (20) is in conformity with what was established by Van Impe (1998), for the energy by volume unit to excavate a pile. It is observed that the formulation presented by Equation (12), is consistent by the physics point of view, taking to values closed to the ones obtained by Van Impe's proposal, which considers in its approach average values. Such fact was expected because both come physically from the universal energy conservation principle represented by Equation (4), where in a closed system, as the existing one during the excavation of a pile, the total work done the external forces has to be equal to the energy variation.

III. ENERGY AND BEARING CAPACITY

During the excavation of a piling, the aim is to achieve a resistant surface where the pile tips must be anchored. Such surface has to be in accordance with the geotechnical and structural ultimate and service limit states. The location of the resistant surface depends on the geological-geotechnical formation of the soil. Its survey during the execution of a piling by hammering is given by the set control or by the elastic rebound, but in the boring case, its survey becomes more difficult

In the traditional execution method, the excavating depth is previously set by the designer and hardly changed during the execution. In spite of that, in a soil profile with folded structural geology, such practice can take to mistakes, especially when the soil which is not sampled, the soil between boring holes, is in the depression zone of the fold, taking to low resistances till the anchoring elevation defined in the design. When the fold inverts its position, the boring machine during many times is not able to achieve the desired depth, providing some doubts concerning the boring quality.

However, Silva & Camapum de Carvalho (2010) noticed that the work done by each pile in the piling executed by a certain process of the set equipment/operator, when joined consisted of a population which fits in a normal probability distribution. Such thing permitted the authors to define acceptance criterions in relation to the mean and standard deviation of the population (demanded energy for each pile) or of a collected sample of that population, and then, they baptized the methodology as SCCAP Such methodology was introduced by the authors in the monitoring system of the excavated piles and CFA ones which allowed them to measure through Equation (12), the work or the required energy to excavate each pile of the piling and it tries to decrease the risk by the energy control during the excavation process and piling execution.

In Figure 3, the results obtained during the execution of seven piles on the Lake Paranoá shore located in Brasília, capital of Brazil are presented. It can be verified that the measured energy in each pile is directly proportional to its bearing capacity. In Table 1 the geometric features and the required energy to execute each pile are presented.

The final behavior of the pile will still depend on the concrete pouring quality, as for example, the concrete injection pressure, depending on the soil type; it can have a great influence on the pile behavior.

IV. CONCLUSIONS

The results which were presented take us to the conclusion that is possible to determine the required energy to excavate a pile from the universal energy conservation principle. It was also verified that under controlled conditions in the pilings executed with the same set of operator/equipment, the demanding energy during the excavation of a pile is directly proportional to its bearing capacity allowing to control and increase15the piling reliability by making a survey concerning the installation energy of the pile, as it was proposed by the SCCAP methodology.

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TABLE I. GEOMETRIC FEATURES OF THE PILES TESTED STATICALLY (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

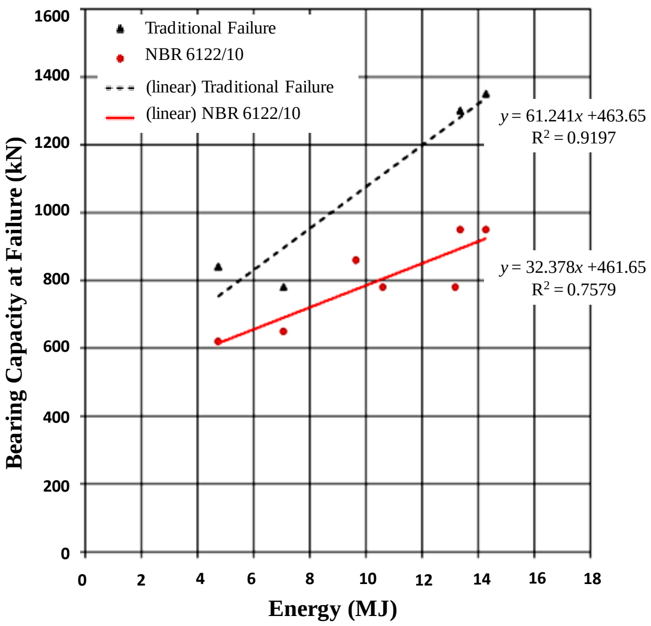

Figure 3. Ultimate bearing capacity versus work done (Silva, 2011).

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