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On the Relation Between the Excavation Energies of Continuous Flight Auger Piles and the Unconfined Compressive Strength of the Surrounding Soils

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Abstract. Foundation design strongly relies on the knowledge of the designer about the implementation site. Both lab and in-situ tests are the best alternatives to obtain reliable information about the soil mass, however, the quantity and quality of such tests may still not be adequate to fully understand the underground terrain. Quantity may be an issue because the general idea to minimize costs by decreasing tests is still present in the engineering market. Quality, on the other hand, is a major issue as poorly-executed or poorly-located tests significantly affect the designed solution. Instead of executing more tests, engineers should understand how to take advantage of common procedures to obtain parameters of interest. In the present paper, it is studied how the execution energy of continuous flight auger piles can be related to the Unconfined Compressive Strength (UCS) of the surrounding soil mass. The excavation of this type of pile can be fully monitored by collecting data from sensors in the drilling machine. Thus, based on models presented in the literature, the collected data was analyzed and it was possible to estimate the UCS of the excavated soil layers. In order to verify the consistency of the values estimated, soil surveys were carried out to identify the soil strata in the site. The indirect measurements considerably agree with typical UCS values of the materials considered. The estimated parameters can be used to update the projects almost instantly. Therefore, allying technology, theory and engineering practice is a good and cheap source of information, which ultimately enhances the quality of foundation designs.

Keywords. Continuous flight auger piles, excavation energy, unconfined compressive strength.

1. Introduction

Better knowing the soil strata is crucial to correctly design geotechnical infrastructures. Constitutive models rely on physical parameters which must be estimated by experiments, whether in-situ or laboratory based.

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Laboratory tests are often considered advantageous because controlling environmental variables (temperature, confining pressure etc) may lead to results that are more reliable. In-situ tests, on the other hand, tend to be more cost effective than laboratory tests. This reduction in costs comes together with less control over environmental variables as well as experimental procedures, possibly leading to poorly executed or poorly located tests [1]. On the other hand, despite these possible issues, a large contingent of researchers consider in-situ testing to be far superior to lab testing.

In the big data era, every professional should try to take advantage of the available data to indirectly obtain new information. Therefore, engineers should understand how to take advantage of common unavoidable procedures to estimate the parameters needed to model soil`s behavior.

Estimating strength parameters based on drilling data of geomaterials is a promising in-situ method that has been studied by many researchers [1,2]. Initial studies of this topic were driven by economic issues, not academic ones. This comes from the fact that, geomaterials such as rock and soils play a very essential role in the drilling speed, depreciation of drilling bit, machines, and overall drilling costs [3]. Thus, understanding the drilling environment and the characteristics of the in-situ rock mass significantly contributes to the selection of the machines and prediction of execution schedules [3].

One may estimate the constitutive parameters either by theoretical and/or experimental approaches. For example, the work [4] presented the development of a penetration rate (P_r) model for soft-formation bits under conditions where cuttings removal does not impact this rate. This model relates P_r to weight on bit, rotary speed, rock strength, and bit size. Later on, the same author presented a P_r model that includes the effect of both the initial chip formation and cuttings-removal processes [5].

Other more recent theoretical models are presented in the literature, as in [2]. Those authors proposed an analytical model to describe rock drilling processes using drag bits and rotary drills, and to deduce the relations among rock properties, bit shapes, and drilling parameters (rotary speed, thrust, torque and stroke). With the models and data studied, the unconfined compressive strength of rocks could be estimated from drilling data [2].

Besides the penetration rate, the energy required to drill a given volume of material can also be correlated to strength and deformability parameters. Even though, as indicated, using the installation energy to correlate to strength is not completely new, the studies carried out so far consider this type of correlation for rocks. In the present paper, on the other hand, soils are considered. This approach is explored in the next section

2. Energy as a useful measured parameter for rocks and soils

2.1. Rocks

As indicated in the pioneering study [6], the work done per unit volume of excavated rock has been named specific energy (S_e). In [6], it has been indicated that S_e can be taken as an index of the mechanical efficiency of a rock-working process. An interesting idea is presented in that work, indicating that the minimum value of S_e could be correlated with the crushing strength of the medium drilled in, for rotary, percussive-rotary and roller-bit drilling.

In rotary non-percussive drilling, work is done both by the thrust, F [MLT^{-2}], and the torque, T [ML^2T^{-2}]. If the rotation speed is N [T^{-1}], the area of the hole or excavation A [L^2] and the penetration rate P_r [LT^{-1}], the total work done is $(FP_r + 2\pi NT)$. The volume of rock excavated is (AP_r). Mathematically, the Specific Energy S_e [$ML^{-1}T^{-2}$] can be described as [6]:

$$S_e = \frac{F}{A} + \frac{2\pi}{A}\frac{NT}{P_r} \quad (1)$$

2.2. Soils

Regarding soil sciences, measuring the installation torque, and therefore consumed energy, of helical piles has been studied in [7]. In that paper, a theoretical model to relate the energy exerted during installation of helical piles to the energy required to displace the foundation or anchor once in place was proposed.

Besides, the SCCAP methodology, which was developed to control the execution of Continuous Flight Auger (CFA) piles foundations, proposes formulations, routines and criteria for pile acceptance based on the comparison of the necessary energy to excavate a particular pile to the statistical characteristics of the energetic population [8].

Energy-based approaches have been studied as tools to enhance the quality and reliability of drilling procedures and foundation design. In the present paper, the Specific Energy of soils are going to be used to estimate their unconfined compressive strength (UCS). This estimation shall be carried out by considering the data presented in the literature as well as execution energies collected during the execution of CFA piles. The data and methodology considered in the current paper is presented in the next sections.

3. Methodology

As indicated, an experimental correlation shall be used to predict UCS data based on the specific energy calculated during the drilling process. The datasets and methods considered are presented in the next subsections.

3.1. Reddish & Yasar [9] Approach

In the work of Reddish & Yasar [9], an experimental setup was created using a modified industrial rotary hammer drill. Samples of different rocks were drilled and their specific energy were recorded. Rock samples were also tested in order to obtain their UCS values [1,9].

On their work, they did not present a direct relation between S_e and the Unconfined Compressive Strength of the rocks, however the data needed to do so is presented in their paper. This dataset is used in the present paper to develop models which can be used to obtain the UCS from S_e. Such data is presented in Table 1, regarding the Specific Energy and UCS of different rock types.

By using the data in Table 1, a linear model has been built to estimate UCS based on S_e. A model of the type UCS = “a” S_e, with fitting parameters “a” is suitable as it accounts follows the general linear behavior predicted by [10]. This fitting is subsequently shown in Figure 3.

Table 1. Reddish & Yasar data [9].

Rock Type	Specific Energy - SE (MJ/m3)	UCS (MPa)
Mudstone	318	19
Sandstone	1745	72
Siltstone	1604	70
Limestone	760	39
Limestone (2)	1617	63.22
Gypsum	470	16.5
Slate	2928	148
Sandstone (2)	1678	82
Cement 1:1	862	11.8
Cement 1:15	663	10.41
Cement 1:2	684	7.89
Cement 2:75	352	5
Cement 1:3	318	2.5

3.2. Checking the accuracy of predicted UCS

Checking the validity of the estimated UCS values is important. Therefore, simple soil surveys were carried out to identify the type of soil presented, allowing one to compare the estimated and typical values of UCS. The typical values for UCS and the corresponding classifications for cohesive soils are presented in Table 2 [11].

Table 2. Unconfined compressive strength classification [11].

UCS (kPa)	Classification
0 – 25	Very Solft
25 – 50	Soft
50 – 100	Medium or firm
100 – 200	Stiff
200 – 400	Very Stiff
>400	Hard

4. Results and discussions

In the current section, the results and discussions shall be presented.

4.1. Pile Selection Based on Distance From Soil Surveys

Four surveys were carried out to identify the soil profile for each drilled pile. The results are presented in Figure 1.

As the piles were executed in the whole terrain, we chose the closest pile to each of the surveys in order to characterize the pile's installation soil profile. Figure 2 presents the surveys locations and the correspondent piles [1].

It can be seen in Figure 2 that the piles P9CF, PR6, P9AF and P6AD are the closest piles to the soil surveys S1, S2, S3 and S4, respectively. Now that the piles have been chosen, its necessary to estimate the UCS values of the soil layers drilled during their executions [1]. The next subsection indicates how to perform the estimation based on Reddish & Yasar [9] dataset, which was previously presented in Table 1.

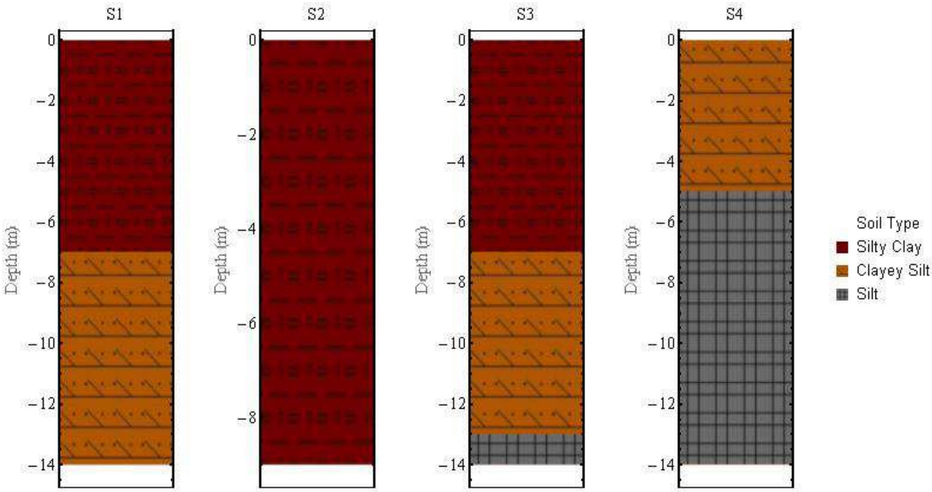

Figure 1. The soil strata based on survey results [1].

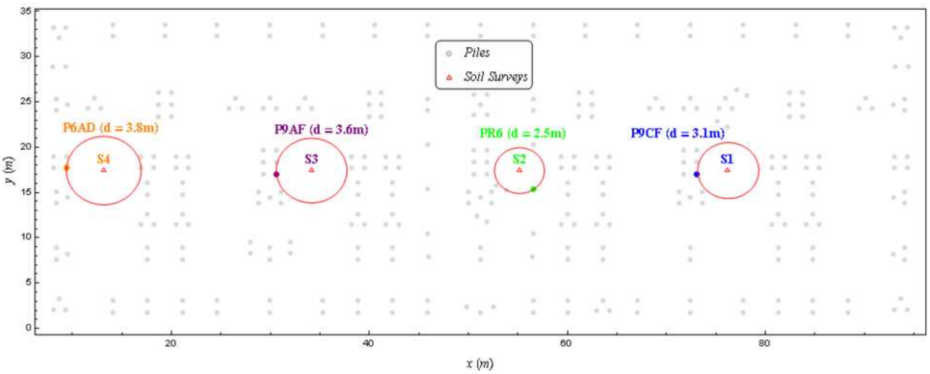

Figure 2. Closest piles to each soil survey [1].

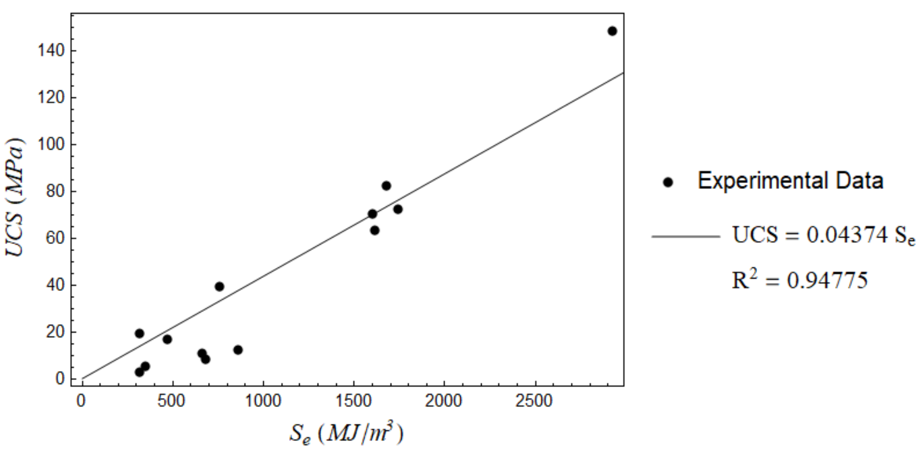

Figure 3. Linear model proposed for the relation between UCS and Se.

4.2. Modelling data from Reddish & Yasar [9]

As previously indicated, a linear equation was used to fit the data presented in [9]. The fitted function as well as its correspondent R^2 value is presented in Figure 3. In general, good fit is observed.

4.3. UCS estimation

Based on the linear models presented in Figure 3, the values of the UCS of the excavated 1m soil layers are presented for each pile considered. Figure 4 present these results.

Layer	P9CF		PR6		P9AF		P6AD	
	Se (MJ/m3)	UCS (kPa)	Se (MJ/m3)	UCS (kPa)	Se (MJ/m3)	UCS (kPa)	Se (MJ/m3)	UCS (kPa)
0m-1m	2,06	89,92	2,07	90,56	2,53	110,81	4,31	188,33
1m-2m	4,45	194,63	7,26	317,60	8,55	374,11	9,16	400,77
2m-3m	5,30	231,62	11,02	481,78	10,91	477,02	9,99	436,86
3m-4m	7,71	337,25	9,22	403,34	10,70	468,03	9,64	421,45
4m-5m	6,33	276,69	12,02	525,67	12,24	535,27	10,35	452,57
5m-6m	7,28	318,46	11,80	516,26	13,20	577,22	11,39	498,13
6m-7m	9,19	402,04	13,65	596,89	13,69	598,92	10,55	461,59
7m-8m	9,37	409,92	15,07	659,12	13,14	574,66	10,83	473,58
8m-9m	10,72	468,99	18,18	795,22	15,11	660,88	12,52	547,53
9m-10m	10,34	452,13			13,86	606,09	15,52	678,71
10m-11m	10,96	479,27			16,73	731,60	10,34	452,39
11m-12m	10,10	441,81			14,96	654,48	11,17	488,72
12m-13m	8,90	389,27			18,05	789,48	16,06	702,58
13m-14m	11,26	492,66			14,07	615,35	14,55	636,37

Figure 4. Estimated values of UCS. The color code follows the soil type, as indicated in Figure 1.

The soil drilled is a deeply weathered lateritic soil. Therefore, direct comparison between the values presented in Table 2 and in Figure 4 must be carried out with caution. Due to the cementations, the soil drilled may have apparent UCS values greater than the ones presented in Table 2.

The interaction between the bits used in [9] and the one used to drill the piles in the present paper with rocks and soil, respectively, is different and leads to different efficiencies throughout the process. This may explain the potential difference observed. One may notice, on the other, that the values presented in Figure 4 are comparable to the ones presented in Table 2. Also, an increasing stiffness is observed as depth increases, which is also expected.

There are other issues which may have impacted the estimates to slightly depart from typical values of UCS of the soils excavated. As indicated in [6], it is axiomatic that, to excavate a given volume of rock, a certain theoretically attainable minimum quantity of energy will be required. Its amount will depend entirely on the nature of the drilled material. Real mechanical processes might or might not approach this theoretical minimum: the difference between actual and theoretical requirements would be a measure of work dissipated in, for example, breaking the excavated material into smaller fragments than necessary, in friction between tools and material (which amounts perhaps to the same thing on a microscopic scale); or in mechanical losses quite outside the rock/soil system. Breaking the debris into 'smaller fragments than necessary' may have a disproportionate effect on the energy needed to excavate the given volume. Not only do more particles have to be broken needlessly, but the specific energy itself increases considerably as the particle size is reduced [1,6]

Therefore, it is believed that excavation of soils is much less efficient than rock excavation, implying that the measured specific energies are far greater than the minimum amount required for soil drilling [1].

It is important to point that the present paper considers a purely experimental approach to estimate UCS from soil drilling data. Physical models must be built to properly address this issue from a theoretical point of view. Thus, the results presented are just a first approximation which need to be enhanced to be used by every-day engineers.

5. Conclusions

Over the past decade, sustainable practices have been implemented on every area of engineering. Mostly, those practices are related to the conception and execution of designs but not to the design process itself.

Understanding how to take advantage of common procedures to obtain parameters of interest is important to avoid wasting resources to perform unnecessary tests. In order to properly estimate parameters of interest from existing data, reliable models must be built. This is the core of the Big Data rationale, which has been increasingly considered in engineering.

In the present paper, it is studied how the execution energy of continuous flight auger piles can be related to the Unconfined Compressive Strength of the surrounding soil mass. This approach has been successfully applied to rocks and now has been considered for soils. Based on an experimental dataset presented in the literature, a simple linear model has been built. By using the fitted model, the collected data was analyzed and it was possible to estimate the UCS of the excavated soil layers.

By directly comparing the estimates to typical values of UCS of cohesive soils, good agreement is present. Some issues may considerably impact the values obtained such as: different materials and geometries of the bits used to drill as well as different efficiency for rock and soil drilling. Since we used rock drilling data to build our models, we ended up performing extrapolations on such dataset. This need to be further studied both experimentally and theoretically.

Another important issue which needs to be further explored is whether the methodology presented could be applied to cohesionless soils. The authors believe that during the excavation of cohesionless soils, the energy dissipated due to friction could considerably affect (increase) the total specific energy measured, demanding a different type of correlation.

Allying technology, theory and engineering practice is a good and cheap source of information, which ultimately enhances the quality of the foundation designs and avoid resources' wasting.

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