A big data approach to estimate shear strength properties of the surrounding soils based on the execution energies of piles

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ABSTRACT: Historically, empirical relations are the basis of every-day foundation design. These relations, however, rely on specific datasets, which may not represent the true conditions observed in the field. Even in-situ tests rely on empirical correlation formulas, which link observed phenomena to soil's properties. These correlations should be updated according to the specific design conditions. Big data (BD) workflows enable the use of the massive data available to update the correlations and to provide more accurate predictions of the parameters studied. Thus, in this paper, a BD approach is used to study the relation between the drilling process of continuous flight auger piles and the shear strength properties (SSPs) of the surrounding soils. Soil surveys were carried out to identify the soil strata in the site and to validate the estimates of the SSPs. The results show that indirect measurements are in accordance with typical undrained shear strength and friction angles of the materials considered.

Keywords: continuous flight auger piles, specific energy, shear strength, friction angle, undrained shear strength.

1. Introduction

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 [1].

One of the main concerns of modern data scientists is to transform raw data into information. The common phases of a traditional analytics workflow for Big Data are: data mining from data sources, data management, data modelling and result analysis and visualization [2].

According to [2], data from various sources are used to build models. In a Big Data environment, the large volume and variety of the dataset can demand pre-processing tasks for integrating the data, cleaning it, and filtering it. Those authors also indicate that the prepared data is then used to train a model and to estimate its parameters. Once the model is estimated, validation must be performed prior to its utilization.

After the model is validated, [2] indicate that it can be applied to data as it arrives. This step, called model scoring, is used to generate predictions, prescriptions, and recommendations. The results are interpreted and evaluated, used to generate new models or calibrate existing ones, or are integrated to pre-processed data [2].

The Big Data rationale can be used to assist Engineers, leading to more accurate and reliable designs. Every foundation designer must have access to tests which characterize the underground medium. This is due to the dependency of constitutive models on some parameters which are only measured during such tests. Foundation design, in general, must account for strength and deformability parameters.

According to [3], using the drilling data of geotechnical materials to estimate strength parameters is a promising *in-situ* method that has been studied by many researchers. Economic interest has driven such studies. In [4] it is indicated that geotechnical materials such as rock and soils, understood as the formation to be drilled, play a very essential role in the drilling speed, depreciation of drilling bit, machines, and overall drilling costs. Thus, understanding the drilling environment and the characteristics of the in-situ rock mass is fundamental to select the machines and predict the execution schedules [4].

In the present paper, a Big Data analytics workflow shall be explored to obtain shear strength parameters of soils drilled during the execution of Continuous Flight Auger Piles (CFAPs). Each of the phases previously described shall be explored and a new model is derived to represent the drilling process of this type of pile.

In the next section, the Big Data Workflow to be considered in the present paper is discussed.

2. Big data workflow

As previously indicated, the common phases of a traditional analytics workflow for Big Data are: data mining from data sources, data management, data modelling and result analysis and visualization [2]. Therefore, each of the next subsection will explore these phases.

2.1. Data mining

Data mining in Engineering depends on gathering data either from laboratory or *in-situ* tests.

When cost is a major issue, *in-situ* tests are good candidates as they tend to be cheaper than laboratory tests. However, this drop in price comes together with less control over environmental variables as well as experimental procedures, which may lead to poorly executed or poorly located tests.

Contractors tend to be worried about the cost/benefit relationship of tests and since *in-situ* tests have been extensively validated in the literature, this type of test is commonly chosen.

The building process (excavation and concreting) of CFAPs can be fully monitored by collecting data from sensors in the drilling machine. Therefore, gathering the data which was recorded by those sensors is the main data mining process considered in the present paper.

2.2. Data management

The Data Management step in the Big Data work-flow can be understood as the process of transforming raw input data into pre-processed information. This process incorporates data storage and manipulation.

In the present paper, as indicated, the drilling process of CFAPs can be fully monitored. The raw data collected is normally stored on simple database *.mdb* files which are then combined and treated. In general, the dataset collected during the drilling of a CFAP contemplates the following items: depth, rotation speed, torque, vertical tilt of the drill and pressure of the injected concrete.

By using the raw data mentioned, one can calculate the energy required to perform the drilling operation. This pre-processed information can be modelled to actually predict some parameters of interest.

2.3. Data modelling

Strength parameters can be estimated from drilling data by both theoretical and experimental approaches. In [5], it has been presented the development of a penetration rate P_r model for soft-formation bits under conditions where cuttings removal does not impede this rate. This model relates P_r to weight on bit, rotary speed, rock strength, and bit size. The same author further developed this model and then presented a P_r model that includes the effect of both the initial chip formation and cuttings-removal processes [6].

An analytical model was proposed in [3] 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). These authors then could estimate the unconfined compressive strength of rocks from drilling data.

In [7], on the other hand, percussive blast hole drills were studied and experimentally related the net penetration rates of the drills to strength parameters. Those authors collected rock samples from the drilling locations and the physical and mechanical properties of the rocks were determined both in the field and in the laboratory. Correlations between penetration rates and uniaxial compressive strength, the Brazilian tensile strength, the point load strength, the Schmidt hammer value, impact strength, Young's modulus (E), natural density and P-wave velocity were studied.

Besides the penetration rate, literature reveals that the energy required for drilling a given volume of material can also be correlated to strength and deformability parameters of the drilled materials.

In [8] is was indicated that the specific energy (S_e), defined as the work done per unit volume excavated, is a useful parameter which can be defined and studied during drilling processes. That author also indicates that S_e can be taken as an index of the mechanical efficiency of a rock-working process. Besides, that author states that the minimum value of the specific energy seems to be very roughly correlated with the crushing strength of the medium drilled in, for rotary, percussive-rotary and roller-bit drilling. Thus, understanding the drilling problem from an energetic point of view is a valid and promising approach.

For continuous flight auger piles, rotary non-percussive drilling is present. In this case, 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. In [8], a mathematical description of the Specific Energy S_e [$ML^{-1}T^{-2}$] was given as Eq. (1):

$$S_e = \frac{F}{A} + \frac{2\pi}{A}\frac{NT}{P_r} \tag{1}$$

Energetic measurements of drilling performance for soils are also presented in the literature. In [9], that author proposed 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. Through the equivalence of energy, the model relates bearing and pullout capacity directly to installation torque. In [9], the influence of downward force during installation, helical blade geometry, multiple helices, blade pitch per revolution, and hub radius were considered to build his formula.

Equation (1) clearly indicates a direct relation between the drilling torque and the specific energy. Therefore, torque-based models are of the same type as energy-based models. In [10], those authores derived a consistent physical model which proposes a theoretical relationship between uplift capacity and installation torque of deep helical piles in sand.

In [11], on the other hand, it was discussed the application of the SCCAP methodology, which was developed to control the execution of Continuous Flight Auger (CFA) piles foundations. The SCCAP methodology proposes formulations, routines and criteria for pile acceptance based on the comparison of the necessary energy to excavate a particular pile to statistical characteristics of the energetic population. Those authors claim that this approach enhances the reliability and mitigates involved risks to the geotechnical job as well as indicating that the SCCAP methodology can relate the necessary energy to excavate a pile and its bearing capacity.

During a drilling process, the penetration rate of the drilling machine can be related to the specific energy of the material being drilled. Both parameters, on the other hand, can also be theoretically and experimentally related to shear strength parameters as friction angle and undrained shear strength. This way, a new physical model shall be derived and used to estimate these parameters of the stratum being drilled. This is the model chosen to be part of the Big data workflow considered in the present paper.

2.4. Result analysis and visualization

The final step in the Big Data workflow hereby considered is the analysis and visualization of the results. This can be achieved by using simple resources, such as spreadsheets. Since the present paper presents a simplified approach, the results will be visualized as table with color codes.

3. Shear strength parameters behavior and estimation

As most of the engineering parameters, shear strength parameters are stress dependent. Such dependency can be formulated based on a number of models present in the literature. Thus, in general, that stress dependency must be accounted when estimating these parameters along a soil profile with increasing confining pressures.

In general, besides triaxial and shear tests, field engineers tend to estimate the shear strength parameters based on other information readily available.

Standard penetration tests are often performed to provide information for foundation designs. Therefore, relations between shear strength parameters and the number of N_{SPT} blows are of interest. Thus, the angle of internal friction ϕ' and the undrained shear strength c_u can be related to the N_{SPT} (hereby equivalent to N_{60}) values as [12] in Eqs. (2) and (3):

$$\phi' = \beta' \tan^{-1}\left[\frac{0.2N_{SPT}}{K(\sigma'/p_a)} - 0.68B\right] \tag{2}$$

$$c_u/p_a = \alpha' N_{SPT} \tag{3}$$

where β', B and α' are constants of proportionality, K is the coefficient of lateral earth pressure and p_a is the atmospheric pressure (100kPa).

In order to obtain Eqs. (2) and (3), the authors in [12] proposed a method which treats SPT analogous to driving a miniature open-ended pipe pile. They discuss that during SPT, part of the energy is transferred into the soil. This energy is dissipated at the soil-sampler interface to overcome skin and point resistance to penetrate a sampler into the soil. Therefore, energy balance was used in [12] to correlate the SPT blow count to the shear strength properties of the soil at the depth of testing.

Regarding other strength parameter, the literature also indicates that the Unconfined Compressive Stress, σ_c, may be estimated in kPa for low plasticity clays and for clayey silts based on N_{SPT} data as [13] in Eq. (4):

$$\sigma_c = 107.3N_{SPT}/13.5 \tag{4}$$

Therefore, in general, field engineers and designers tend to take advantage of existing data to estimate strength parameters. This estimation is performed, in general, based on field test results, such as NSPT values and CPT values. The rationale behind the present paper is extrapolate this intuitive procedure to consider a big data approach to the problem: use existing information continuously collected on the field to predict shear strength parameters.

CFA piles, as previously indicated, can have their execution fully monitored. The most important pre-processed information obtained from the raw data collected is the energy used to drill the strata at the pile location. Thus, to use the data available (big data as a huge number of piles are drilled everyday), either a good experimental relation should be found, or a consistent physical model should be built. The former approach shall be considered in the present paper. In the next section, the derivation of a simple, yet powerful, model for the drilling phenomena is presented.

3.1. Simplified model for shear strength parameters prediction

As previously discussed, the concepts introduced by Teale and further developed by other authors, such as [14], indicate that the Specific Energy, S_e, can be correlated to the Unconfined Compressive Stress, σ_c , of a given Rock by means of the Eq.(5):

$$S_e = \eta\sigma_c \tag{5}$$

in which η represents the efficiency of the drilling process. Greater values of η imply on less efficient drilling processes.

Combining Eqs. (4) and (5), one obtains Eq.(6), for S_e given in kJ/m^3:

$$S_e = 107.3\eta N_{SPT}/13.5 \tag{6}$$

Finally, by the direct combination of Eqs. (2), (3) and (6), the Specific Energy can be correlated to the shear strength parameters of the material being drilled (rocks) or excavated (soils). Mathematically, one can write for both σ' and c_u given in kPa in terms of Eqs. (7) and (8):

$$\phi' = \beta' \tan^{-1}\left[\frac{2.516S_e}{K\eta\sigma'} - 0.68B\right] \tag{7}$$

$$c_u = 12.581\alpha' S_e/\eta \tag{8}$$

One shall notice that the friction angle calculation in Eq. (7) incorporates some in-situ characteristics, namely: depth dependence, degree of saturation, stress memory and so on. Besides, both Eqs. (7) and (8) are applicable to low plasticity clays and for clayey silts. The next section presents the methodology used in the present paper to perform the parameter estimations.

4. Methodology

As indicated, the simple models presented in Eqs. (7) and (8) have been obtained from experimental correlation. These models shall be used to estimate shear strength parameters based on the specific energy calculated during the drilling process. The methodology strictly follows the Big Data workflow previously indicated.

The values indirectly obtained are compared to the values presented in the literature for the materials drilled. These materials were identified after soil surveys were carried out.

5. Results and discussions

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

5.1. 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 Fig. 1. SPT tests were also performed.

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. Fig. 2 presents the surveys locations and the correspondent piles.

It can be seen in Fig. 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 shear strength parameters of the soil layers drilled during their executions.

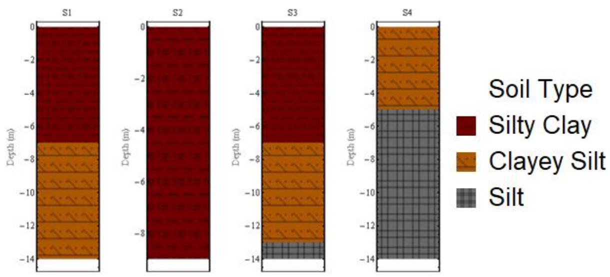

Figure 1. The soil strata based on survey results.

In order to use Eqs. (7) and (8), we should firstly estimate the input parameters needed. According to [12], the calibration of Eqs. (2) and (3) with experimental data provided β'=2.61, K=0.8, B=0.6 and α'=0.041. Also, to obtain the vertical stress at a point, a linear varying stress with depth is considered. The specific weight of the soils is vastly reported in the literature. To the best of the authors knowledge, a mean value of 15 kN/m3 is consistent and shall be considered. Therefore, the only parameter which still needs evaluation is η.

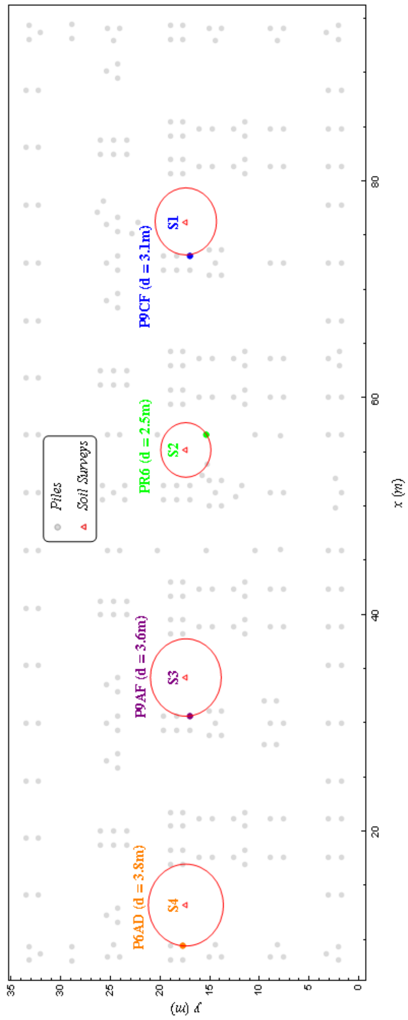

Figure 2. Closest piles to each soil survey.

The efficiency parameter η is related to the energetic balance during drilling. As indicated in [8], 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 [8].

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.

Since the literature does not present a survey on the value of η, these values have been calculated in the present paper. By Eq. (5), η can be estimated by fitting a line to the relation between S_e and σ_c. This last parameter can be estimated from N_{SPT} data by using Eq. (4). For each of the soil surveys performed, a SPT test has been carried out. Thus, we are able to estimate the UCS of the soils drilled and, therefore, estimate η.

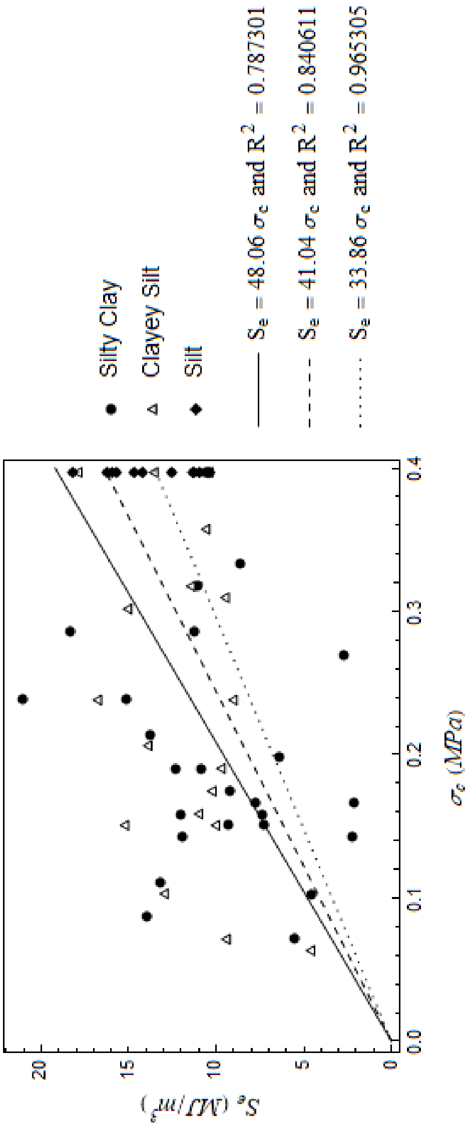

Figure 3. Relation S_e vs σ_c.

From Fig. 3, it can be seen that different soils have different values of η. Greater values of this parameter imply less efficient drilling, as the energy needed to perform the drilling increases (considering that there is an optimal S_e value). Soils with lower plasticity tend to have a more efficient drilling, as expected. Thus, based on the linear regressions presented, for the Silty Clay, Clayey Silt and Silt, the values of η are 48.06, 41.04 and 33.86, respectively.

Being all the parameters obtained, one may proceed to use Eqs. (7) and (8). Tables 1 and 2 present the results. A comparison between these Tables and commom literature values for the parameters involved indicate that the results obtained are consistent with the soils drilled.

It is worth noticing that the approach hereby presented is a first approximation to the process of estimation of deformability parameters from drilling data of soils. The experimental prediction models hereby proposed could benefit from considering more data.

Table 1. Friction Angle Estimation

Layer	P9CF		PR6		P9AF		P6AD	
	Se (MJ/m³)	ϕ'^o	Se (MJ/m³)	ϕ'^o	Se (MJ/m³)	ϕ'^o	Se (MJ/m³)	ϕ'^o
0m-1m	2.06	37	2.07	38	2.53	41	4.31	48
1m-2m	4.45	39	7.26	45	8.55	47	9.16	48
2m-3m	5.3	34	11.02	45	10.91	45	9.99	46
3m-4m	7.71	36	9.22	39	10.7	42	9.64	42
4m-5m	6.33	26	12.02	40	12.24	40	10.35	40
5m-6m	7.28	25	11.8	37	13.2	39	11.39	42
6m-7m	9.19	27	13.65	36	13.69	37	10.55	38
7m-8m	9.37	28	15.07	36	13.14	36	10.83	36
8m-9m	10.72	29	18.18	37	15.11	37	12.52	37
9m-10m	10.34	25			13.86	33	15.52	39
10m-11m	10.96	23			16.73	35	10.34	28
11m-12m	10.1	17			14.96	30	11.17	27
12m-13m	8.9	8			18.05	33	16.06	34
13m-14m	11.26	15			14.07	29	14.55	30

Table 2. c_u Estimation

Layer	P9CF		PR6		P9AF		P6AD	
	Se (MJ/m³)	c_u (kPa)	Se (MJ/m³)	c_u (kPa)	Se (MJ/m³)	c_u (kPa)	Se (MJ/m³)	c_u (kPa)
0m-1m	2.06	22	2.07	22	2.53	27	4.31	54
1m-2m	4.45	48	7.26	78	8.55	92	9.16	115
2m-3m	5.3	57	11.02	118	10.91	117	9.99	126
3m-4m	7.71	83	9.22	99	10.7	115	9.64	121
4m-5m	6.33	68	12.02	129	12.24	131	10.35	130
5m-6m	7.28	78	11.8	127	13.2	142	11.39	174
6m-7m	9.19	99	13.65	147	13.69	147	10.55	161
7m-8m	9.37	118	15.07	162	13.14	165	10.83	165
8m-9m	10.72	135	18.18	195	15.11	190	12.52	191
9m-10m	10.34	130			13.86	174	15.52	236
10m-11m	10.96	138			16.73	210	10.34	158
11m-12m	10.1	127			14.96	188	11.17	170
12m-13m	8.9	112			18.05	227	16.06	245
13m-14m	11.26	142			14.07	214	14.55	222

6. Conclusions

In the present paper, the relation between the execution energy of continuous flight auger piles and the strength parameters of the surrounding soil mass is studied. Based on two experimental models presented in the literature and a new physical model hereby derived, the collected data was analyzed, and it was possible to estimate the friction angle and the undrained shear strength of the excavated soil layers.

The simple method proposed provides consistent results, indicating its validity. Greater datasets, especially to better estimate η, could be used to enhance the applicability of the model.

Instant updating of designs can be achieved by using the methodology hereby proposed. This avoids common spatial interpolation errors which would arise while using segregated test results. The experimental prediction models hereby proposed could benefit from considering more data.

It could be seen that allying technology, theory and engineering practice is a good and cheap source of information, which ultimately enhances the quality of the foundation designs. This is a key aspect in the Big Data era, where taking advantage of available information can be crucial to enhance the quality of designs. In order to further validate the results and discussions hereby presented, independent laboratory and in-situ test data must be collected and compared to those considered in the current paper.

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