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Determination of fine-grained soil parameters using an automated system

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ABSTRACT: Performing numerical analysis successfully depends on several factors. One of the most important factors is determining the constitutive model parameters correctly. It is often the case that these parameters are determined based on limited soil data. Using in-situ tests for determining these parameters has several advantages such as minimal disturbance of the soil and lower cost compared to laboratory tests. However, it is not possible to determine soil parameters directly from in-situ tests results. Thus, empirical correlations are required for interpreting soil parameters. Generally, several correlations exist for the same parameter, which will lead to calculating several values for the same parameter. An ongoing research project focuses on formulating an automated parameter determination (APD) framework that uses a graph-based approach to identify constitutive model parameters based on in-situ tests. This is achieved by using two spreadsheets as an input, one for parameters and the other for equations (correlations used to calculate parameters). Based on these two spreadsheets, the system generates paths between the parameters and calculates the value(s) for each individual parameter. So far, the research project focused on determining the parameters for coarse-grained soil based on cone penetration test (CPT) results. Due to the fact that the system was set up in a modular and adaptable way, it is possible to expand the system to accommodate more soil types and in-situ tests. It is the aim of the research project to increase the reliability of the parameters values (required to perform numerical analysis) determined from in-situ tests. This paper focuses on expanding the current framework to determine parameters for fine-grained soil. By using the two spreadsheets as an input, the system successfully calculates the value(s) for fine-grained parameters. Further validation, dealing with several values for each parameter, determining the accuracy of derived parameters and expanding the system to accommodate other in-situ tests and types of soils are part of ongoing research.

1 INTRODUCTION

There are several reasons that make the use of numerical analysis preferable compared to the traditional methods. One of the main advantages is the level of detail that can be obtained in several geotechnical engineering problems such as soil-structure interaction Brinkgreve (2019). Several factors influence the success of the numerical analysis. One of the most important factors is determining the constitutive model parameters properly. The main challenge in determining these parameters is the limited available soil data. It is often the case that these parameters need to be defined based on experimental tests (e.g., triaxial and oedometer tests) which are not always available in all projects.

On the other hand there are in-situ investigations, where the cone penetration test (CPT) is one of the most popular in-situ tests as it is quick and often used in soil profiling and estimating soil parameters. Moreover, CPT has other advantages such as minimal disturbance of the soil and lower cost compared to laboratory tests. The main disadvantage of the interpretation of in-situ tests is that parameters cannot be determined directly from the results of the tests as the laboratory tests. However, a number of empirical relationships exist that link soil parameters to in-situ tests results, it is often the case that several relationships exist to determine the same parameter, which lead to a wide range of values for the parameter of interest. The reason for this variation is mainly related to the fact that these relationships are not applicable for all situations (e.g., specific soil types). In literature, several guides exist dealing with the interpretation of CPT such as Kulhawy & Mayne (1990), Lunne, Robertson, & Powell (1997), Mayne (2014) and Robertson (2015).

An ongoing research project focuses on creating an automated parameter determination (APD) system to determine constitutive model parameters based on in-situ tests. The framework relies on a graph-based approach that uses some of the characteristics of graph

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theory. The project aims to create a transparent and an adaptable parameters determination framework. Transparency is achieved by illustrating how the available information is used to compute parameters and adaptability is achieved by allowing the users of the system to incorporate their knowledge and experience into the system. Van Berkom et al. (2022) illustrated the determination of parameters for coarse-grained soils based on CPT data. This paper extends the framework presented in Van Berkom et al. (2022) by including parameters for fine-grained soils.

The 2nd section briefly describes the APD framework, while the 3rd section presents selected empirical relationships used to determine parameters for fine-grained soils. In the 4th section, the output of the APD for a simple example is illustrated. In the final section the conclusions of this study are summarized.

2 AUTOMATED PARAMETER DETERMINATION (APD) FRAMEWORK

2.1 *Framework*

The framework consists of several modules that are connected together. A schematic representation of the modules is shown in Figure 1. CPT raw data, in Geotechnical Exchange Format (GEF) are imported to the first module (GEF Reader). Afterwards the CPT measurements (cone resistance q_c, sleeve friction f_s & porewater pressure readings u_2) are passed to the second module (CPT layer interpretation). The second module determines the SBT based on Robertson (2010) modified non-normalized SBT chart and stratifies the CPT profile into several layers sharing the same SBT. For each layer, the average of the CPT measurements (q_c, f_s & u_2) within this layer is computed. The averaged CPT measurements are used by module 3 (Layer state), to determine the state of all layers (overconsolidation ratio OCR and coefficient of earth pressure K_0). The output of modules 2 and 3 is transferred to module 4, where the parameters are connected with the equations (correlations) and the parameters of interest are calculated. In the final module, parameters calculated in module 4 are converted to constitutive model parameters. The system is built in the programming language Python.

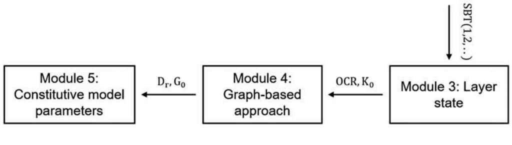

Figure 1. Schematic representation of the parameter determination modules.

The paper focuses on the output of module 4 at a specific depth. The layering process is not considered (modules 2 and 3) in this contribution. Moreover, the paper only presents the determination of fine-grained soil parameters (output of module 4) without the transition to constitutive model parameters (module 5).

Table 1. SBT zones according to Robertson (2010).

Zone	Soil Behaviour Type (SBT)
1	Sensitive fine-grained
2	Clays – organic soil
3	Clays: clay to silty clay
4	Silt mixtures: clayey silt & silty clay
5	Sand mixtures: silty sand to sandy silt
6	Sands: clean sands to silty sands
7	Dense sand to gravelly sand
8	Stiff sand to clayey sand (overconsolidated)
9	Stiff fine-grained (overconsolidated)

2.2 *SBT interpretation*

Robertson (2010) modified non-normalized SBT chart is used to classify the CPT profile. This SBT chart is based on dimensionless cone resistance, (q_c/p_a), where p_a is the atmospheric pressure and friction ratio (R_f in percent, $R_f = f_s/q_c$ 100%). The chart consists of 9 different zones, each corresponding to a different soil behaviour type (Table 1). At each depth, q_c and R_f are used to access the chart and determine the SBT for this depth. As a result, this module is used to distinguish between fine and coarse-grained soils.

2.3 *Graph-based approach*

The graph-based approach used in APD is described in detail in Van Berkom et al. (2022) and illustrated in Figure 2. The idea is to create links between source parameters (CPT raw data) via intermediate parameters to destination parameters (final soil or model parameters). Based on a given set of correlations, the system will create all the paths (chains of correlations) that provide the link from the source parameters all the way to the destination parameters and the system will calculate the destination parameter values from the input values of the source parameters (CPT data).

In the APD framework, the terms 'correlation', 'formula', 'equation', 'rule of thumb' is replaced by the term 'method'. This general term is used as parameters could be determined based on several ways (e.g., tables and charts) (Van Berkom et al. (2022)). The system must link the methods and parameters that share a relationship. As an example, a method to compute the coefficient of earth pressure at rest according to Jaky (1944) is defined as follows, $K_0 = 1 - \sin(\phi')$, where K_0 is the coefficient of earth pressure at rest and ϕ', is the effective internal friction angle of the soil. The system must identify the input and output for this method (the output is K_0 and the input is ϕ'). Consequently, links connecting these parameters should be generated.

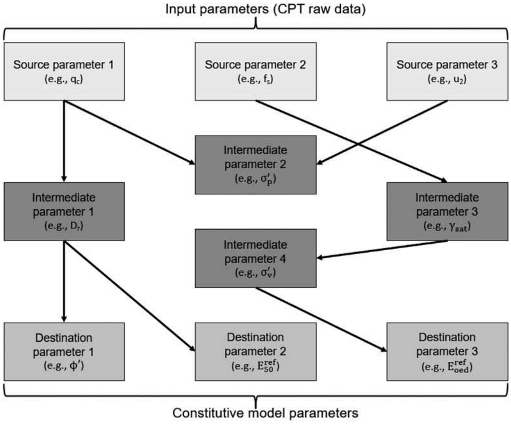

Figure 2. Graph-based approach implemented in APD.

2.4 *Generating the graph*

As shown in the previous subsection, the relationships between methods and parameters are defined by the output and input(s) of different methods. The parameters and methods are considered as external inputs to the system. The system requires two input files: methods and parameters. Users of the system may extend the standard database of methods and parameters provided with the system. The system connects the methods and parameters together, and computes the intermediate and destination parameters. Two different spreadsheets in comma-separate values (CSV) format corresponding to parameters and methods are used to generate the graph.

Each of the two CSV files has special properties. The methods CSV file requires the following properties, *method_to*, *formula*, *parameters_in*, *parameters_out*, *validity* and *reference*. Each of these unique properties need to be provided by the user in a CSV file. Taking the coefficient of earth pressure at rest method presented in the previous subsection as an example, *method_to* would present the name of the method, in this case it might be *method_to_K0*. In the field of *formula*, the equation should be defined, $1 - \sin(\phi')$. *Parameters_in* implicitly states the input for this method, ϕ'. Similar to *parameters_in*, the output of the method is stated in the field of *parameters_out*, K_0. The validity field specifies the applicability of different methods. Some methods are applicable for all types of soils, other methods are only valid for coarse-grained soils and others are only suitable for fine-grained soils. As shown in Table 1, the SBT is based on Robertson (2010) modified non-normalized SBT chart. In that sense, the validity is defined in terms of SBT. If the method is only valid for silt, the validity would be SBT(4). Regarding the method of coefficient of earth pressure at rest, the validity would be SBT(1234567). The reference field is an optional argument, where the user could state the author of the method (e.g., Jaky_1944).

The parameters CSV file requires the following properties, *symbol*, *value*, *unit*, *constraints*, and *description*. All of the parameters that have been used in the methods CSV files (in the fields of *formula*, *parameters_in* and *parameters_out*) must be defined in the parameters CSV file. The notation of the parameter (which was used in the methods CSV file) is stated in the *symbol* field (e.g., u for porewater pressure). In case the user wants to fix a value for a parameter (e.g., unit weight of water), the *value* field is used for this purpose. The *unit* field is an optional argument where the user could specify the unit of the parameter. It is highly recommended to provide the unit for all parameters to avoid unit conversion mistakes (e.g., using q_c in MPa in a method that requires q_c in kPa). Lower and upper bounds could be applied to parameters through the *constraints* field. Any computed value lower than the lower bound or higher than the upper bound would be discarded for the given parameter. The *description* field is an optional argument, where the user could define the parameter (e.g., OCR is the overconsolidation ratio).

By formulating the two CSV files (methods and parameters) as described, the system imports the two files and forms links between the methods and parameters (*parameters_in* & *parameters_out*) that are related together. The output of this procedure is a graph showing the links between all the defined parameters and methods. Moreover, the computed values for different parameters are shown on the graph. The current version of APD contains more than 100 methods.

3 SELECTED CPT FINE-GRAINED SOIL CORRELATIONS

A standard validated database for methods and parameters has been compiled and is continuously updated and improved. However, users are responsible for validating the outcome of the system, even if they used the provided standard database. Users still need to apply their geotechnical experience and knowledge to the outcome. Nevertheless with limited geotechnical knowledge, the system should result in reasonable values for different parameters. In this section, some methods for different fine-grained soil parameters are presented. These methods and parameters are used to generate the graph in the following section.

3.1 *Unit weight*

The calculation of the total unit weight (γ_t) is required to compute the total and effective vertical stress, that are important in many correlations between CPT results and soil parameters. The selected correlations for estimating the unit weight in the APD system are:

- $\gamma_t = \gamma_w[0.27[\log R_f] + 0.36[\log(q_t/p_a)] + 1.236]$ (1)

by Robertson & Cabal (2010), where γ_w is the unit weight of water and q_t is the corrected cone resistance (defined as $q_t = q_c + (1 - a) \times u_2$, where a is the cone tip net area ratio).

- $\gamma_t = 19 - 4.12\left[\frac{\log(\frac{5}{q_t})}{\log(\frac{30}{R_f})}\right]$ (2)

by Lengkeek, de Greef, & Joosten (2018).

- $\gamma_t = 26 - \frac{14}{1 + [0.5\log f_s + 1]^2}$ (3)

by Mayne (2014).

3.2 *Stress history*

The stress history is often represented by the overconsolidation ratio ($OCR = \frac{\sigma_p'}{\sigma_v'}$, where σ_p' is the preconsolidation stress and σ_v' is the effective vertical stress). The selected correlations for estimating OCR in the APD system are:

- $OCR = \frac{\sigma_p'}{\sigma_v'} = \frac{0.33(q_t - \sigma_v)^{m'}}{\sigma_v'}$ (4)

by Mayne et al. (2009), where σ_v is the total vertical stress and m' is the yield stress exponent that increases with fines content and decreases with mean grain size. Mayne (2017) proposed determining m' from CPT material index I_c as follows:

– $m' = 1 - \frac{0.28}{1+(\frac{8I_c}{2.65})^{25}}$, where I_c is determined by an iterative process Robertson (2009) based on normalized cone parameter (Q_{tn}) with variable stress exponent (n) that varies with I_c).

- $OCR = 0.33 \times Q_{tn}$ (5)

by Kulhawy & Mayne (1990) and Robertson (2009), where:

– $Q_{tn} = \frac{q_t - \sigma_v}{p_a} / (\frac{p_a}{\sigma_v'})^n$, where p_a is in the same units as q_t and σ_v

– $n = 0.381(I_c) + 0.05(\frac{\sigma_v'}{p_a}) - 0.15 \leq 1.0$

– $I_c = \sqrt{(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2}$

3.3 *Strength parameters*

The following correlation is used to determine the effective friction angle (ϕ') in the APD system:

$$\phi' = 29.5B_q^{0.121}(0.256 + 0.336B_q + \log(Q_t)) \quad (6)$$

by Mayne et al. (2009), where B_q is the normalized porewater pressure ($B_q = (u_2 - u_0)/(q_t - \sigma_v)$) and Q_t is the normalized cone resistance ($Q_t = \frac{q_t - \sigma_v}{\sigma_v'}$). The valid range for this correlation is $0.1 \leq B_q \leq 1.0$ and $20 \leq \phi' \leq 45$.

3.4 *Stiffness parameters*

The 1-D constrained tangent modulus, M is used to estimate settlements. The following correlation is used to determine the constrained modulus in the APD system:

$$M = \alpha_M(q_t - \sigma_v) \quad (7)$$

Robertson (2009) suggested an approach based on I_c to determine α_M as follows:

- When $I_c > 2.2$:
  $\alpha_M = Q_{tn}$ (if $Q_{tn} < 14$)
  $\alpha_M = 14$ (if $Q_{tn} > 14$)

- When $I_c < 2.2$:
  $\alpha_M = 0.03[10^{(0.55I_c+1.68)}]$

4 DETERMINING FINE-GRAINED SOIL PARAMETERS

In this section, an example of the output of the system is presented. The methods CSV file used for this example, contains the correlations presented in the previous section, as well as other formulas used to compute some intermediate parameters (e.g., methods to calculate q_t,B_q,R_f,Q_t). The parameters CSV file includes all the parameters defined in the methods CSV file.

The system imported a CPT GEF file and determined the SBT at each depth. The interpreted SBT at each depth is shown in Figure 3. For generating the graph, a CPT measurement at a depth of 10 m ($z = 10$ m) was chosen (Figure 3). This measurement has the following properties, $q_c = 1015.5\ kPa$, $f_s = 31.5\ kPa$ and $u_2 = 351.6\ kPa$. The ground water level (GWL) is located at 6 m below the ground level. The cone tip net area ratio is provided in the CPT GEF file as 0.85 ($a = 0.85$).

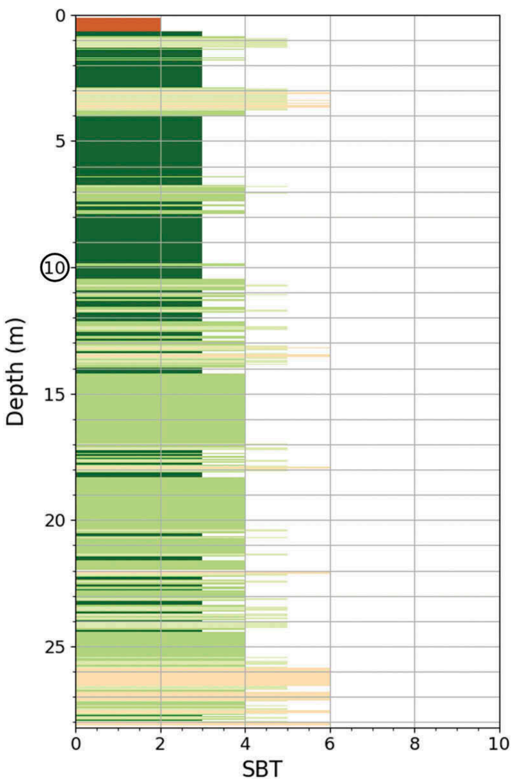

Figure 3. Interpreted SBT at each depth.

The unit weight of water (gamma_w) is defined as 10 kN/m^3. The atmospheric pressure (p_a) corresponds to 100 kPa. The interpreted SBT is 3, therefore, the soil type at this depth is clay (according to Table 1). The generated graph is shown in Figure 4.

The graph consists of green and blue nodes. The green nodes correspond to parameters, while the blue nodes correspond to methods. The arrows between different nodes, show the link between different entities (parameters and methods) within the system. The arrows have a defined direction (going from a parameter to a method or from a method to a parameter).

Focusing on the unit weight of the soil (gamma_sat located at the lower left corner in Figure 4), it is clear that three methods contribute to gamma_sat. The methods correspond to the three correlations presented in the previous section, where method_to_gamma_sat_1 is Equation 1, method_to_gamma_sat_2 is Equation 2 and method_to_gamma_sat_3 is Equation 3. Three values were computed respectively as, 17.33, 16.25 and 17.09 kN/m^3. Moving to OCR (located at the lower right corner in Figure 4), two methods contribute to OCR, where method_to_OCR_1 corresponds to Equation (4) and method_to_OCR_2 corresponds to Equation (5). Two values were computed respectively as 2.14 and 2.18. The friction angle (phip located at the lower part in Figure 4) is obtained by only one method (method_to_phip) corresponding to Equation (6). The friction angle was computed as 30.99. Similar to the friction angle, the constrained modulus (M_CPT located at the right-hand side of the graph in Figure 4) is obtained by only one method (method_to_MCPT) corresponding to Equation 7. The constrained modulus was computed as 5903 kPa.

As discussed in Equation 4, I_c, Q_{tn} and n are determined through an iterative process. This iterative process requires the knowledge of the total and effective vertical stress. As a result, an initial

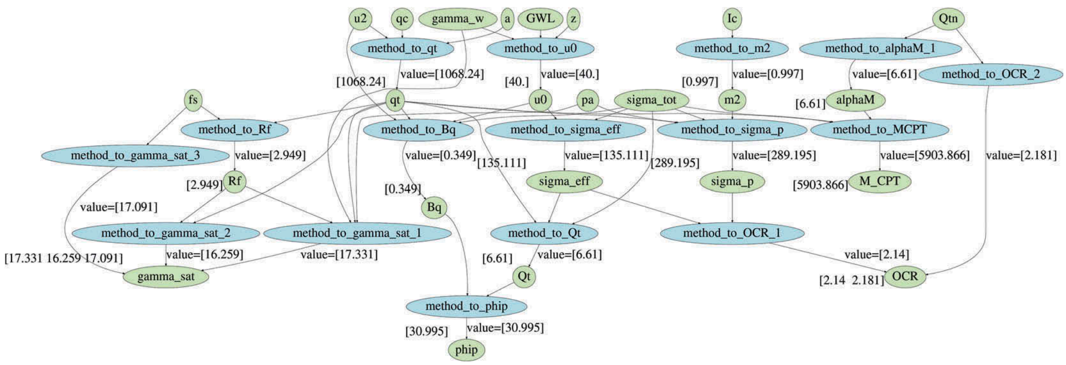

Figure 4. An example of a graph.

estimate for the unit weight is required to compute these parameters. In that sense, Equation 1 is used to compute an initial value for the unit weight, which in turn, is used to calculate the total stress (sigma_tot in Figure 4), effective stress, I_c, Q_{tn} and n. Consequently, it might be noticed from Figure 4 that Q_{tn} and I_c (located at the top right corner in 4) are used directly as source parameters because they were calculated in a previous step internally before the graph was generated. Therefore, Equations 2 and 3 are only used to compute gamma_sat for comparison purposes and they do not influence the calculation of the total and effective stress. As the system is formulated in an adaptable way, the user can decide which correlation for the unit weight to be used for the initial estimate for the total, effective stress and for the calculation of I_c, Q_{tn} and n.

5 CONCLUSIONS

This paper is an extension to the automated parameter determination system presented in Van Berkom et al. (2022). The previous section presented proof of concept where a graph-based approach was used to calculate parameters for fine-grained soil. The presented system is transparent, flexible, and adaptable where the users can incorporate their experience and knowledge into the system by extending the standard database of methods and parameters provided with the system. The research project aims to increase the confidence in the parameters values (required to perform numerical analysis) determined from in-situ tests.

Figure 4 presented a simple example where a limited number of methods were used. In case of using several methods, this will lead to a scatter for the computed parameters. Dealing with this scatter and determining which approach is more suitable for choosing a specific value from the range of the computed values is part of an ongoing research. In addition, other SBT charts (e.g., Robertson (2009)) normalized SBTn chart and Robertson (2016) SBT chart) are added to the system. Moreover, the compiled correlations database is continuously validated, updated and the output of different correlations is compared to laboratory tests results whenever they are available. Correlations for calculating typical fine-grained soil parameters (e.g., plasticity index, *PI*, liquid limit, *LL*, compression index, C_c and swelling index, C_s) were also added to the database. Furthermore, the connection between soil parameters and constitutive model parameters is to be established. The database includes several correlations between soil parameters and Plaxis Hardening Soil model with small-strain stiffness (HSsmall) (Benz (2007)). This is one of the main aspects of the research project as it will allow the transition from the CPT measurements to constitutive model parameters that could be used directly for numerical analysis.

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