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Expansion of an automated system for determining soil parameters using in-situ tests

I. Marzouk[1], F. Tschuchnigg[1], R.B.J. Brinkgreve[2]

[1]*Graz University of Technology, Graz, Austria*
[2]*Delft University of Technology, Delft, The Netherlands*

ABSTRACT: An ongoing research project aims to create an automated parameter determination (APD) framework relying on a graph-based approach for determining constitutive model parameters from in-situ tests. The system requires two spreadsheets as inputs. One spreadsheet defines the parameters, while the other spreadsheet specifies the correlations. The system connects parameters and methods by generating paths between them and calculates the value(s) for different parameters. So far, the framework focused on determining soil parameters based on the cone penetration test (CPT). This paper focuses on expanding the framework by adding the dilatometer test (DMT). A new database of correlations for the DMT is compiled. The expanded APD framework successfully calculates soil parameters for coarse and fine-grained soils based on CPT as well as DMT data. Validating the output of the system, assessing the accuracy of the derived parameters, and connecting soil parameters to constitutive model parameters are part of ongoing research.

Keywords: automated parameter determination; in-situ testing; graph theory; soil parameters; DMT

1 INTRODUCTION

Soil constitutive models developed significantly over years, where more advanced models can capture the soil behaviour much better compared to simple ones. Nevertheless, the more advanced the model, the more parameters are required. Determining those parameters accurately is one of the key factors in the success of numerical analyses. Very often these parameters need to be determined based on laboratory tests (e.g., triaxial and oedometer tests) which might not always be available in all projects (especially in early design stages).

In-situ tests offer an alternative way for determining soil parameters. When compared to laboratory testing, in-situ tests are faster, cheaper and introduce small disturbance during the execution of the test. On the other hand, it is not possible to assess soil parameters directly from in-situ measurements. As an alternative, several empirical correlations have been developed to connect in-situ measurements to soil parameters. However, for a given parameter, various number of correlations exist which leads to a scatter when comparing the obtained results. The reason for the scatter is accredited to the applicability of the correlations. Some correlations are only valid for specific soil types while others are only valid for specific conditions (e.g., overconsolidation ratio). In literature, several guides are available dealing with the interpretation of in-situ tests such Marchetti et al. (2001) for the dilatometer test (DMT). One attempt to determine constitutive model parameters based on very limited soil data has been presented by Brinkgreve et al. (2010) where the Hardening Soil Small Model (HSsmall) (Benz 2007) parameters were assessed only by using the relative density.

An ongoing research project aims to formulate an automated parameter determination (APD) framework to determine constitutive model parameters based on in-situ tests. The parameters are evaluated based on a graph-based approach that inherits some of the characteristics of graph theory (van Berkom et al. 2022). The goal of the project is to create a parameter determination system which is characterized by transparency and adaptability. The former is ensured by illustrating how the parameters are assessed based on the available information, while the latter is achieved by allowing the users to incorporate their expertise (e.g., developed correlations) into the system.

The framework and an example for determining parameters for coarse-grained soils is illustrated in van Berkom et al. (2022). Afterwards, the system was extended and parameters were determined for fine-grained soils in Marzouk et al. (2022). So far, the system was only able to determine soil parameters based on CPT. This paper presents another extension to the framework, where an additional in-situ test, namely the DMT is added to the system. This extension is used to derive some soil parameters based on selected correlations and the output is compared to reference values (laboratory test data). This study is based on Onsøy soft clay site which is part of the Norwegian GeoTest Sites (NGTS) (L’Heureux and Lunne 2020).

2 AUTOMATED PARAMETER DETERMINATION FRAMEWORK EXTENSION

The APD system is built in the programming language Python. As illustrated in Marzouk et al. (2022), the framework consists of several modules connected together to compute the parameters from CPT. Determining parameters from DMT follows the same definition. Firstly, DMT raw data is imported by the DMT reader (1st module). Afterwards, DMT measurements are transferred to the 2nd module (DMT layer interpretation), where layers are identified. CPT layer interpretation is based on one of Robertson's soil behaviour type (SBT) charts (Robertson 2009, 2010, 2016), where SBT is determined at each CPT measurement and measurements are grouped together into layers. Following the same definition, Marchetti's chart (Marchetti and Crapps 1981) for estimating the soil type is used to determine SBT at each DMT measurement. Marchetti's chart is divided into 4 different zones, mud/peat (SBT 1), clay (SBT 2), silt (SBT 3), and sand (SBT 4) as shown in Figure 1.

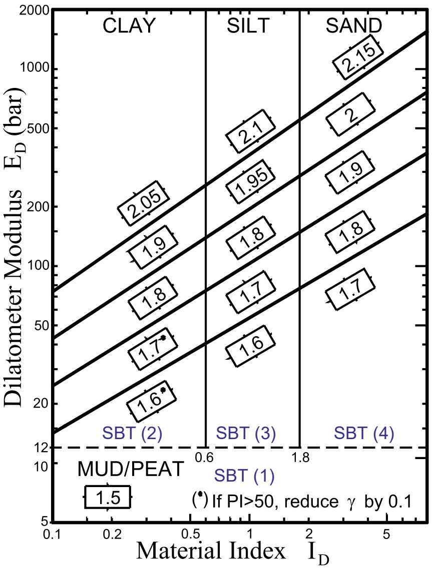

Figure 1. Marchetti's chart (unit weight is normalized to the unit weight of water γ_w) (Marchetti and Crapps 1981)

After determining the SBT at each DMT measurement, the DMT profile is stratified into layers sharing the same SBT. The stratification could be carried out manually by the users of the system where they specify the boundaries of the layers or by the implemented stratification algorithms. In this study, manual stratification of the DMT profile was carried out. Consequently, the stratification algorithms are out of scope of this paper.

In the next step, DMT measurements are averaged for each layer. Module 3 (Layer state) assesses the state (overconsolidation ratio OCR and coefficient of earth pressure K_0) of each layer based on the averaged DMT measurements. Module 4 (Graph-based approach) imports the output of the 2nd and 3rd modules and calculates soil parameters using the correlations provided by the user. Soil parameters computed in module 4 are transferred to module 5 (Constitutive model parameters) and constitutive model parameters are determined. As this study focuses on soil parameters (output of module 4), the transition to constitutive model parameters (module 5) is not considered.

2.1 Graph-based approach

Van Berkom et al. (2022) illustrated the graph-based approach implemented in APD in detail. An example of the generated graph is shown in Figure 2, where source parameters are connected to destination parameters (soil/constitutive model parameters) through intermediate parameters. This connection is created based on the given set of correlations. All paths (chains of correlations) that connect source parameters to destination parameters are created by the system. Moreover, the value(s) of the destination parameters are calculated.

As there are several ways to determine parameters (e.g., tables or charts), in the framework of APD the general term 'method' replaces the terms of 'correlation', 'formula', 'equation', 'rule of thumb' (van Berkom et al. 2022). The system creates paths between methods and parameters sharing a relationship. This relationship is defined based on the input(s) and output of the method.

Methods and parameters are external inputs to the system. They are defined separately in two spreadsheets in comma-separated values (CSV) format. A database of methods and parameters is provided with the system. Nevertheless, users can apply modifications to the provided database. The system imports the two spreadsheets and generates the links connecting different methods and parameters and computes the value(s) of intermediate and destination parameters (as shown exemplary in Figure 2).

The CSV files need to be defined following a specified format. Each column in both files correspond to a special property that defines the method or the parameter. The format of both files is illustrated in detail in Marzouk et al. (2022). The current version of APD (CPT and DMT) consists of more than 150 methods.

3 TEST SITE

"Datamap" is a web application that has been created to collect and classify geotechnical data in an organized manner. It is a platform that aims to make geotechnical data available and give researchers the opportunity to create and share their projects. It can be accessed through www.geocalcs.com/datamap (Doherty et al. 2018). The data from the NGTS soft clay site discussed in Section 3.1 is available at Datamap.

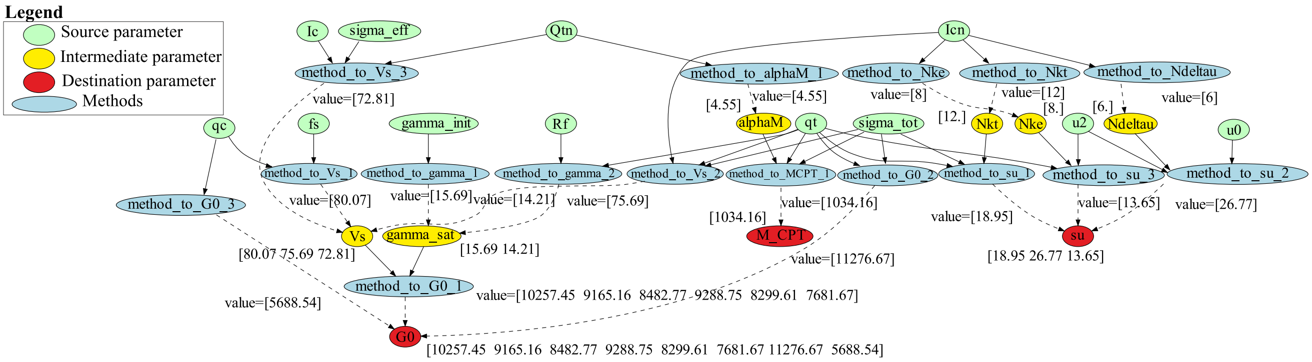

Figure 2. Example for a generated graph for a CPTu test.

3.1 *NGTS soft clay site*

The soft clay site located in Onsøy was established in 2016. An extensive testing program including both laboratory and field testing has been executed and is illustrated in detail in NGI's report (Norwegian Geotechnical Institute 2019).

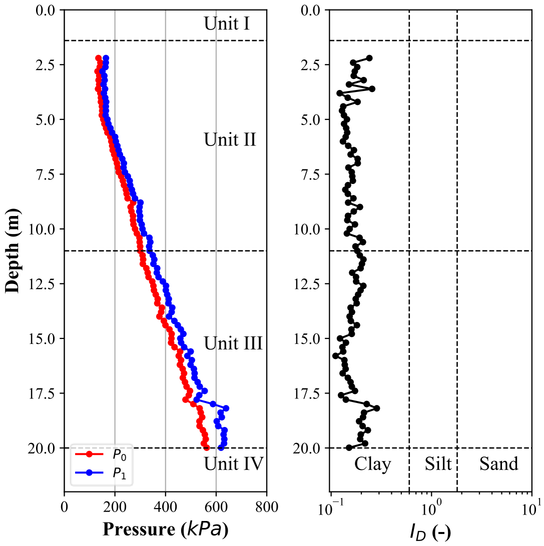

Figure 3. DMT results

The test site consisted of two main testing areas, namely south-central area (SC) and southeast corner area (SEC). The groundwater level was located 1 m below the ground surface. The test site was stratified into four units (Gundersen et al. 2019). Unit I is characterized as weathered clay, while Unit II consisted of clay of high to very high plasticity index (around 44%). Unit III is described as clay of medium high plasticity index (around 27%), while Unit IV has similar properties as Unit II except the fact that plasticity index, water content and clay content decreases towards the bedrock. The main difference between the two testing areas lies in the thickness of those individual units. As the SDMT was executed in the SEC area, only the results of SEC area are presented in this paper. The thickness of Units I, II and III in the SEC area are 1 m, 9.5 m and 5.5 m respectively (Gundersen et al. 2019). Figure 3 shows the DMT sounding in terms of corrected first and second readings (p_0 and p_1 respectively) with the associated DMT material index (I_D). The measurements lie entirely within Units II and III. The boundaries of the individual units are presented by the black dotted horizontal lines in Figure 3. This DMT was imported by the APD system to determine soil parameters and the computed values were compared with laboratory results.

4 DMT INTERPRETATION

The database that is provided alongside APD is continuously improved and updated. Nevertheless, it is the responsibility of the users to validate the outcome of the system, even if the provided database is used. Experience and knowledge of the users should be applied to the output of the system. Nonetheless, with minimum experience in geotechnical engineering, the system should result in reliable values for all parameters. Using all of the methods in the database will lead to a wide scatter in the obtained values, which will make the representation of the results challenging. Consequently, in this study, graphs are only created based on a selected number of methods that are presented in the following subsections to simplify the representation of the results (Section 5).

4.1 *Initial parameters*

The intermediate DMT parameters are required to use Marchetti's soil type and unit weight chart (Marchetti and Crapps 1981) and to compute other parameters. The material index I_D is defined as follows:

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \tag{1}$$

where u_0 is the in-situ porewater pressure. The measured ground water level (GWL) is used to calculate u_0.

The dilatometer modulus E_D is calculated as follows:

$$E_D = 34.7(p_1 - p_0) \tag{2}$$

Initial estimation of the unit weight is necessary to calculate the total (σ_v) and effective (σ_v') stresses, that are required to compute other parameters (e.g., horizontal stress index K_D). As a result, the value of the unit weight should be determined as a first step. The unit weight could be determined from Marchetti's chart (Figure 1) or from one of the following methods:

$$\gamma_t \text{ (from Figure 1)} \tag{3}$$

$$\gamma_t = \gamma_w * 1.32 \left(\frac{p_1}{p_a}\right)^{0.091} \left(\frac{p_0}{p_a}\right)^{0.0733} \tag{4}$$

$$\gamma_t = \gamma_w * 1.47 \left(\frac{E_D}{p_a}\right)^{0.045} \tag{5}$$

where p_a is the atmospheric pressure. However, Equations (4-5) are only valid for clay (Ozer et al. 2012).

In this study, the unit weight from Marchetti's chart was used to calculate the total and effective stresses. A comparison between the three methods is provided in Section 5.

The horizontal stress index K_D is calculated as follows:

$$K_D = \frac{p_0 - u_0}{\sigma_v'} \tag{6}$$

4.2 Stress history

Very often, the stress history is defined based on the overconsolidation ratio (OCR = σ_p'/σ_v'), where σ_p' is the vertical preconsolidation stress. The following three methods were used to determine OCR:

$$OCR = (0.5\ K_D)^{1.56} \tag{7}$$

by Marchetti (1980) for cohesive soils characterized by 0.2 < I_D < 2.

$$OCR = 2 \left(\frac{p_0 - \sigma_v}{6.63\ \sigma_v'}\right)^{1.19} \tag{8}$$

by Cao et al. (2016) for normally to overconsolidated clay (OCR ≥1).

$$OCR = 0.24\ K_D^{1.32} \tag{9}$$

by Powell and Uglow (1989) for clays.

4.3 Stiffness parameters

The 1-D constrained tangent modulus, M is often used to estimate settlements. The following method by Marchetti (1980) is used:

$$M = R_M\ E_D \tag{10 a}$$

where R_M is a correction factor. R_M is obtained as follows (Marchetti et al. 2001):

For $I_D \leq 0.6$ $\quad R_M = 0.14 + 2.36 \log K_D \quad (10\ b)$
For $I_D \geq 3.0$ $\quad R_M = 0.5 + 2 \log K_D \quad (10\ c)$
For $0.6 < I_D < 3$ $\quad R_M = R_{M,o} + \left(2.5 - R_{M,o}\right) \log K_D \quad (10\ d)$
with $R_{M,o} = 0.14 + 0.15(I_D - 0.6)$
For $K_D > 10$ $\quad R_M = 0.32 + 2.18 \log K_D \quad (10\ e)$

R_M should always be greater than 0.85.

Small-strain shear modulus (G_0) is generally determined from the shear wave velocity (V_s). Alternatively, the following methods by Marchetti et al. (2008) could be used to compute G_0:

$$G_0 = 26.177\ K_D^{-1.0066} M_{DMT} \text{ for } I_D < 0.6 \tag{11 a}$$

$$G_0 = 15.686\ K_D^{-0.921} M_{DMT} \text{ for } 0.6 < I_D < 1.8 \tag{11 b}$$

$$G_0 = 4.6513\ K_D^{-0.7967} M_{DMT} \text{ for } I_D > 1.8 \tag{11 c}$$

Choo et al. (2019) suggested the following method for normally consolidated clays ($I_D < 0.6, K_D \approx 2$) to estimate G_0:

$$G_0 = 2.97 * \left(\frac{1}{I_D}\right) \left(\frac{p_a}{\sigma_v'}\right)^{\frac{2}{3}} M_{DMT} \tag{12}$$

4.4 Strength parameters

The undrained shear strength (s_u) could be obtained from DMT results using the following methods:

$$s_u = 0.12(p_0 - \sigma_v) \tag{13}$$

by Cao et al. (2016) for normally to overconsolidated clay (OCR ≥1).

$$s_u = 0.22\sigma_v'(0.5\ K_D)^{1.25} \tag{14}$$

by S. Marchetti (1980).

$$s_u = 0.018\ E_D \tag{15}$$

by Kamei and Iwasaki (1995).

Soil parameters were determined using the methods presented in the previous subsections for the DMT (shown in Figure 3). In this contribution, DMT results were averaged every 1 m and these averaged values were used in the 2nd module (described in Section 2). As the layers were determined manually, the SBT for each layer must be provided by the user. In this case, SBT acts as a validity criterion for the methods CSV file. As the test site consists mainly of homogenous soft clay deposit, SBT(2) was selected for all layers. The averaging process resulted in 18 layers.

5 RESULTS

The output of different methods presented in Section 4 is compared with laboratory results as shown in Figure 4. The black dotted, horizontal lines denote the respective unit boundaries.

The total unit weight was determined based on direct measurements and from measured water contents (Gundersen et al. 2019). Figure 4(a) shows that Equation (3) underestimates the unit weight in Units II and III. While Equation (4) underestimates the unit weight in the top of Unit II, however a reasonable fit is obtained in the lower part of Units II and III. Equation (5) underestimates the unit weight in Unit III, nevertheless it provides a good estimate for Unit II. As mentioned in Section 4, Equation (3) was used for assessing the total and effective stresses.

OCR was assessed from oedometer tests (either from incremental loading (IL) tests or from constant rate of strain (CRS) tests). The quality of the tested samples was determined according to Lunne et al. (1997). Samples of quality class 1 and 2 are considered for the comparison as discussed in more detail in Gundersen et al. (2019), however in Figure 4(b) all samples results were added irrespective of their sample quality as there were only two soil specimens of high quality (at area SEC where the DMT was executed). Figure 4(b) shows that Equation (7) overestimates OCR. As OCR has a lower limit of 1, Equation (8) results in a nearly constant value of 1 which underestimates OCR. Equation (9) results in a good agreement with the laboratory values.

Janbu modulus concept was used to determine the constrained modulus (Gundersen et al. 2019). Figure 4(c) indicates an overall good agreement between Equation (10) and laboratory results.

Figure 4(d) presents G_0 assessed based on in-situ shear wave velocity measurements from 4 seismic cone penetration tests (SCPTu 7, 8, 18 and 23 (ONSC 7, 8, 18 & 23 in the database uploaded to Datamap)), and 1 seismic dilatometer test. Equation (11) underestimates G_0 in both units. Similarly, Equation (12) underestimates G_0 in Unit II, however, a good fit is obtained in the lower part of Unit III. These results shows that further investigation concerning the methods used to determine G_0 is required. It is part of ongoing research to add measured V_s data (including methods using V_s) to APD. This extension of APD will allow to have more reliable estimates of G_0.

Figure 4(e) shows the comparison for the undrained shear strength. s_u was derived based on triaxial compression tests (Gundersen et al. 2019). Equation (13) underestimates s_u especially in Unit III. Equation (14) provides a reasonable agreement to the laboratory results. Equation (15) results in a good fit to the laboratory results in Unit II, however in Unit III, s_u is underestimated at the top of the unit and overestimated at the lower part.

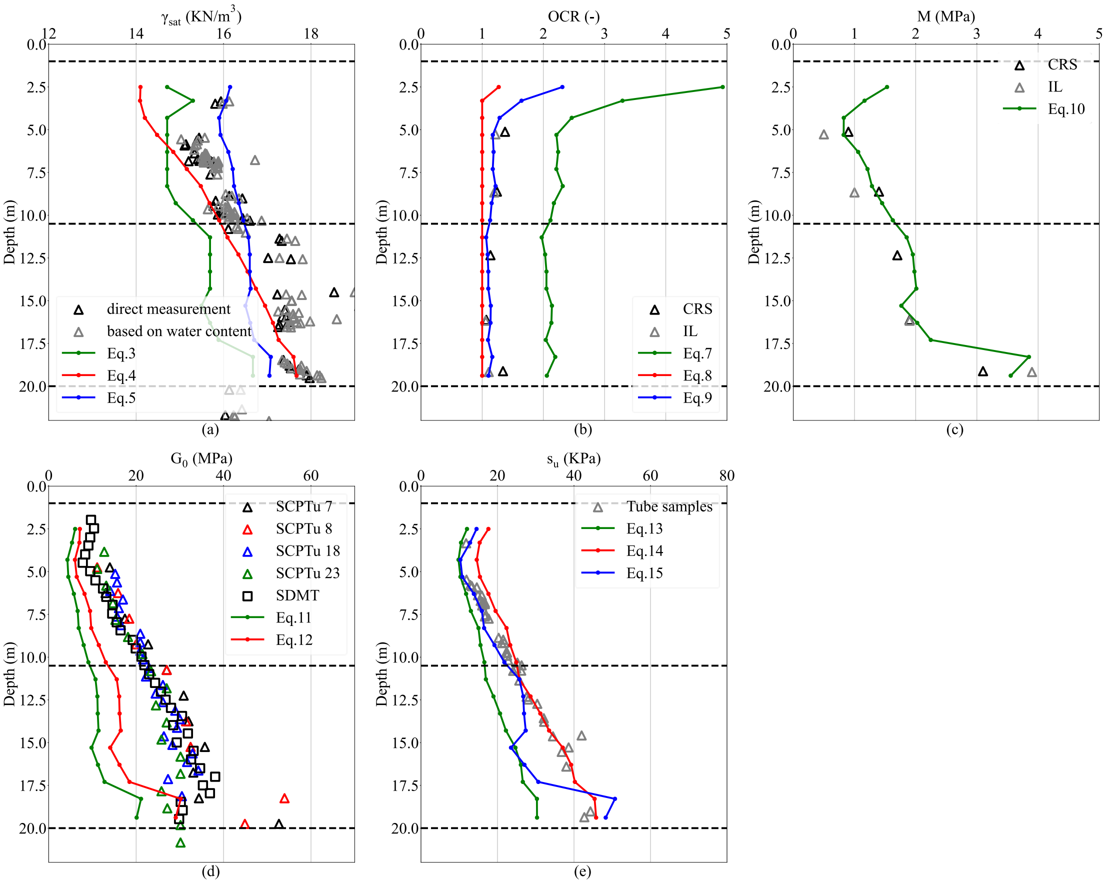

Figure 4. Comparison between APD and interpreted values at Onsøy soft clay site

6 CONCLUSIONS

In the present contribution, the expansion of the APD system by adding the DMT was illustrated. Furthermore, soil parameters were computed based on DMT and the output was compared with laboratory results at Onsøy soft clay test site (NGTS). Figure 4 shows that some methods perform better than others. In this study, selected number of methods were used. When all the methods in the database are selected, a wider scatter in the computed values is obtained (e.g., as shown in Figure 2, 11 different values for G_0 (lower left corner of the figure) were computed). The current version of APD consists of more than 150 methods. One of the current research activities is to deal with this scatter and to select an appropriate approach for choosing a specific value from the range of the computed values.

In this paper, the transition from soil parameters to constitutive model parameters was not performed. The database already includes several methods for computing parameters for some constitutive models such as the Hardening Soil Small Model (HSsmall) (Benz 2007). The above-mentioned transition is a key aspect of the research project.

Finally, it has to be pointed out that APD has two main characteristics, transparency and adaptability. Users of the system can integrate their knowledge and experience into the system. Updating, improving, validating and expanding the framework is part of ongoing research.

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