A combined approach to automated parameter determination (APD)

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ABSTRACT

The success of numerical analysis relies on several factors, with one crucial aspect being the accurate determination of constitutive model parameters. Extracting these parameters directly from in-situ tests has several advantages, such as cost-effectiveness and minimal soil disturbance. However, obtaining soil parameters directly from in-situ tests is not feasible, as empirical correlations are used to interpret them. An ongoing research project aims to create an automated parameter determination (APD) framework using a graph-based approach to determine constitutive model parameters from in-situ tests. The process involves using two spreadsheets as input: the first defines the parameters, while the second specifies the correlations used to compute them. The system then generates connections between the parameters and computes values for each one. The paper discusses the validation of the correlations database used by the system, which includes over 100 correlations for deriving parameters for various soil types. The framework determines parameters based on cone penetration tests (CPT), dilatometer tests (DMT), and in-situ shear wave velocity measurements. The system's output is compared to values interpreted from laboratory tests. To collect data for this validation, a web-based application "Datamap" was employed, which stores and categorizes geotechnical data. The validation process utilized data from the Norwegian GeoTest Sites (NGTS), specifically the NGTS-silt project. The parameters were calculated based on CPT, DMT, and in-situ shear wave velocity measurements. Ongoing research aims to evaluate the accuracy of the derived parameters and expand the system's capabilities to include additional in-situ tests.

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

1. Introduction

The development of soil constitutive models has led to advanced models that can simulate soil behaviour more accurately than simple models. However, one drawback of using advanced models in numerical analysis is the increased number of required parameters compared to simple models. Calibrating and determining these parameters requires laboratory tests, such as triaxial and oedometer tests. These tests may not always be available in all projects, especially in the early design phases.

An alternative method for determining soil parameters is by conducting in-situ tests. In-situ tests are relatively cheaper and faster than laboratory tests, and soil sampling is not required. However, it is not possible to assess the parameters directly from the results of in-situ tests. Therefore, several correlations have been developed over the years to link the in-situ measurements to different soil parameters. The existence of several correlations for a given parameter can result in a scatter in the obtained values. This scatter is mainly attributed to the applicability of the correlations. Some correlations are only valid for specific soil types, while others are only valid for specific site conditions, such as the overconsolidation ratio.

Several guides are available in literature for interpreting in-situ tests, such as (Kulhawy and Mayne 1990; Schnaid 2009), (Lunne et al. 1997; Mayne 2014; Robertson 2015) for cone penetration test (CPT), and (Marchetti et al. 2001) for dilatometer test (DMT). Other attempts to assess constitutive model parameters based on very limited soil data has been presented by Brinkgreve et al. (2010), where the parameters of the Hardening Soil Small Model (HSsmall) (Benz 2007) were determined by using only the relative density.

Automated parameter determination (APD) is an ongoing research project that aims to create a tool for determining constitutive model parameters based on in-situ tests. The parameters are determined using a graph-based approach that incorporates graph theory principles (Van Berkom et al. 2022; Marzouk et al. 2024). The project's primary objective is to establish a transparent and adaptable framework for parameter determination. The first objective is achieved by displaying how the parameters are computed based on the available information. The second objective is ensured by allowing the system users to incorporate their expertise, for example, by selecting the correlations.

Van Berkom et al. (2022) illustrated the framework and graph-based approach. The framework currently consists of three main workflows for determining parameters: CPT, DMT, and shear wave velocity measurements. The CPT-based workflow was used to determine soil parameters for one of the Norwegian GeoTest Sites (NGTS), a soft clay site in Marzouk et al. (2023a). While the DMT-based workflow was used to evaluate soil parameters for the same site in Marzouk et al. (2023b). This paper employs all three main workflows to evaluate soil parameters for the silt site of NGTS. The results are then compared to reference values.

2. Test site

2.1. Datamap

Datamap is a web application designed to collect, classify, and store geotechnical data in an organized manner. Its purpose is to make geotechnical data accessible and available to researchers, as well as to provide them with the opportunity to create and share their projects. It can be accessed through www.geocalcs.com/datamap (Doherty et al. 2018).

2.2. Norwegian GeoTest Sites (NGTS)

The Norwegian Geotechnical Institute (NGI), the Norwegian University of Science and Technology (NTNU), SINTEF Building and Infrastructure, the University Centre in Svalbard (UNIS), and the Norwegian Public Roads Administration (NPRA) established five GeoTest Sites (NGTS) in Norway between 2016 and 2019 (L'Heureux and Lunne 2020). Each site corresponds to a different soil type, including clay, silt, quick clay, sand and permafrost.

2.3. Halden silt site

Halden is situated in Southeastern Norway, around 120 km south of Oslo. It spans an area of approximately 6000 m² and has a predominantly flat topography. The site has been thoroughly characterized by combining the results of various geological, geophysical, and geotechnical site investigation tools (Blaker et al. 2019).

Based on the geological history of the site, there is no evidence of any loading events. Therefore, it can be inferred that the soil at the site is likely to be geologically normally consolidated, with the exception of some surface weathering, desiccation, and aging (Blaker et al. 2019).

The evaluation of soil stratification was based on geophysical, in-situ, and laboratory testing. Four soil units, numbered Unit I to Unit IV, were identified. Unit I extends to a depth of approximately 4.5 to 5 m and consists of medium dense silty, clayey sand with some organic material. Units II and III extend down to a depth of approximately 15 to 16 m. The material (Units II and III) is characterized as clayey silt and is separated into two units based on the results of in-situ tests. However, it is regarded as the same material with the same geologic origin. Unit IV contains low to medium strength clay. Bedrock is typically encountered at a depth of 21 m. The groundwater table is situated at a depth of approximately 2 m (Blaker et al. 2019).

Fig. 1. presents the in-situ tests selected as input for APD. The results of the selected CPTu (HALC 11 in the project) in terms of the corrected cone tip resistance (q_t), sleeve friction (f_s) and pore pressure measurements (u_2) are shown in Figs 1(a-c), while the results of the selected seismic dilatometer test (SDMT) (HALD01 in the project) in terms of the corrected pressure readings (P_0 and P_1) and shear wave velocity (v_s) are shown in Figs 1(d-e). The four different soil units are highlighted in the figure.

The selected CPTu had a 10 cm^2 compression cone with 150 cm^2 friction sleeve and the pore pressure transducer was located in the u_2 position. In Units II and III, the q_t plots at approximately 1 MPa. In the deeper parts of Unit III, q_t increases from 1 to 2 MPa (at around 16 m). P_0 and P_1 are scattered above 5 m. However, the results are more consistent in the silt and clay layers (Units I, III and IV). The profile of shear wave velocity was recorded at intervals of 0.5 m. The results indicate an increasing trend from approximately 110 m/s at a depth of 2 m to about 200 m/s at a depth of 16 m (Blaker et al. 2019).

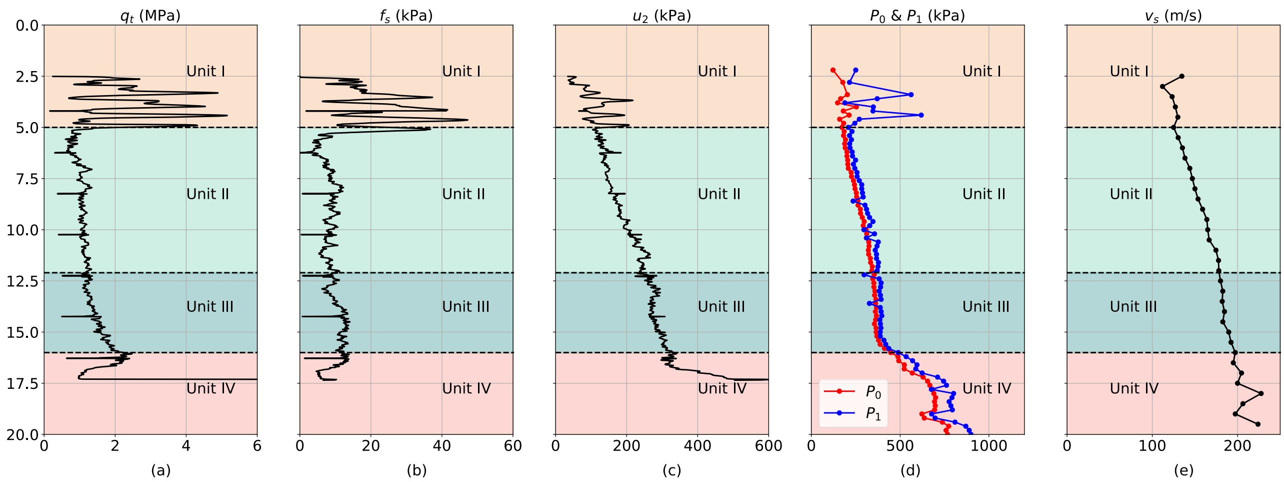

Figure 1. Results of selected in-situ tests, (a-c): CPT results (profiles of q_t, f_s and u_2), (d): DMT results (P_0 and P_1); (e): v_s profile from the SDMT.

3. Automated Parameter Determination (APD)

The framework of APD is discussed in detail in the following publications: Van Berkom et al. (2022), Marzouk et al. (2022), Marzouk et al. (2023a) and Marzouk et al. (2023b). In summary, the framework comprises several interconnected modules that link raw measurements to constitutive model parameters. The APD system is developed using the Python programming language.

Using the CPT-based workflow as an example, module 1 is a CPT reader, importing raw data for further interpretation. In the 2nd module, the stratification is carried out according to one of Robertson's soil behaviour type (SBT) charts (Robertson 2009; Robertson 2010; Robertson 2016). The stratification is achieved by one of the implemented stratification algorithms or manually by the user. The stratification algorithms are not discussed in this contribution as the stratification of the in-situ tests was carried out manually in this study. After evaluating the layers, the in-situ measurements are averaged to determine the representative value for each layer. The 3rd module utilises the averaged measurements to determine the state of the layer, specifically the overconsolidation ratio (OCR) and coefficient of earth pressure (K_0). The computed OCR and K_0 values can be considered as initial values at this stage, and their computation is based on correlations selected by the user. Module 4 is the primary module of the framework, implementing a graph-based approach to compute soil parameters using the outputs of modules 2 and 3. Similarly, module 5 assesses constitutive model parameters. This paper compares the computed soil parameters from module 4 to reference values at the test site, and therefore does not consider the transition to module 5.

The graphs are generated using the user's provided list of correlations. In accordance with APD terminology, the terms 'correlation', 'formula', 'equation', and 'rule of thumb' are replaced with the term 'method'. This term is chosen because there are multiple ways to determine the parameters. To generate the graph, two CSV files containing the methods (list of correlations) and parameters are required. The two files have a unique format that requires the definition of several properties. The file format is explained in more detail in the publications mentioned above. The system provides a standard database of over 100 methods and parameters. Users can modify, edit, and extend this database. The system generates links connecting methods and parameters and computes the value(s) of different parameters using the two CSV files.

The following three subsections discuss the main differences between the three primary workflows (CPT, DMT and shear wave velocity), as well as the initial parameters that need to be computed before accessing the graph-based approach (module 4).

3.1. CPT-based workflow

To determine the total (σ_v) and effective (σ_v') vertical stresses required for computing CPT parameters (e.g., normalized cone resistance), an initial estimate of the unit weight is necessary. Therefore, it is crucial to determine the unit weight at an early stage. Subsection 4.1 discusses the methods for determining the unit weight.

In addition to the initial unit weight, some normalized CPT parameters are computed such as the pore pressure parameter ratio (B_q), normalized cone resistance corrected for stress level (Q_{tn}). The definition of these CPT parameters is illustrated in several CPT guides, such as Robertson (2015).

The initial parameters mentioned above, including the initial unit weight, do not need to be defined in the methods CSV file. The system calculates them internally and they act as source parameters, similar to CPT raw data.

The validity of CPT methods for different parameters is determined based on the SBT of Robertson's 2010 SBT chart, as presented in Table 1. For instance, if a method is only applicable to sands, it is assigned a validity of SBT(567). This approach enables the system to distinguish between methods suitable for fine-grained and coarse-grained soils.

Table 1. Definition of SBT 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)

3.2. DMT-based workflow

Similar to the CPT-based workflow, some initial DMT parameters are needed (e.g., to use Marchetti's soil type and unit weight chart). Additionally, an initial estimate of the unit weight is necessary to calculate the total and effective stresses. Subsection 4.1 discusses the methods for determining the unit weight. The DMT parameters are calculated as follows:

- Material index

$$I_D = \frac{P_1 - P_0}{P_0 - u_0} \quad (1)$$

- Dilatometer modulus

$$E_D = 34.7(P_1 - P_0) \quad (2)$$

- Horizontal stress index

$$K_D = \frac{p_0 - u_0}{\sigma'_v} \quad (3)$$

The validity of DMT methods for different parameters is determined based on Marchetti's chart, as presented in Table 2. For instance, if a method is only applicable to clays, it is assigned a validity of SBT(2).

Table 2. DMT SBT according to Marchetti's chart (Marchetti and Crapps 1981).

Zone	Soil Behaviour Type (SBT)
1	Mud / Peat
2	Clay
3	Silt
4	Sand

3.3. Shear wave velocity-based workflow

The motivation of implementing the shear wave velocity-based workflow is to accurately determine the small-strain shear modulus (G_0). Previous experience has shown that correlations of shear wave velocity are prone to uncertainties.

The main challenge in implementing the shear wave velocity-based workflow within the APD framework lies in the stratification. APD computes parameters based on layers, while in-situ shear wave velocity measurements are recorded in larger intervals (0.5 to 1 m) compared to CPT (1 or 2 cm) and DMT (20 cm). This may result in layers without v_s measurements, thus the workflow would be unusable for the entire analysis. To overcome this limitation, several approaches are currently being considered. Machine learning models could be used to predict additional shear wave velocity points, thereby filling in the missing data. Alternatively, a site-specific approach could be employed, where several CPT v_s correlations are compared to the in-situ shear wave velocity profile and the correlation with the least error is selected to predict the missing points. These approaches are still under investigation and are not considered in this contribution. In this study, in-situ shear wave velocity measurements were available for all layers in the analysis.

4. Parameter interpretation

The unit weight (γ_t), undrained shear strength (s_u), constrained modulus (E_{oed}) and small-strain shear modulus (G_0) were assessed using the three different workflows (CPT, DMT and v_s). The methods chosen for these parameters, based on different in-situ tests, are presented in Table 3. It should be noted that there are many more methods available in the APD database. The methods presented in Table 3 have been selected to illustrate the workflow and show the potential of APD. Validating the output of the methods database by comparing it to reference values interpreted from laboratory tests is part of ongoing research. Additionally, a statistical module is currently in development to aid in selecting the representative value for different parameters.

4.1. Unit weight

As mentioned in subsection 3.1, an initial estimate of the unit weight is required to calculate the total and effective vertical stresses. Any method can be used to compute this initial value. Table 3 presents the methods selected to compute the unit weight for the three different workflows. In this study, Eq. (5) was used to compute the initial unit weight for the CPT workflow, while Eq. (8) was used for the DMT workflow. Since the v_s add-on is an extension of the CPT workflow, Eq. (5) is also used as the initial unit weight for the v_s workflow. This unit weight was also used for calculating σ'_v in Eqs. (14-15).

4.2. Strength parameters

Table 3 also presents the selected methods used to determine the undrained shear strength (s_u). Bearing factors for net tip resistance, excess porewater pressures, and effective cone resistance are denoted by N_{kt}, $N_{\Delta u}$, and N_{ke}, respectively, in Eqs. (17-19). Several researchers concluded the N_{kt} and N_{ke} vary inversely with B_q, while $N_{\Delta u}$ varies directly with B_q (Mayne et al. 2023).

4.3. Stiffness parameters

The 1-D constrained tangent modulus (E_{oed}) is often used to predict settlements. The methods selected for computing E_{oed} are presented in Table 3. The value of α_M for Eq. (28) is presented for the case of soil behaviour type index (I_{cn}) > 2.2 and $Q_{tn} < 14$, as all the layers evaluated for the CPT analysis had I_{cn} values greater than 2.2 and Q_{tn} less than 14. The correction factor R_M for Eq. (29) is presented for the case of $I_D \leq 0.6$, as all the layers evaluated for the DMT analysis had I_D less than 0.6. Similarly, the DMT correlation for the small-strain shear modulus (G_0) is presented in Eq. (40) for the case of $I_D \leq 0.6$.

5. Results

The previous subsection presented methods for determining soil parameters for the CPT and SDMT shown in Fig. 1. In this study, CPT and SDMT results were averaged every 1 m (manual layering), and these values were used as input for the analysis. The focus was solely on the geological Units II and III, where silt was encountered. The averaging process resulted in 11 layers for the CPT, DMT, and v_s profiles. A few measurements indicating that $P_1 < P_0$ for the DMT results were filtered out to avoid affecting the interpretation of the DMT parameters.

Performing DMT in silty soil can cause partial drainage due to the expansion of the DMT membrane, which can affect the DMT readings and lead to errors when deriving parameters using typical DMT correlations (Marchetti and Marchetti 2016). To correct for these effects, methods such as the one presented in Schnaid et al. (2018) can be used. However, it was not possible to correct the DMT readings for partial drainage effects due to the absence of time data for the DMT test conducted at this site.

Table 3. Selected Methods

Parameter	Workflow	Method		Author
γ_t	CPT	$\gamma_w\left[0.27\left(\log R_f\right)+0.36(\log q_t/p_a)+1.236\right]$	(4)*	Robertson and Cabal (2010)
		$19.5-2.87\left[\frac{\log(\frac{9000}{q_t})}{\log(\frac{20}{R_f})}\right]$	(5)	Lengkeek and Brinkgreve (2022)
		$26-\frac{14}{1+[0.5\log f_s+1]^2}$	(6)	Mayne (2014)
		$0.254.\log\left(\frac{q_t-u_2}{p_a}\right)+1.54$	(7)	Mayne et al. (2023)
	DMT	from Marchetti's chart	(8)	Marchetti and Crapps (1981)
		$\gamma_w.1.31\left(\frac{P_1}{p_a}\right)^{0.161}$	(9)	Ozer et al. (2012)
		$\gamma_w.1.35\left(\frac{P_0}{p_a}\right)^{0.159}$	(10)	Ozer et al. (2012)
		$\gamma_w.1.32\left(\frac{P_1}{p_a}\right)^{0.091}\left(\frac{P_0}{p_a}\right)^{0.0733}$	(11)	Ozer et al. (2012)
		$\gamma_w.1.47\left(\frac{E_D}{p_a}\right)^{0.045}$	(12)	Ozer et al. (2012)
	v_s	$8.31\log v_s-1.61\log z$	(13)	Mayne (2001)
		$4.17\ln v_{s1}-4.03$	(14)#	Mayne (2007)
		$\frac{6.87v_s^{0.227}}{\sigma_v'^{0.057}}$	(15)	Burns and Mayne (1996)
		$4.96+5.97\log v_s$	(16)	Duan et al. (2019)
s_u	CPT	$\frac{q_t-\sigma_v}{N_{kt}}$; $N_{kt}=10.5-4.6\ln(B_q+0.1)$	(17)	Mayne et al. (2023)
		$\frac{u_2-u_0}{N\Delta u}$; $N_{\Delta u}=7.9+6.5\ln(B_q+0.3)$	(18)	Mayne et al. (2023)
		$\frac{q_t-u_2}{N_{ke}}$; $N_{ke}=4.5-10.66\ln(B_q+0.2)$	(19)	Mayne et al. (2023)
	DMT	$0.12(P_0-\sigma_v)$	(20)	Cao et al. (2016)
		$0.09(P_1-\sigma_v)$	(21)	Cao et al. (2016)
		$0.22\sigma_v'(0.5K_D)^{1.25}$	(22)	Marchetti (1980)
		$0.018E_D$	(23)	Kamei and Iwasaki (1995)
		$0.35(0.47K_D)^{1.14}\sigma_v'$	(24)	Kamei and Iwasaki (1995)
	v_s	$0.152v_s^{1.142}$	(25)	Agaiby and Mayne (2015)
		$0.021v_s^{1.52}$	(26)	L'Heureux and Long (2017)
		$0.016v_s^{1.50}$	(27)	Duan et al. (2019)
E_{oed}	CPT	$\alpha_M(q_t-\sigma_v)$; $\alpha_M=Q_{tn}$; for $I_{cn}\geq 2.2$ & $Q_{tn}<14$	(28)	Robertson (2009)
	DMT	$R_M E_D$; for $I_D\leq 0.6$; $R_M=0.14+2.36\log K_D$	(29)	Marchetti (1980), (Marchetti et al. 2001)
		$R_M E_D$; for $I_D\leq 0.6$; $R_M=0.6\,I_D^{-0.8}$	(30)	Oberhollenzer (2022)
	v_s	$0.00010v_s^{2.212}$ (E_{oed} in MPa)	(31)	L'Heureux and Long (2017)
G_0	CPT	$v_s=(10.1\log q_c-11.4)^{1.67}(f_s/q_c\times 100)^{0.3}$	(32)	Hegazy and Mayne (1995)
		$v_s=3.18q_c^{0.549}f_s^{0.025}$	(33)	Hegazy and Mayne (1995)
		$v_s=[\alpha_{vs}(q_t-\sigma_v)/p_a]^{0.5}$; $\alpha_{vs}=10^{(0.55I_{cn}+1.68)}$	(34)	Robertson (2015)
		$v_s=1.75q_c^{0.627}$	(35)	Mayne and Rix (1995)
		$v_s=6.53(q_c-\sigma_v)^{0.461}$	(36)	Mayne and Rix (1995)
		$v_s=0.831Q_{tn}\left(\frac{\sigma_v'}{p_a}\right)^{0.25}e^{1.786I_{cn}}$	(37)	Hegazy and Mayne (2006)
		$2.78q_c^{1.335}$	(38)	Mayne and Rix (1993)
	DMT	$7.5\,E_D$	(39)	as mentioned in Tanaka and Tanaka (1998)
		$26.177K_D^{-1.0066}M_{DMT}$; for $I_D<0.6$	(40)	Marchetti et al. (2008)
		$2.97.\left(\frac{1}{I_D}\right).\left(\frac{P_a}{\sigma_v'}\right)^{2/3}.M_{DMT}$	(41)	Choo et al. (2019)
	v_s	ρv_s^2	(42)	

* R_f is the friction ratio ($R_f=f_s/q_c$ 100%), q_t is the corrected cone resistance and p_a is the atmospheric pressure

\# v_{s1} is the effective stress-normalized shear wave velocity ($v_{s1}=v_s/(\sigma_v'/p_a)^{0.25}$)

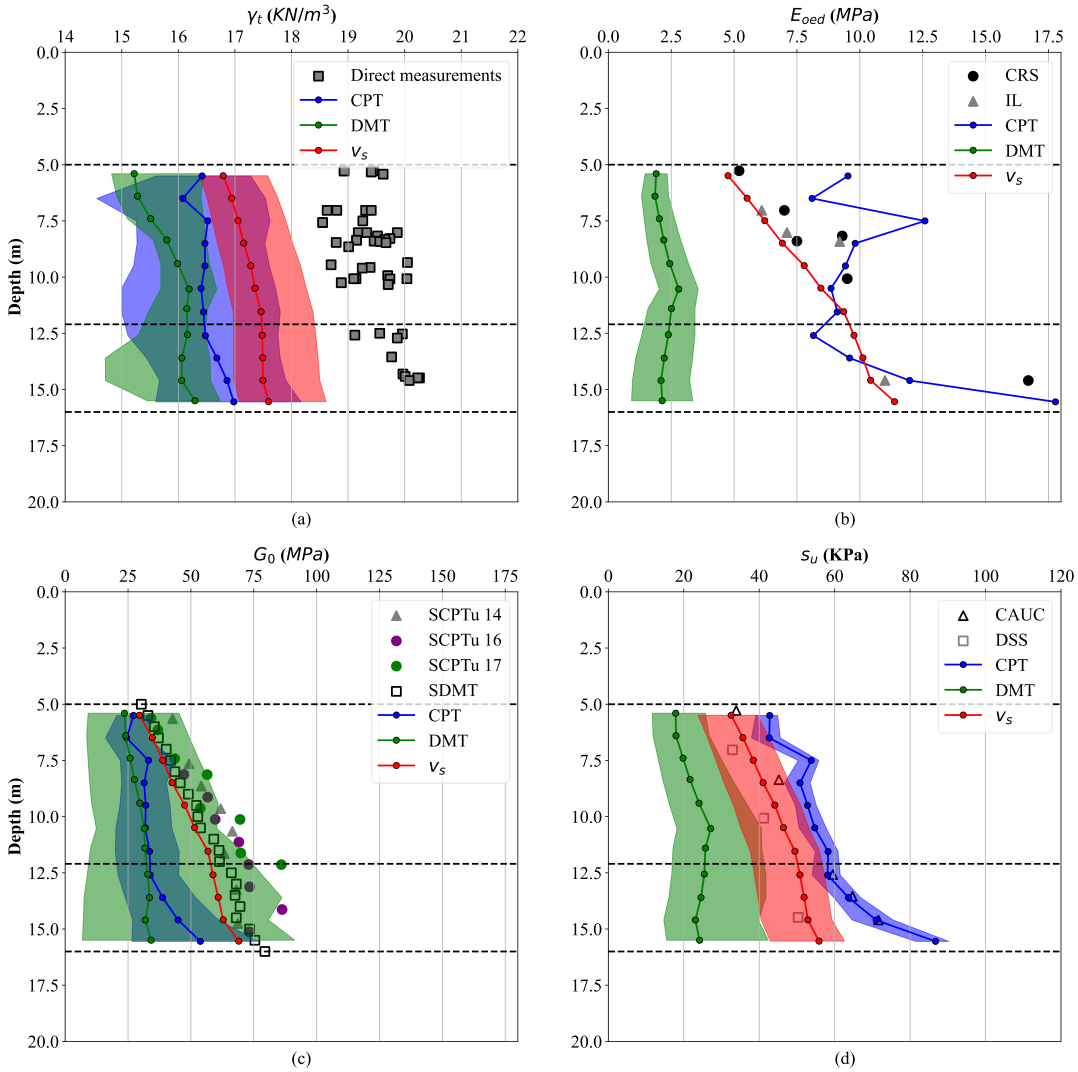

Figure 2. Comparison between APD and interpreted values at Halden silt test site.

The total unit weight was also assessed from direct measurements (Blaker et al. 2019). Fig. 2a displays the measured unit weights and the unit weights obtained from the three workflows. The blue, green, and red shaded areas represent the range of values obtained from the CPT, DMT, and v_s workflows, respectively. The blue, green, and red lines with circle markers correspond to the average value of the selected methods for the three workflows (CPT, DMT and v_s). The circle markers indicate the mid-depth of the 11 thin (1 m thick) layers. None of the selected methods were able to predict the measured unit weight. The methods used for the v_s-based workflow produced the highest values for γ_t. This indicates that caution should be exercised when determining unit weight from correlations.

E_{oed} was determined from oedometer tests, either from incremental loading (IL) tests or from constant rate of strain (CRS) tests. The tested samples were obtained from block samples (Blaker et al. 2019). Fig. 2b shows that the CPT and v_s-based workflows produce good to reasonable estimates for E_{oed}. However, E_{oed} obtained from the DMT-based workflow (using Eqs. (29-30) for R_M) underestimates the reference values in this particular case. This underestimation is most probably attributed to the partial drainage effects. One consequence of the partial drainage is that the difference between the two DMT readings is too low leading to low values of I_D and consequently E_{oed} (Marchetti and Marchetti 2016).

Reference G_0 values were assessed using several SCPTs and one SDMT. An approximate unit weight of 19 kN/m^3 and 20 kN/m^3 was used for Units II and III, respectively. The results are shown in Fig. 2c. The blue, green, and red shaded areas represent the range of values obtained from the CPT, DMT, and v_s workflows, respectively. It is evident that the v_s-based workflow output would provide the most accurate prediction of G_0. The difference between the v_s-based workflow output and the reference values interpreted from the SDMT is attributed to the unit weight used (Eq. (5). In general, the G_0 values obtained from the CPT-based workflow tend to underestimate the in-situ G_0 values. However, some CPT methods showed a reasonable fit at the top of Unit II and at the bottom of Unit III. Similar to the CPT-based workflow, most of the values obtained from the DMT-based workflow underestimate the reference G_0 values. However, the upper limit of the values shows reasonable agreement with the in-situ G_0 values. This confirms that it is recommended to use the v_s-based workflow to accurately determine G_0.

The "reference" s_u values were obtained from undrained anisotropically consolidated triaxial (CAUC) tests and direct shear (DSS) tests. All the reference values presented in Fig. 2d are derived from block samples (Blaker et al. 2019). The blue, green, and red shaded areas represent the range of values obtained from the CPT, DMT, and v_s workflows, respectively. The output of the CPT-based workflow is in reasonable agreement with the values interpreted from the CAUC tests. The values of s_u interpreted from the v_s-based workflow fall between the reference values from the CAUC and DSS tests. The upper limit of the values obtained from the DMT-based workflow corresponds with the values derived from the DSS tests in Unit II. However, in general, the values are underestimated.

The influence of the initial unit weight on the determined parameters was investigated by using representative values determined from laboratory tests for Units II and III. The predictions from the DMT-based workflow did not improve when representative unit weight values were used. This indicates that the underestimation of the values for different parameters is most likely due to the partial drainage effects.

To assess the OCR, it is necessary to reliably interpret the preconsolidation stress (σ_p') from oedometer tests. However, this can be challenging in silts such as the Halden silt. Despite this, the geological history of the test site area is well understood and indicates that the silt is normally consolidated (Blaker et al. 2019). The OCR values obtained from the DMT-based workflow indicate that both silt units are normally consolidated. However, the OCR values obtained from the CPT-based workflow suggest that they are slightly overconsolidated. This indicates that correlations for OCR in particular should be used with caution.

6. Conclusions

APD is a framework for determining parameters that relies on a graph-based approach to evaluate soil and constitutive model parameters based on in-situ tests. The main motivation is to provide assistance in the early stages of projects, especially when limited soil data is available. At this stage, "relatively inexpensive" in-situ tests, such as CPT and DMT, are executed prior to a full laboratory testing programme. The goal is not to substitute laboratory tests with in-situ tests. The final design will still require improvement of the soil and constitutive model parameters. This is because APD aims to automatically connect the determined parameters to finite element (FE) software for numerical analysis.

This study presents APD's predictions for four different soil parameters at a silt test site in Norway. Silts and other intermediate soils pose a challenge as they are difficult to sample, and less information is available for selecting appropriate values for engineering properties compared to sands or clays. Many methods used to predict parameters for silts were originally formulated for clays. This can increase uncertainty in the derived values for different parameters. Further research includes validation on sites with well-defined drainage conditions.

Fig. 2 displays the lower and upper bounds, along with the average, for the three workflows using selected methods. Using the average as a representative value for different parameters is questionable because it might take into account inaccurate methods. This is currently the biggest challenge due to the large number of methods and the wide range of values obtained. A statistical add-on is being developed to assist in selecting the representative value. However, apart from the unit weight, the obtained values align well with the reference values. Ongoing research includes automatically combining the results of the analysis of different APD workflows (CPT and DMT), performing analysis for other test sites, expanding the system by adding more in-situ tests, and validating the output.

References

Agaiby, S. S., Mayne, P. W. 2015. "Relationship Between Undrained Shear Strength And Shear Wave Velocity For Clays", In: Deformation Characteristics of Geomaterials, pp. 358–365. https://doi.org/10.3233/978-1-61499-601-9-358

Benz, T. 2007. "Small-strain stiffness of soils and its numerical consequences", Ph.D. thesis, Germany, University of Stuttgart.

Blaker, Ø., Carroll, R., Paniagua, P., J. DeGroot, D., L'Heureux, J.-S. 2019. "Halden research site: geotechnical characterization of a post glacial silt", AIMS Geosciences, Volume(5), (2), pp. 184–234. https://doi.org/10.3934/geosci.2019.2.184

Brinkgreve, R.B.J., Engin, E., Engin, H. K. 2010. "Validation of empirical formulas to derive model parameters for sands", NUMGE, Trondheim, Norway. CRC press, 137-142.

Burns, S., Mayne, P. 1996. "Small- and High-Strain Measurements of In Situ Soil Properties Using the Seismic Cone Penetrometer", Transportation Research Record: Journal of the Transportation Research Board, Volume(1548), pp. 81–88. https://doi.org/10.3141/1548-12

Cao, L. F., Peaker, S. M., Ahmad, S. 2016. "Use of Flat Dilatometer in Ontario", ISC'5 Conference.

Choo, H., Hong, S.-J., Lee, W.,Lee. 2019. "Use of the dilatometer test to estimate the maximum shear modulus of normally consolidated Busan clay", Marine Georesources & Geotechnology, Volume(37), (5), pp. 547–557. https://doi.org/10.1080/1064119X.2018.1458927

Doherty, J. P., Gourvenec, S., Gaone, F. M., Pineda, J. A., Kelly, R., O'Loughlin, C. D., Cassidy, M. J., Sloan, S. W. 2018. "A novel web based application for storing, managing and sharing geotechnical data, illustrated using the national soft soil field testing facility in Ballina, Australia", Computers and Geotechnics, Volume(93), pp. 3–8. https://doi.org/10.1016/j.compgeo.2017.05.007

Duan, W.,Cai, G.,Liu, S.,Puppala, A. J. 2019. "Correlations between Shear Wave Velocity and Geotechnical Parameters for Jiangsu Clays of China", Pure Appl. Geophys., Volume(176), (2), pp. 669–684. https://doi.org/10.1007/s00024-018-2011-x

Hegazy, Y. A., Mayne, P. 1995. "Statistical correlations between Vs and CPT data for different soil types".

Hegazy, Y. A., Mayne, P. 2006. "A Global Statistical Correlation between Shear Wave Velocity and Cone Penetration Data", pp. 243–248. https://doi.org/10.1061/40861(193)31

Kamei, T., Iwasaki, K. 1995. "Evaluation of Undrained Shear Strength of Cohesive Soils Using a Flat Dilatometer", Soils and Foundations, Volume(35), (2), pp. 111–116. https://doi.org/10.3208/sandf1972.35.2_111

Kulhawy, F. H., Mayne, P. 1990. "Manual on Estimating Soil Properties for Foundation Design.".

L'Heureux, J. S., Lunne, T. 2020. "Characterization and Engineering properties of Natural Soils used for Geotesting", AIMS Geosciences, Volume(6), (1), pp. 35–53. https://doi.org/10.3934/geosci.2020004

L'Heureux, J.-S., Long, M. 2017. "Relationship between Shear-Wave Velocity and Geotechnical Parameters for Norwegian Clays", J. Geotech. Geoenviron. Eng., Volume(143), (6), pp. 4017013. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001645

Lengkeek, H. J., Brinkgreve, R. 2022. "CPT-based unit weight estimation extended to soft organic clays and peat: An update", In: Cone Penetration Testing 2022, pp. 503–508. https://doi.org/10.1201/9781003308829-71

Lunne, T.,Robertson, P. K.,Powell, J. J. M. 1997. "Cone Penetration Testing in Geotechnical Practice", CRC Press, Boca Raton, FL.

Marchetti, S. 1980. "In Situ Tests by Flat Dilatometer", J. Geotech. Engrg. Div., Volume(106), (3), pp. 299–321. https://doi.org/10.1061/AJGEB6.0000934

Marchetti, S., Crapps, D. K. 1981. "Flat Dilatometer Manual".

Marchetti, S., Monaco, P.,Totani, G.,Calabrese, M. 2001. "The Flat Dilatometer Test (DMT) in Soil Investigations – A Report by the ISSMGE Committee TC16".

Marchetti, S., Monaco, P., Totani, G., Marchetti, D. 2008. "In Situ Tests by Seismic Dilatometer (SDMT)".

Marchetti, D. and Marchetti S. 2016. "Flat Dilatometer (DMT). Some Recent Advances." Procedia Engineering 158: 428–433. https://doi.org/10.1016/j.proeng.2016.08.467

Marzouk, I., Tschuchnigg, F., Paduli, F., Lengkeek, H. J., Brinkgreve, R.B.J. 2022. "Determination of fine-grained soil parameters using an automated system." In Cone Penetration Testing 2022, 540–45.

Marzouk, I., Oberhollenzer, S., Tschuchnigg, F. 2023a. "An automated system for determining soil parameters: Case study", Proceedings of the 8th International Symposium on Deformation Characteristics of Geomaterials, Porto.

Marzouk, I., Tschuchnigg, F., Brinkgreve, R. 2023b. "Expansion of an automated system for determining soil parameters using in-situ tests", Proceedings of the 10th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE 2023), London. https://doi.org/10.53243/NUMGE2023-70

Marzouk, I., Granitzer, A-N., Rauter, S., Tschuchnigg, F. 2024. "A Case Study on Advanced CPT Data Interpretation: From Stratification to Soil Parameters", Geotech Geol Eng. https://doi.org/10.1007/s10706-024-02774-9

Mayne, P. 2007. "In-Situ Test Calibrations for Evaluating Soil Parameters", In Characterisation and engineering properties of natural soils.

Mayne, P. 2014. "Interpretation of geotechnical parameters from seismic piezocone tests".

Mayne, P. W. 2001. "Stress-strain-strength-flow parameters from enhanced in situ tests", International conference on in situ measurement of soil properties & case histories.

Mayne, P. W., Rix, G. J. 1995. "Correlations Between Shear Wave Velocity and Cone Tip Resistance in Natural Clays", Soils and Foundations, Volume(35), (2), pp. 107–110. https://doi.org/10.3208/sandf1972.35.2_107

Mayne, P. W.,Cargil, E.,Greig, J. 2023. "A CPT Design Parameter Manual", ConeTec Group.

Mayne, P., Rix, G. J. 1993. "Gmax-qc Relationships for Clays", Geotech. Test. J., Volume(16), (1), pp. 54. https://doi.org/10.1520/GTJ10267J

Oberhollenzer, S. 2022. "Characterization of postglacial, fine-grained sediments by means of in-situ and laboratory testing", Ph.D. thesis, Austria, Graz University of Technology.

Ozer, A. T., Bartlett, S. F., Lawton, E. C. 2012. "CPTU and DMT for estimating soil unit weight of Lake Bonneville clay", Proceeding of the 2nd International Symposium on cone Penetration Testing, Huntington Beach (USA).

Robertson, P. K. 2009. "Interpretation of cone penetration tests — a unified approach", Can. Geotech. J., Volume(46), (11), pp. 1337–1355. https://doi.org/10.1139/T09-065

Robertson, P. K. 2010. "Soil Behaviour Type from the CPT: An Update", 2nd International Symposium on Cone Penetration Testing, Huntington Beach 2, pp. 575–583.

Robertson, P. K. 2015. "Guide to cone penetration testing for geotechnical engineering", Proceedings of the 3rd International Symposium on Cone Penetration Testing (CPT14, Las Vegas).

Robertson, P. K. 2016. "Cone penetration test (CPT)-based soil behaviour type (SBT) classification system — an update", Can. Geotech. J., Volume(53), (12), pp. 1910–1927. https://doi.org/10.1139/cgj-2016-0044

Robertson, P. K., Cabal, K. L. 2010. "Estimating soil unit weight from CPT".

Schnaid, F. 2009. "In situ testing in geomechanics", Taylor & Francis, London.

Schnaid, F., Belloli, M. V. A., Odebrecht, E., Marchetti, D. 2018. "Interpretation of the DMT in Silts." Geotechnical Testing Journal 41, no. 5: 868–76. https://doi.org/10.1520/GTJ20170374

Tanaka, H., Tanaka, M. 1998. "Characterization of Sandy Soils Using CPT and DMT", Soils and Foundations, Volume(38), (3), pp. 55–65. https://doi.org/10.3208/sandf.38.3_55

Van Berkom, I.,Brinkgreve, R.,Lengkeek, H. J.,Jong, A. K. de. 2022. "An automated system to determine constitutive model parameters from in situ tests", Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering, Sydney 2021.