Incorporating shear wave velocity measurements into an Automated Parameter Determination (APD) system

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ABSTRACT: The determination of constitutive model parameters is of paramount importance in the success of numerical analysis. The assessment of these parameters from in-situ tests offers several advantages, primarily in terms of time and cost. However, it is not possible to evaluate the parameters directly from the results of in-situ tests; rather, this task often relies on interpretation, with the use of empirical correlations being the most common approach. An ongoing research project aims to create an automated parameter determination system using a graph-based approach to determine constitutive model parameters from in-situ tests and automatically connect the output to finite element analysis. The framework has been implemented to determine parameters based on cone penetration tests, dilatometer tests and shear wave velocity measurements. This contribution focuses on the implementation of the shear wave velocity-based workflow. The ongoing research project is currently focusing on evaluating the accuracy of the derived parameters.

1 INTRODUCTION

The proper application of constitutive models is essential for the performance of numerical analysis. Over time, the development of constitutive models has progressed significantly, with more advanced models being able to simulate soil behaviour with greater precision than their simpler counterparts. However, as models become more sophisticated, the number of required parameters also increased. Determining these parameters and calibrating the models requires the use of laboratory tests, such as oedometer and triaxial tests. However, such tests are not always available, particularly in the early stages of a project.

An alternative approach is to assess soil parameters by conducting in-situ tests. In comparison to laboratory tests, in-situ tests are faster, relatively cheaper, and there is no requirement to retrieve soil samples. However, evaluating the parameters directly from the results of in-situ tests is not possible. This task relies on interpretation through the use of correlations or experience. Several correlations have been formulated to assess different soil parameters from the in-situ measurements. The presence of multiple correlations for a given parameter may result in a degree of scatter in the obtained values. The reason for this scatter is primarily attributable to the applicability of the correlations. As some correlations are only valid for specific soil types, while others are only valid for specific site conditions, such as the overconsolidation ratio, this can lead to discrepancies in the results.

Several literature sources offer guidance on the interpretation of in-situ tests, including Kulhawy & Mayne (1990) and Schnaid (2009). There have been other attempts to evaluate constitutive model parameters based on very limited soil data. One such attempt was presented by Brinkgreve et al. (2010), in which the parameters of the Hardening Soil Small Model (HSsmall) (Benz 2007) were assessed using only the relative density.

The Automated Parameter Determination (APD) project is an ongoing research initiative with the objective of developing a tool for evaluating constitutive model parameters based on in-situ tests and automatically connecting the output to finite element (FE) analysis. The parameters are computed utilizing a graph-based approach that inherits certain characteristics of graph theory

(Van Berkom et al. 2022; Marzouk et al. 2023a; Marzouk et al. 2023b; Marzouk et al. 2024). The primary objective of APD is to develop a transparent and adaptable framework for parameter determination. Transparency is achieved by illustrating how the available information was used to compute the parameters. Adaptability is ensured by allowing system users to incorporate their knowledge, expertise, and experience into the framework.

2 AUTOMATED PARAMTER DETERIMANTION (APD)

Further details on the APD framework can be found in the publications of Van Berkom et al. (2022), Marzouk et al. (2023a), Marzouk et al. (2023b) and Marzouk et al. (2024). The APD tool is developed using the Python programming language, with the framework constructed in a modular manner. The framework is comprised of several interconnected modules that establish a link between in-situ raw measurements and constitutive model parameters. At present, two principal workflows are available for determining parameters from CPT, DMT and shear wave velocity (V_s) measurements. These are the CPT-based and DMT-based workflows. The V_s-based workflow may be regarded as a supplement to either the CPT-based or DMT-based workflows.

The CPT-based workflow provides a useful framework for illustrating the functionality of the APD modules. Module 1 is the CPT reader, which imports and transfers the CPT raw data to a data frame (a data structure in Python) for further interpretation. The second module is responsible for stratifying the CPT according to one of Robertson's soil behaviour type (SBT) charts (e.g., (Robertson 2010). The stratification is carried out by one of two methods: the first is by using one of the implemented stratification algorithms, and the second is by manual stratification, whereby the user provides the boundaries for individual layers. In this study, the stratification algorithms are not discussed, as the layers were identified manually. Once the layers have been determined, the in-situ measurements are averaged within each layer to determine the representative value for that layer. In Module 3, the averaged measurements are used to determine the state of the layer, namely the overconsolidation ratio (OCR) and the coefficient of earth pressure (K_0). At this stage, the determined OCR and K_0 values are considered as initial values, and their calculation is based on correlations selected by the user. Module 4 is considered as the main module of the framework where the soil parameters are computed using a graph-based approach. Similarly, module 5 evaluates constitutive model parameters. In this study, the parameters obtained from module 4 are compared to reference values at two test sites. Consequently, the transition to module 5 is not considered in this contribution.

The graphs are generated based on the user's provided list of correlations. In the context of APD, the terms "correlation," "formula," "equation," and "rule of thumb" are replaced with the term "method." This general term is selected as there are multiple ways to determine parameters. The graphs are generated by defining the parameters, methods, and the connection between them. This is accomplished by providing the system with two input files in comma-separated value format (CSV). The two files correspond to the methods (list of correlations) and the parameters. The two files have a distinctive format that necessitates the specification of a number of attributes. The format of the files is further described in more detail in the aforementioned publications. A standard, validated database comprising in excess of 100 methods and parameters is provided in association with the system. The system imports the two files, generates the links connecting the parameters and methods, and computes the values of different parameters.

This contribution is concerned with the illustration of the implementation of the V_s-based workflow. It highlights the motivation, challenges and performance by comparing the values (for different parameters) obtained from the V_s-based workflow to reference values interpreted from laboratory tests at two test sites.

2.1 *Shear wave velocity-based workflow (supplement to the CPT/DMT-based workflows)*

There has been a notable increase in recent years in the performance of seismic tests, including seismic dilatometer tests (SDMT) and seismic cone penetration tests (SPCT/SCPTu). The principal objective of developing the V_s-based workflow is to utilise the in-situ measured V_s to accurately evaluate the small-strain shear modulus (G_0). Consequently, the uncertainty associated with the reliance on shear wave velocity correlations to determine V_s and G_0 is eliminated.

2.1.1 *Shear wave velocity modules*

The V_s-based workflow is a complementary approach that may be employed alongside either the CPT- or DMT-based workflows and adheres to the same module definition. In the event that the CPT-based workflow is employed, modules 1, 2, 3, 4 and 5 (as described in Section 2) are utilized. The same is true of the DMT-based workflow.

In module 1 (either for the CPT or DMT-based workflows), it is necessary to have an initial estimate of the unit weight as the determination of the effective vertical stress is necessary in the computation of some CPT and DMT intermediate parameters (e.g., normalized cone tip resistance (Q_t) and horizontal stress index (K_D)).

In this study, the V_s-based workflow was employed in conjunction with the CPT-based workflow. The initial unit weight that was used for computing the effective vertical stress for both sites was evaluated based on the method of Lengkeek & Brinkgreve (2022).

$$\gamma_t = 19.5 - 2.87\left[\frac{\log\left(\frac{9000}{q_t}\right)}{\log\left(\frac{20}{R_f}\right)}\right] \tag{1}$$

2.1.2 *Layers without shear wave velocity measurements*

One of the main challenges in implementing the shear wave velocity-based workflow within the APD framework is the stratification. The APD framework computes parameters based on layers, whereas 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 the absence of shear wave velocity measurements within specific layers, rendering the workflow unusable for the entire analysis. To address this limitation, a number of potential solutions are currently under consideration. It is possible that machine learning models could be employed to predict additional shear wave velocity points (Felic et al. 2024), thereby filling in the missing data. An alternative approach would be to employ a site-specific methodology, whereby several CPT shear wave velocity correlations are compared to the in-situ shear wave velocity profile. The correlation with the least error is then selected to predict the missing points. Both approaches are still under investigation and show promising results. However, these approaches are not considered in this contribution. In this study, in-situ shear wave velocity measurements were available for all layers under consideration.

3 TEST SITES

3.1 *Datamap*

Datamap is an online tool (web application) designed to facilitate the collection, storage, and classification of geotechnical data in an organized manner. The objective of the Datamap tool is to facilitate the accessibility and availability of geotechnical data to researchers, enabling them to create and share their projects. The tool can be accessed via the following link: www.geocalcs.com/datamap (Doherty et al. 2018).

3.2 *Norwegian GeoTest Sites (NGTS)*

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

3.3 *Onsøy soft clay site*

The NGTS soft clay site at Onsøy was established in 2016. A comprehensive laboratory and field testing programme has been conducted and is presented in NGI's report (Norwegian Geotechnical

Institute, 2019). In situ testing comprised piezocone tests (CPTu), seismic cone penetration tests (SCPT), a seismic flat dilatometer test (SDMT), and a self-boring pressuremeter test (SBPMT). The laboratory testing programme comprised the determination of the in-situ water content, unit weight, Atterberg limits and the execution of constant rate of strain oedometer tests (CRS), triaxial tests and direct simple shear tests (DSS). A variety of sampling techniques were employed, including the use of block and tube samplers (Gundersen et al. 2019).

The investigation was conducted in two main areas: the south-central (SC) and the southeast corner (SEC). The test site's stratigraphy comprises four main units, which are slightly overconsolidated (Gundersen et al. 2019). Unit I is composed of weathered clay, while Unit II is characterized as a clay with a high to very high plasticity index (approximately 44%). Unit III is identified as a clay with a medium-high plasticity index (approximately 27%). Unit IV exhibits similar index properties to Unit II, although the plasticity index, water content, and clay content decrease towards the bedrock. This analysis is limited to the southeast corner (SEC) area, where the SDMT was conducted. Unit I is 1 m thick, Unit II is approximately 9.5 m thick, and Unit III is 9 m thick (Gundersen et al. 2019). CPTu ONSC 18 (as named in the project) was selected to compute the initial unit weight using Equation (1). Figure 1a presents the in-situ shear wave velocity profile obtained from the SDMT, with the four different soil units highlighted in the figure.

3.4 *Halden silt site*

Halden is situated in southeastern Norway, approximately 120 km south of Oslo. The site covers an area of approximately 6,000 m^2 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).

A review of the geological history of the site revealed no evidence of any loading events. Consequently, it can be postulated 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 distinct soil units, designated as Units I to IV, were identified. Unit I extends to a depth of approximately 4.5 to 5 m and is composed of medium-dense silty clayey sand with some organic material. Units II and III extend to a depth of approximately 15 to 16 m. The material (Units II and III) is characterized as clayey silt and is divided into two units based on the results of in-situ tests. Nevertheless, it is regarded as the same material with the same geologic origin. Unit IV is composed of low to medium strength clay. Typically, bedrock is encountered at a depth of 21 m. The groundwater table is situated at a depth of approximately 2 m (Blaker et al. 2019). CPTu HALC 11 (as named in the project) was selected to compute the initial unit weight using Equation (1). Figure 1b presents the in-situ shear wave velocity profile obtained from the SDMT, with the four different soil units highlighted in the figure.

4 APPLICATION OF V_s-BASED WORKFLOW ON BOTH TEST SITES

Exemplary, the unit weight (γ_t), constrained modulus (E_{oed}), small-strain shear modulus (G_0) and undrained shear strength (s_u) were assessed using the V_s-based workflow for the two test sites, in accordance with the methods presented in Table 1. The APD database contains many more methods for determining different parameters for the three based workflows. However, for the purpose of illustrating the workflow and the results of APD, it was decided to use only these selected methods.

In this study, the in-situ shear wave velocity measurements (Figure 1) obtained from the SDMT at both sites were averaged every 1 m (manual layering), and these values were used as input for the analysis. For the silt site (Figure 1b), the focus was solely on the geological Units II and III, where silt was encountered. The averaging process resulted in 18 and 11 layers for the soft clay and silt sites, respectively. The four parameters (γ_t, E_{oed}, G_0 & s_u) were determined for the aforementioned layers (18 layers for the soft clay site and 11 layers for the silt site). The output of APD is compared to reference values that were interpreted from laboratory tests for the two test sites. The comparison is presented in Figure 2, where Figures 2a, c, e and g illustrate the results for the Onsøy soft clay site and Figures 2b, d, f and h show the comparison for the Halden silt site.

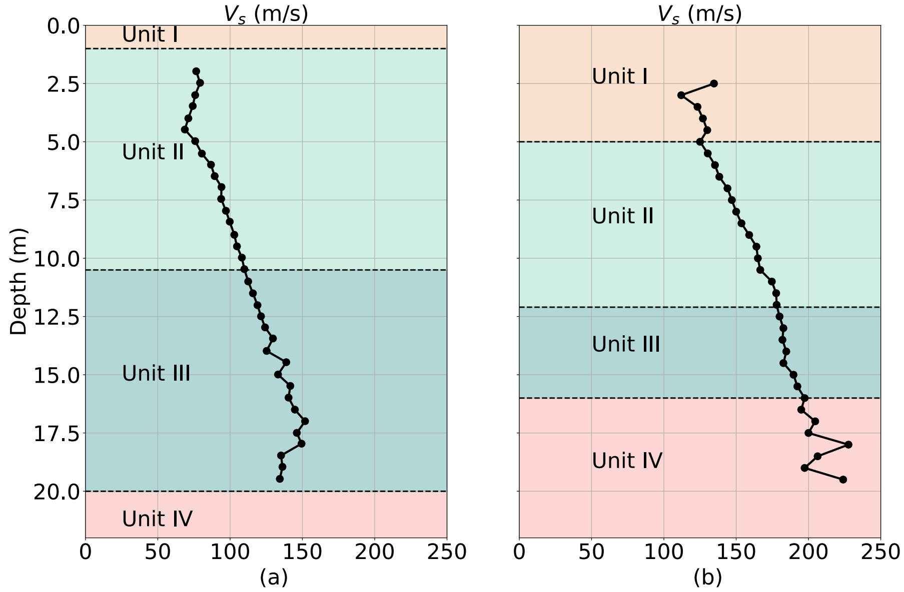


Figure 1. Results of the V_s profile obtained from SDMT for (a) Onsøy soft clay site and (b) Halden silt site.

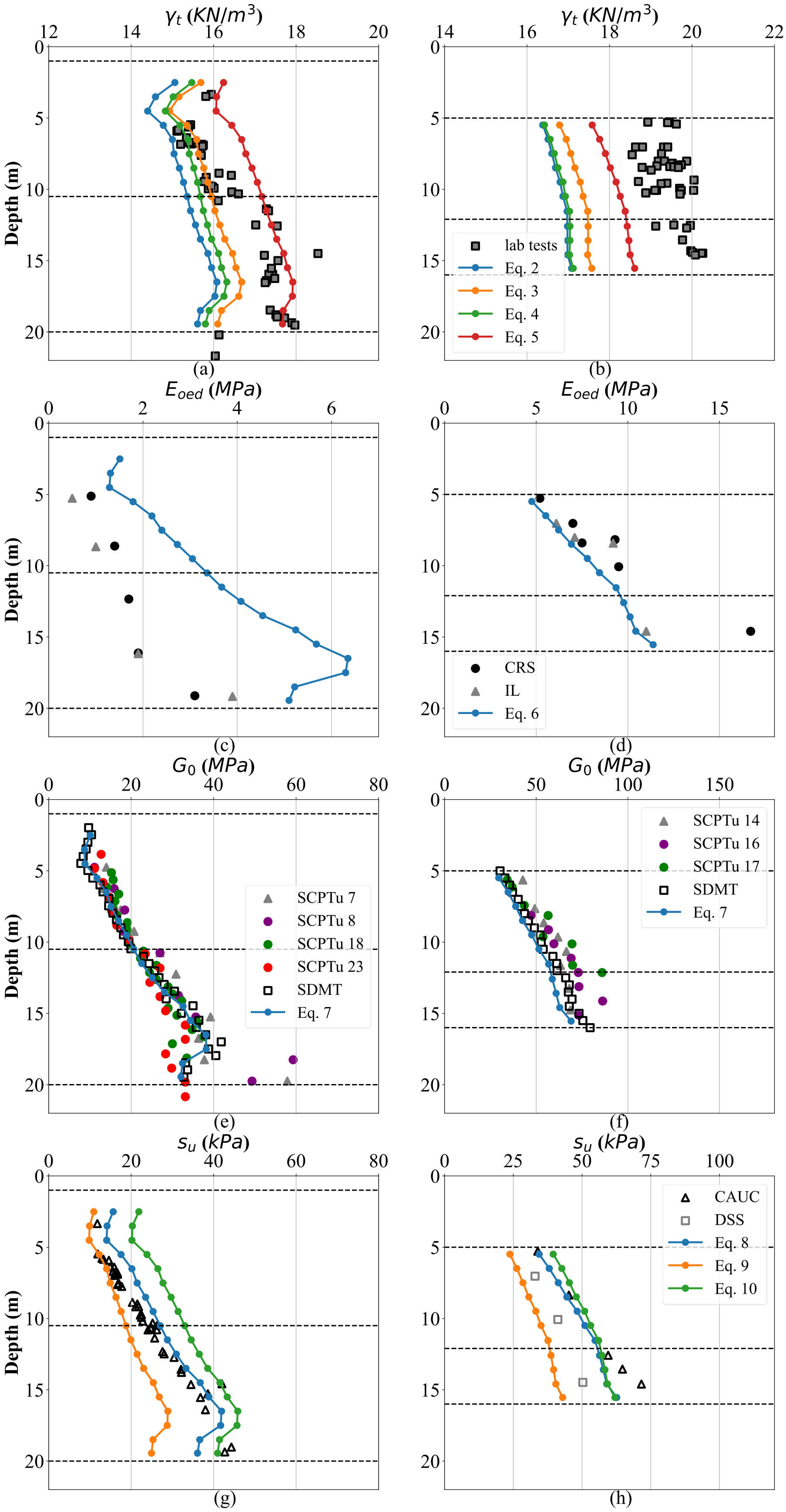
The total unit weight was determined based on direct measurements (Gundersen et al. 2019; Blaker et al. 2019). Figure 2a illustrates that Equation (2) underestimates the laboratory results for both units II and III. Equations (3-4) demonstrate a satisfactory degree of correlation with the reference values for Unit II. However, they exhibit a tendency to underestimate the laboratory results for Unit III. Equation (5) predicts reasonable values for the unit weight for Unit III, although in Unit II the unit weight is overestimated. Figure 2b demonstrates that all methods tend to underestimate the reference unit weight values. Nevertheless, Equation (5) yielded the highest predictions, yet still underestimated the laboratory results. This clearly indicates that caution should be exercised when determining unit weight from correlations, using particularly V_s measurements in the case of intermediate soils (e.g., silts).

E_{oed} was determined from oedometer tests, either from incremental loading (IL) or constant rate of strain (CRS) tests (Gundersen et al. 2019; Blaker et al. 2019). Figure 2c shows that the V_s-based workflow overestimates the reference E_{oed} values. In contrast, Figure 2d demonstrates that the V_s-based workflow provides a reasonable estimate for E_{oed}.

Table 1. Selected methods.

Parameter	Method		Author
γ_t	$8.31 \log V_s - 1.61 \log z$	(2)	Mayne (2001)
	$4.17 \ln V_{s1} - 4.03$	(3)*	Mayne (2007)
	$\frac{6.87 V_s^{0.227}}{\sigma_v'^{0.057}}$	(4)	Burns and Mayne (1996)
	$4.96 + 5.97 \log V_s$	(5)	Duan et al. (2019)
E_{oed}	$0.00010 V_s^{2.212}$ (E_{oed} in MPa)	(6)	L'Heureux and Long (2017)
G_0	ρV_s^2	(7)	
s_u	$0.152 V_s^{1.142}$	(8)	Agaiby and Mayne (2015)
	$0.021 V_s^{1.52}$	(9)	L'Heureux and Long (2017)
	$0.016 V_s^{1.50}$	(10)	Duan et al. (2019)

* V_{s1} is the effective stress-normalized shear wave velocity ($V_{s1} = V_s/(\sigma_v'/p_a)^{0.25}$)



(a) (b)

(c) (d)

(e) (f)

(g) (h)

Figure 2. Comparison between APD and interpreted values at Onsøy soft clay and Halden silt test sites. Figures (a), (c), (e) and (g) present the results for the Onsøy soft clay site, while figures (b), (d), (f) and (h) present the results for the Halden silt site.

The G_0 values were evaluated using a number of seismic tests. In the case of the soft clay site, four SCPTs (SCPTu 7, 8, 18 and 23 (ONSC 7, 8, 18 and 23) in the database uploaded to Datamap) and one SDMT were employed. With regard to the silt site, three SCPTs (SCPTu 14, 16 and 17 (HALC 14, 16 and 17) in the database uploaded to Datamap) and one SDMT were employed. The results are presented in Figures 2e, f. It is evident that the V_s-based workflow provides the most accurate estimate of G_0. The discrepancy between the values obtained from the V_s-based workflow and the reference values from the SDMT (in both sites) can be attributed to the unit weight employed (Equation (1).

The reference s_u values were obtained from undrained anisotropically consolidated triaxial (CAUC) tests for both sites and from direct shear (DSS) tests for the silt site (Gundersen et al. 2019; Blaker et al. 2019). Figure 2g indicates that Equation (8) provides only a slight overestimation of the reference values, while Equation (9) demonstrates a satisfactory fit to the reference values observed at the upper portion of Unit II. However, it tends to underestimate the reference values observed at the lower portion of Unit II and in Unit III. Equation (10) overestimates the reference values. However, the reference values were accurately captured at the bottom of Unit III. Figure 2h demonstrates that Equation (8) provides an overall satisfactory level of agreement with the reference values. It can be observed that Equation (9) tends to underestimate the s_u values determined from both CAUC and DSS. Equation (10) provides a slight overestimation of the reference values in Unit II, however it provides a reasonable predictions in Unit III.

5 CONCLUSIONS

APD represents a framework for determining soil and constitutive model parameter values. It employs a graph-based approach for evaluating these parameters based on in-situ tests, with the objective of providing assistance in the early stages of projects, particularly when limited soil data is available. In such cases, relatively inexpensive in-situ tests, such as CPT and DMT, are conducted prior to implementing a full laboratory testing programme. The objective is not to replace laboratory tests with in-situ tests. The final design will still require optimization of the soil and constitutive model parameters, as APD is intended to automate the transfer of these parameters to finite element (FE) software for numerical analysis. Furthermore, the objective of APD is to integrate multiple data sources (e.g., CPT, DMT, V_s measurements and other tests) in order to determine different parameters.

This study presents the predictions of the V_s-based workflow for four different soil parameters at two test sites. The principal objective of incorporating the V_s-based workflow within the APD framework is to achieve accurate estimations of G_0. With regard to the selected four parameters, some V_s methods demonstrated the potential to provide reliable estimates (e.g., for the undrained shear strength), although this was not the case for γ_t at the silt site.

Currently, the main task is to identify representative values for different parameters. Due to the vast number of methods within APD, a considerable degree of variability in values is often observed for a given parameter. Consequently, a statistical module is being developed to assist users in selecting representative values. Ongoing research includes the development of an automated process for combining the results of different APD workflows (CPT and DMT), the analysis of additional test sites, the expansion of the system through the addition of further in-situ tests, and the validation of the output.

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