

CPTu based parameter estimation with closed-loop validation approach combining automated parameter determination and numerical simulation

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ABSTRACT: A closed-loop validation approach is introduced to improve soil parameter determination by linking cone penetration measurement data with numerical simulations. This approach integrates an automated parameter determination framework with numerical simulations using the geotechnical particle finite element method. Soil parameters are derived from in-situ measurements and refined through iterative back analysis until the numerically simulated soil responses align with in-situ measurements. To support the soil parameter selection process, a sensitivity analysis is conducted to examine the relationship between each soil parameter and the soil response. The closed-loop validation approach is demonstrated through a case study using data from the Ballina soft soil test site in Australia. The parameters generated by the automated parameter determination framework show a reasonable match with the reference values from laboratory test results, and the soil response from the numerical back-analysis align well with in-situ measurements. This practical approach reduces uncertainty associated with empirical correlations and offers an alternative method for parameter estimation when laboratory data are limited or unavailable.

KEYWORDS: In-situ testing, Soil parameters, CPT, Graph theory, GPFEM, Particle Finite Element Method (PFEM).

1 INTRODUCTION

Numerical analysis has become increasingly popular in geotechnical engineering due to its ability to model complex soil behavior and boundary conditions that are difficult to capture using traditional analytical or empirical methods. To accurately reflect the complexity of soil behavior, the correct selection of a constitutive model and the accurate determination of soil parameters are paramount.

Ideally, soil parameters are derived from laboratory tests on undisturbed soil samples, which often take considerable time to perform and require skill to obtain and to preserve sample quality. As a result, such tests may not always be available or sufficient, particularly during the early stages of a construction project.

On the other hand, in-situ testing is typically conducted during the initial site investigation to characterize subsurface soil conditions. Among the various in-situ testing techniques, cone penetration testing with pore pressure measurements (CPTu) has gained widespread acceptance due to its reliability, efficiency, and ability to provide a continuous soil profile and behavior type.

However, CPTu does not directly yield the soil parameters required for geotechnical analyses. The measurements must be connected to soil parameters through empirical correlations.

Many guidelines are available for the CPTu interpretation, such as Lunne, Robertson and Powell (1997), Robertson and Cabal (2022) and Mayne, Cargill and Greig (2023). To streamline this process, recent advancements have led to the development of the Automated Parameter Determination (APD) framework, which aims to improve the accuracy and efficiency of parameter estimation from in-situ data (Marzouk, et al., 2024; Marzouk, et al., 2025; Marzouk and Tschuchnigg, 2025b). This framework systematically links CPTu measurements to soil constitutive parameters using a graph-based methodology derived from multiple empirical correlations. The APD framework eliminates subjectivity in parameter selection and enables the generation of a wide range of possible soil properties based solely on field data, without the need for laboratory input.

In parallel, significant progress has been made in the field of numerical modeling for CPTu simulation, such as the Geotechnical Particle Finite Element Method (GPFEM). GPFEM has demonstrated promising capabilities in simulating large deformations and complex interactions between the cone

penetrometer and the soil (Monforte, et al., 2018; Hauser and Schweiger, 2021; Monforte, et al., 2021; Boschi, et al., 2023; Boschi, et al., 2024; Hauser, et al., 2025). With numerically simulated CPTu, the link between constitutive soil parameters can be established back to the soil response (i.e., q_t , f_s , and u_2).

Building on these advancements, this study proposes a Closed-Loop Validation (CLV) approach that integrates the APD framework with CPTu simulations to validate soil parameters. In this approach, the APD is used to generate a range of soil parameter sets derived from in-situ CPTu data. Within this range, a set of constitutive parameters is selected and iteratively refined through numerical CPTu simulations until the simulated soil response matches field measurements. The flow of this approach is presented in Figure 1.

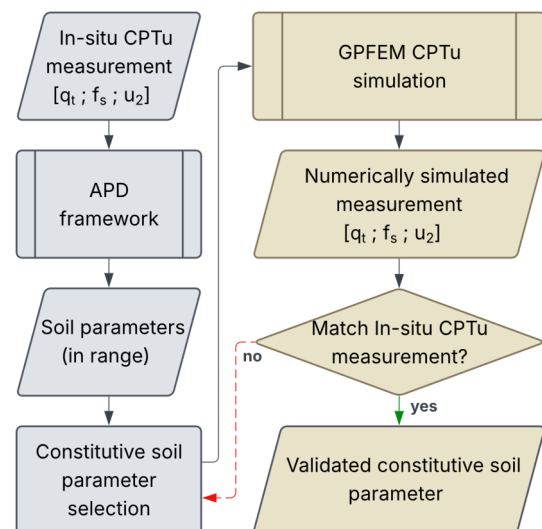


Figure 1. Closed looped validation flow.

The motivation here is not to replace parameter determination from laboratory tests with in-situ tests, but rather to reduce uncertainty associated with empirical correlations, to provide an alternative method for parameter estimation when laboratory data are limited or unavailable, and to offer a basis for parameter selection during final design.

2 TEST SITE AND USED METHODS

In this study, the CLV approach, as described in the previous section, is applied to a case study. To support the selection of the soil parameters process, a sensitivity analysis is also conducted to examine the relationship between each soil parameter and the resulting soil response.

The data used in this study are obtained from a test site at the National Soft Soil Field Testing Facility (NFTF), established by the Australian Research Council Centre of Excellence for Geotechnical Science and Engineering (CGSE). Data from this facility are available through the web-based application 'Datamap' and can be accessed at www.geocalcs.com/datamap (Doherty, et al., 2018).

2.1 Test site

The test site is located northwest of Ballina, Australia. This 6.5 ha facility features a trial embankment constructed on soft soil and equipped with extensive geotechnical instrumentation. Prior to construction, a comprehensive site investigation was conducted, and high-quality soil samples were collected to characterize the soft estuarine clay deposits.

In this case study, soil parameters are derived from four cone penetration tests conducted around the test embankment (see Figure 2). Additionally, high-quality laboratory test results on tube specimens obtained from two continuous boreholes serve as reference values for the soil parameters.

The site consists of a generally homogeneous soil profile, with groundwater level observed approximately 0.5 m below existing ground elevation. It includes a 1.5 m thick alluvial silt layer at the surface, followed by a transitional layer extending from -1.5 m to -4.5 m, and an estuarine clay layer from -4.5 m to -10.5 m. Detailed site characterization is provided by Kelly, et al. (2017), while the results of advanced laboratory tests on high-quality undisturbed soil samples are discussed in detail by Pineda, et al. (2016).

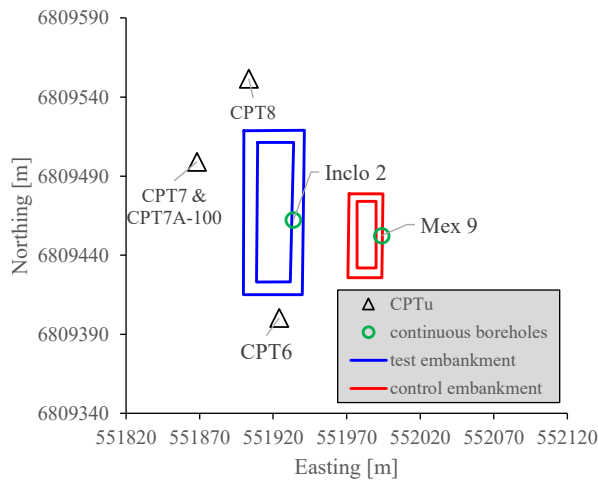


Figure 2. Location of CPTu and soil sample at NFTF, Ballina, Australia.

2.2 APD framework

The APD framework is described in detail in Marzouk, et al. (2024). It is designed in a modular structure that links raw in-situ measurements to finite element (FE) software. Currently, the framework includes three workflows for determining parameters based on the cone penetration test (CPT), dilatometer test (DMT), and shear wave velocity measurements (V_s).

The framework consists of five modules. In the CPT-based workflow, module 1 imports raw data and computes various

CPT parameters (e.g., normalized cone resistance Q_t). Module 2 stratifies the CPT data into soil layers using either implemented stratification algorithms or external sources. Module 3 assesses the layer state, including the over-consolidation ratio (OCR) and the coefficient of earth pressure at rest (K_0). A graph-based approach is implemented in modules 4 and 5 to determine both soil parameters and constitutive model parameters. Finally, the output is transferred to the FE software.

To generate the graphs, two input spreadsheets are required: one describing the methods (i.e., correlations), and the other defining the parameters. The framework is developed in Python, and the current version includes a validated database of more than 200 methods, covering both soil and constitutive model parameters.

2.3 Numerical simulation

2.3.1 GPFEM

In this study, GPFEM code is employed to handle large-deformations and large-strains that occur during CPTu penetration (Monforte, et al., 2017a; Monforte, et al., 2017b; Monforte Vila, 2018). GPFEM was developed at the Center for Numerical Methods in Engineering (CIMNE) and the Polytechnic University of Catalonia (UPC), and is integrated into the Kratos Multi-Physics framework (Dadvand, Rossi and Oñate, 2010).

GPFEM adopts a Lagrangian formulation of motion, with continuous regeneration of the low-order finite element mesh to overcome numerical challenges. A fully coupled hydro-mechanical formulation is implemented, using a mixed formulation to avoid volumetric locking during cone penetration problems. Monforte, et al. (2017b) investigated and found that mixed formulation with displacement, the determinant J of the deformation gradient, and water pressure ($U - J - p_w$) as degrees of freedom performed effectively. Interested readers are referred to Monforte Vila (2018), and Carbonell, et al. (2022) for further details on GPFEM.

2.3.2 CPTu model

CPTu model is set up at axisymmetric conditions. The bottom boundary is fixed in both directions, while the lateral boundary allows only vertical displacement. Pore water is allowed to drain freely through the upper and lower boundaries, while the lateral boundaries are considered impermeable.

The simulation is conducted under weightless soil conditions, postulating a homogeneous in-situ effective stress (σ'_v , σ'_h) and water pressure (u_0) throughout domain. To maintain equilibrium, total stress is applied at the upper horizontal boundary. The CPT cone with a 1.78 cm radius is initially embedded 20 cm and pushed at a constant rate of 2 cm/s. Figure 3 illustrates the geometry and boundary condition of the CPTu model, along with a comparison of meshes between the initial phase and the final configuration after penetration.

A time step of 0.0022 s is adopted, with a re-meshing size of 0.004 m for the interior and 0.008 m at the boundaries. For penetration under constant in-situ stress, the CPTu response is taken from the average value after the steady condition is reached, which occurs at approximately 0.25 m of penetration.

Given the homogeneous stress as initial conditions, each simulation represents soil condition at a specific depth corresponding to the in-situ stress and water pressure at that level. In this study, simulations are performed at several depths to evaluate soil responses along the penetration, focusing on the soft estuarine clay and transitional layer found between depths of -1.5 m to -10.5 m.

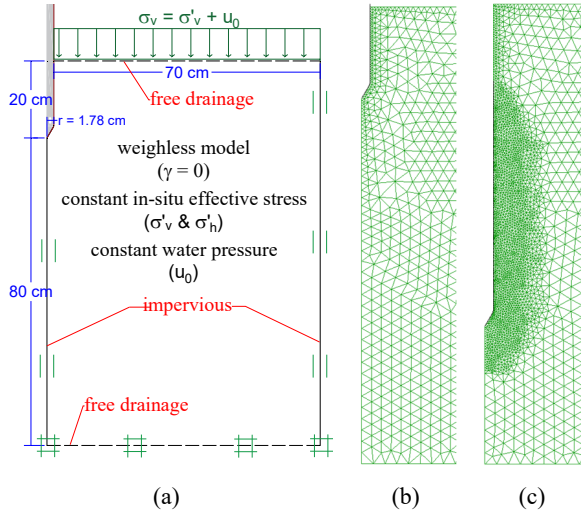


Figure 3. Axisymmetric model for CPT: (a) geometry and boundary conditions, (b) initial mesh before penetration, (c) updated mesh at the end of penetration.

2.3.3 Frictional contact

In the GPFEM code, frictional contact is governed by the Coulomb friction law using a penalty approach. Besides constitutive parameters and in-situ stress, frictional contact between the cone and the soil domain also influences the soil response.

Interface efficiency is defined as the ratio between tangent contact friction angle ($\tan \delta$) with tangent of internal friction angle ($\tan \phi'$). It can be estimated from the ratio between the cone roughness and the soil particle size. According to Eid, et al. (2015), the estimated interface efficiency for clay ranges between 0.65 to 0.95.

2.4 Constitutive model (CASM-MCC)

The Modified Cam Clay (MCC) constitutive model was selected in this study to represent soft soil behavior, as it offers a simple framework for approximating the characteristics of lightly overconsolidated clays such as Ballina clay. However, since GPFEM currently supports only the Clay and Sand Model (CASM) by Yu (1998), the MCC yield surface function from Equation (1) is recovered here by adjusting the spacing ratio (r) to 2 and the shape parameter (n) to 1.5.

$$f(p', q, p'_0) = \left(\frac{q}{Mp'}\right)^n + \frac{\ln\left(\frac{p'}{p'_0}\right)}{\ln(r)} = 0 \quad (1)$$

where, p' is mean effective stress, q is deviatoric stress, M is stress ratio at critical state, and p'_0 is the isotropic pre-consolidation pressure.

The plastic potential is an ellipse in the $(p' - q)$ space equivalent to the yield surface of the MCC with a horizontal tangent at critical state. Unlike the original MCC formulation, where the plastic potential and yield surface have a circular shape in the deviatoric plane, here a continuous-smoothing approximation of the Mohr-Coulomb envelope (Abbo, et al., 2011) is adopted. This model is referred as CASM-MCC.

The constitutive soil parameter required for CASM-MCC formulation include: initial void ratio (e_0), modified isotropic swelling slope (κ^*), modified isotropic compression slope (λ^*), shear modulus (G) defined by Equation (2), slope of critical state line under compression (M_{comp}) defined by Equation (3), permeability (k) and OCR , which is used to expand the yield surface by adjusting the (p'_0) according to Equation (4).

$$G = \frac{3(1 - 2\nu_{ur})}{2(1 + \nu_{ur})} \frac{p'}{\kappa^*} \quad (2)$$

$$M_{comp} = \frac{6 \sin \phi'}{3 - \sin \phi'} \quad (3)$$

$$p'_0 = \left(\frac{\sigma'_v OCR (3 - 2 \sin \phi')}{3}\right) \cdot r^{\left(\frac{3 - \sin \phi'}{2(3 - 2 \sin \phi')}\right)^n} \quad (4)$$

where ν_{ur} is poisson's ratio in the elastic region, assumed to be 0.15 in this study.

3 RESULTS AND DISCUSSION

3.1 APD process

Four in-situ CPTu performed around the test embankment (CPT 6, 7, 8 and 7A-100 in Figure 4) indicate a relatively homogeneous soil stratification across the project site. The four CPTu profiles were averaged to produce a single representative CPTu profile for parameter determination in APD. This profile was stratified at 3 cm intervals, resulting in very thin layers for the parameter determination. This averaging process also smooths out sudden increases in f_s and decreases in u_2 . These behaviors are caused by dissipation tests performed during penetration and this effect is not expected from a normal (continuously pushed) CPTu.

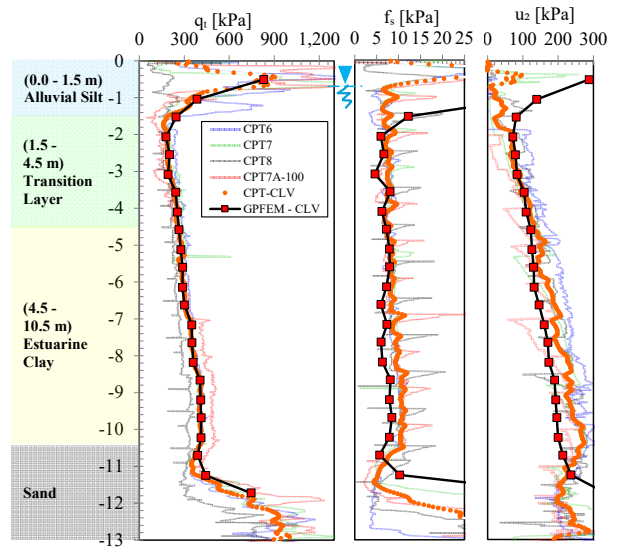


Figure 4. CPTu measurements over depth: in-situ tests (line), average value for APD input (dots), and GPFEM simulation results (squares).

As described previously, Module 1 computes several CPT parameters. Some of these parameters are stress-normalized (e.g., Q_t), which requires an initial estimate of the unit weight. At this stage, it is referred to as the *initial unit weight* and can be determined using empirical methods or engineering judgment. In this study, the method proposed by Mayne, Cargill and Greig (2023) is adopted.

The methods selected for determining the unit weight, k , OCR , ϕ' , e_0 , λ^* and κ^* are presented in (Marzouk and Tschuchnigg, 2025a). The soil parameter results generated by the APD framework are presented as lines in Figure 5. Overall, these values correspond well with the reference parameters obtained from laboratory tests on undisturbed soil samples collected near the center of the embankment marked with a cross in Figure 5. Empirical correlations estimated higher unit weight and lower void ratio compared with the reference value for the estuarine clay layer.

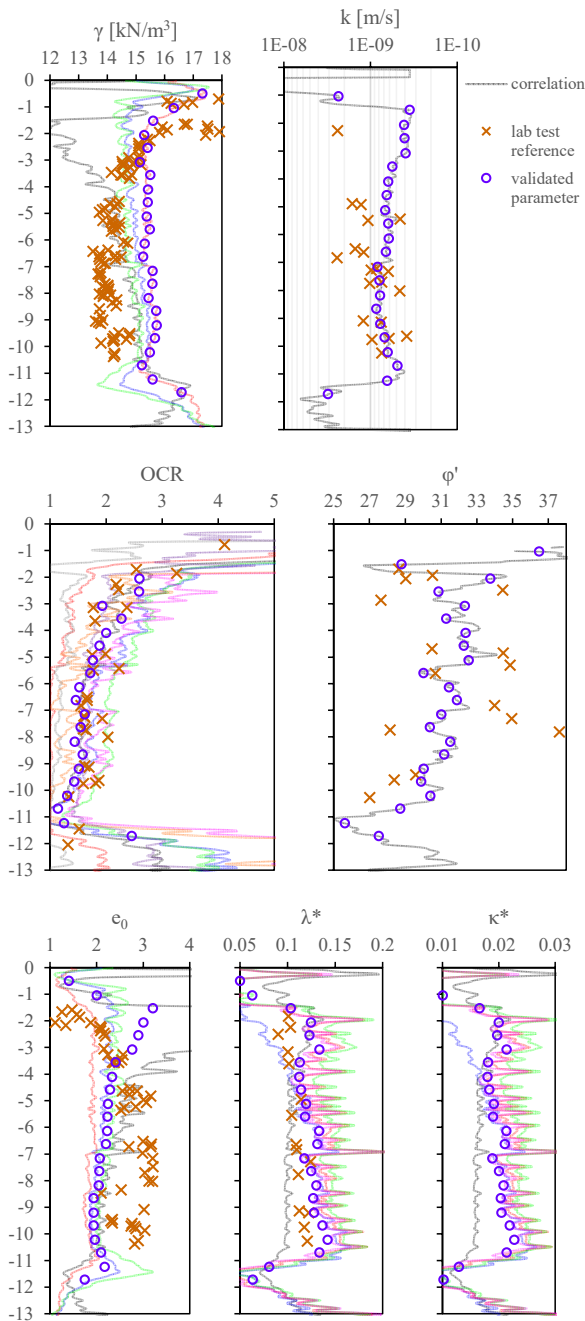


Figure 5. Soil parameter over depth: empirical correlation (line), laboratory test result (cross), and CLV result (circle).

3.2 GPFEM simulation

A sensitivity analysis was conducted at a single depth (7.165 m). For each parameter variation, three simulations were performed using the lower, average, and upper values. The simulation results are shown as a bar chart in Figure 6, with a line behind the chart representing the average value and range of the in-situ measurements at this depth.

The analysis indicates that the most sensitive parameter is the *OCR* value. Additionally, the simulation results using the average APD input (middle bar) show that q_t is matching the average of the in-situ data, f_s is below the measurement value, and u_2 slightly lower than the average measured value. It was also found that certain soil parameters, such as λ^* , in this case study are not an ideal parameter for calibration using this approach.

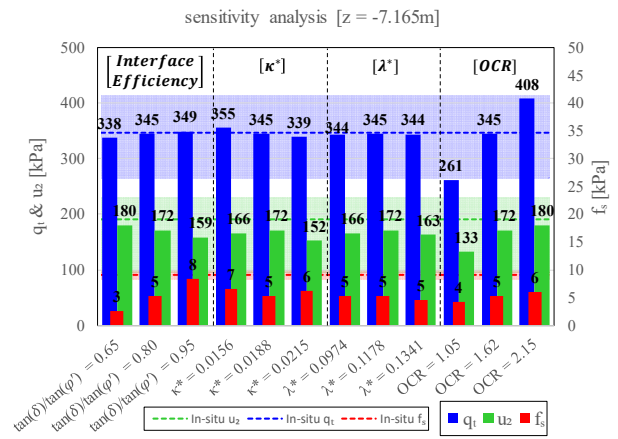


Figure 6. Sensitivity analysis for depth 7.165 m.

Based on this initial analysis, the interface efficiency was adjusted to the upper boundary value of 0.95 during full-depth back analysis validation. The input values for back-analysis are shown as a circles plot in Figure 5, with detail provided in Table 1 and Table 2. Simulation were performed at approximately half meter intervals between -0.5 m and -12.0 m. Simulation results for each model are shown in Figure 7. To improve visualization, moving averages (shown in color) are plotted over the raw results (shown in grey).

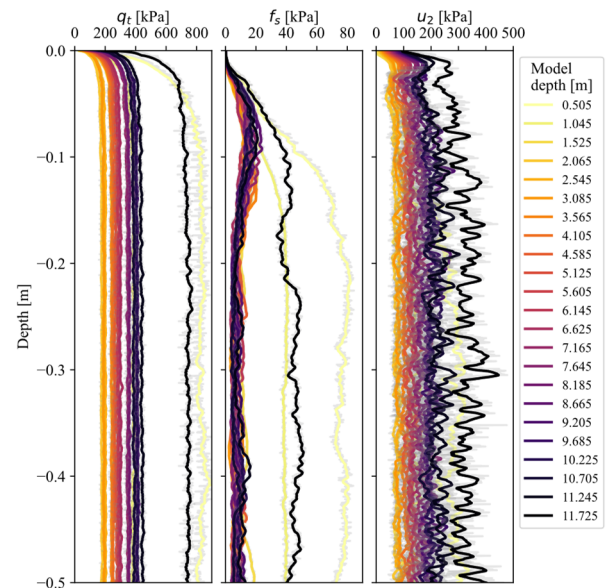


Figure 7. Simulation result for the back analysis.

The comparison between the numerically simulated CPTu results using the validated parameter with the in-situ measurement is shown in Figure 4 (see square plot). Overall, simulated soil response aligns well within range of the in-situ measurement for the primary focus layers in this study which are estuarine clay layer and soft clay within the transition layer from -1.5 m to -10.5 m.

For the alluvial silt and sand layer, only the q_t matches the in-situ test data, which might be coincidental, while the f_s and u_2 are overestimated. This behavior is expected because the yield surface parameter (n and r) are set for clay material, the empirical correlations used in this study is for fine-grained soils, and the contact efficiency is estimated based on clay particle size.

Table 1. Validated in-situ stress and hydraulic parameter.

z [m]	σ_v [kPa]	σ_h [kPa]	u_0 [kPa]	OCR [-]	k [m/s]	δ [°]
-0.505	9	24	0	25.77	3.3E-08	47
-1.045	12	20	5	9.95	2.3E-09	35
-1.525	15	18	10	5.67	3.5E-10	28
-2.065	18	14	15	2.59	4.1E-10	32
-2.545	21	17	20	2.59	4.0E-10	30
-3.085	24	16	25	1.93	3.9E-10	31
-3.565	27	20	30	2.27	5.6E-10	30
-4.105	30	20	35	2.00	6.2E-10	31
-4.585	32	21	40	1.88	6.5E-10	31
-5.125	35	22	45	1.76	6.7E-10	31
-5.605	38	25	50	1.72	6.2E-10	29
-6.145	41	24	55	1.52	6.1E-10	30
-6.625	44	25	60	1.46	6.6E-10	31
-7.165	47	29	65	1.62	8.3E-10	30
-7.645	49	30	70	1.55	7.8E-10	29
-8.185	52	30	75	1.44	7.7E-10	30
-8.665	55	34	80	1.58	8.6E-10	30
-9.205	58	36	85	1.51	7.7E-10	29
-9.685	61	37	90	1.43	6.8E-10	29
-10.225	64	36	96	1.31	6.3E-10	29
-10.705	67	37	100	1.14	4.9E-10	27
-11.245	70	44	106	1.25	6.4E-10	24
-11.725	73	59	110	2.46	3.1E-09	26

Table 2. Validated soil constitutive parameter.

z [m]	e_0 [-]	κ^* [-]	λ^* [-]	G [kPa]	M [-]	ϕ' [°]
-0.505	1.41	0.008	0.050	2170	1.98	48
-1.045	2.00	0.010	0.063	1556	1.48	36
-1.525	3.21	0.017	0.104	955	1.15	29
-2.065	3.01	0.020	0.125	701	1.36	34
-2.545	2.90	0.020	0.123	837	1.24	31
-3.085	2.77	0.021	0.134	791	1.30	32
-3.565	2.41	0.018	0.113	1107	1.26	31
-4.105	2.33	0.018	0.113	1174	1.30	32
-4.585	2.29	0.018	0.114	1238	1.30	32
-5.125	2.25	0.019	0.120	1264	1.31	33
-5.605	2.24	0.019	0.119	1406	1.20	30
-6.145	2.23	0.021	0.133	1280	1.26	31
-6.625	2.20	0.021	0.132	1355	1.28	32
-7.165	2.07	0.019	0.118	1687	1.24	31
-7.645	2.06	0.020	0.125	1673	1.22	30
-8.185	2.05	0.021	0.130	1648	1.27	32
-8.665	1.94	0.020	0.127	1833	1.25	31
-9.205	1.94	0.021	0.128	1932	1.20	30
-9.685	1.94	0.022	0.137	1868	1.20	30
-10.225	1.96	0.023	0.142	1832	1.22	30
-10.705	2.10	0.021	0.134	2005	1.144	29
-11.245	2.18	0.013	0.081	3707	1.010	26
-11.725	1.74	0.010	0.064	5731	1.092	28

4 CONCLUSIONS

This study introduces a CLV approach for parameter determination by integrating the APD framework with numerically simulated CPTu using GPFEM. The method reduces uncertainty by selecting parameter sets that replicate soil responses observed in in-situ CPTu tests.

Applied to the Ballina site, the approach demonstrates that a reasonable match can be achieved between APD-generated parameters with reference values from laboratory tests result and results from GPFEM back-analysis to the in-situ measurements. Sensitivity analysis confirms that certain parameters strongly influence the simulation result while others have minimal effect.

Overall, this study offers a practical approach that links in-situ testing with constitutive modeling to improve confidence in parameter estimation, particularly when laboratory data are limited.

5 ACKNOWLEDGEMENTS

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