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Research article

Variability of in situ test results from a coastal silt deposit in Finland

Marco D'Ignazio*, Mohammad Sadegh Farhadi and Tim Länsivaara

Terra Research Centre, Faculty of Built Environment, Tampere University, P.O. Box 600, FI-33014, Tampere, Finland

* **Correspondence:** Email: marco.dignazio@tuni.fi; Tel: +358 (0)294 5211.

Abstract: The geotechnical characterisation of silty soils remains a challenge due to their transitional behaviour and high variability. In Finland, silts are widespread but poorly represented in existing correlations, which are largely based on clays or sands. Current practice often relies on Weight Sounding (Painokairaus, PK) and Combined Static–Dynamic Penetration Testing (Puristinheijari, PH), supported by empirical guidelines developed several decades ago. While these methods are cost-effective, their reliability in silts is uncertain and often conservative. In this study, we reported results from a benchmarking campaign at the Haistila test site in south-west Finland, where PK, PH, and piezocone penetration tests (CPTU) were performed independently by Tampere University and Ramboll Finland Oy. The objective was to quantify variability between methods and operators, and to assess implications for geotechnical design. Results showed that CPTU provided the most repeatable measurements, with cone tip resistance showing the lowest relative error and coefficient of variation. In contrast, PH results displayed greater variability, particularly in torque, and resulted in possibly conservative design parameters according to national guidelines. The findings confirmed that PK and PH are useful for stratigraphic profiling but not for parameter derivation in silts. CPTU, if calibrated with laboratory data, offers a more robust alternative and highlights the need for updated, silt-specific correlations in Finland.

Keywords: silt; in situ testing; CPTU; weight sounding; static–dynamic penetration testing; variability; geotechnical design

1. Introduction

The geotechnical characterisation of silty soils remains a longstanding challenge. Unlike clays, which have been extensively studied and benefit from well-developed regional correlations, databases, and interpretation frameworks, silts continue to pose challenges. Their transitional nature, spanning from silty clays to silty sands, combined with variable mineralogy and particle size distribution, leads to complex mechanical behaviour that is not easily captured by approaches derived for sands or clays [1–6]. The result is often highly variable in laboratory and in situ tests, creating significant uncertainty in geotechnical design.

In Finland, this issue is of particular interest. Glacial and post-glacial processes have left widespread silt deposits, especially along the west coast and in former lacustrine basins. Finnish soft clays have been the subject of extensive research [7–29]. Work at the benchmark sites provided core insight into clay properties, sampling quality, anisotropy, and strain-softening behaviour [7,9,11,12,16, 27–29]. Several studies developed and refined CPTU-based correlations for undrained shear strength and preconsolidation stress using database analyses [8,10,13,14], analytical CPTU modelling [17,23], and validation against laboratory reference data [19,22–24]. Additional research examined the reliability of CPTU measurements and equipment performance, including sleeve-friction accuracy and broader findings [15,25]. Moreover, through numerical and constitutive-model investigations, researchers further explored uncertainties in strength evaluation using Finite Element, as well as normalized and Critical State frameworks [18,21,26]. Seismic methods were also introduced to support strength characterisation in Nordic clays (20). These studies led to reliable empirical clay correlations and incorporation into official guidelines [30]. On the other hand, comparable efforts for silts have been limited [31–33]. The scarcity of high-quality undisturbed samples has posed a limitation in the calibration of in situ test results, such as piezocone penetration test (CPTU). Consequently, design parameter selection has frequently relied on guideline values developed decades ago [34].

The most common site investigation methods in Finland are the Weight Sounding Test (Painokairaus, PK) [35] and the Combined Static–Dynamic Penetration Test (Puristinheijarikairaus, PH) [36]. These sounding techniques have been used routinely for over half a century and form the backbone of preliminary geotechnical investigation practice [37]. Their results are linked to soil parameters through empirical relationships that were originally developed between the 1960s and 1990s, which were incorporated into the Finnish National Annex to Eurocode 7 (NCCI7, Annex 6) [34]. While convenient and inexpensive, the interpretation of PK and PH results is highly empirical, strongly operator-dependent, and known to be less reliable in soft soils. The correlations tend to be conservative, often underestimating soil strength, which can lead to costly overdesign or unnecessary ground improvement.

In contrast, the Cone Penetration Test with pore pressure measurement (CPTU) has become the international reference for in situ characterisation of fine-grained soils. CPTU provides continuous, high-resolution measurements of cone resistance, sleeve friction, and pore pressure response, and has well-established interpretation frameworks [38]. However, CPTU is not without challenges in silts: Partial drainage effects during penetration complicate interpretation, and transitional behaviour may not conform to clay- or sand-based correlations [4,33,39,40]. Despite these limitations, CPTU offers greater repeatability and objectivity than PK and PH, making it a promising method for advancing the characterisation of Finnish silts.

Recognising the limitations of current practice, Tampere University and the Finnish Transport Infrastructure Agency (FTIA, Väylävirasto) launched the FINCONE II project (2021–2025). The project aims to develop silt-specific correlations between CPTU results and laboratory parameters while exploring the use of artificial intelligence tools to model stratified deposits. The overarching goal is to reduce uncertainty in parameter selection and to modernise geotechnical design practice for silty soils in Finland.

As part of FINCONE II, a comparative field campaign was carried out at the Haistila test site near Pori in south-western Finland. The site consists of sandy and lightly overconsolidated silts in a coastal post-glacial environment and offers relatively homogeneous stratigraphy, making it well suited for benchmarking purposes. In this campaign, Tampere University conducted PK, PH, and CPTU tests, which were independently repeated by Ramboll Finland Oy, one of the country's largest geotechnical engineering consultancies. This setup provided a unique opportunity to compare results not only across methods but also across operators, thereby quantifying the impact of methodological and operator variability.

Our objectives of this study are:

- Benchmarking: To compare PK, PH, and CPTU results in a coastal silt deposit, as tested independently by Tampere University and Ramboll Finland Oy.
- Variability assessment: To quantify the variability between methods and operators using relative error and coefficient of variation metrics.
- Design implications: To evaluate how these variabilities influence the derivation of engineering parameters, particularly soil strength, and to assess whether reliance on PK/PH guidelines may lead to conservative or misleading design outcomes.

The findings are of direct relevance to geotechnical engineering practice in Finland, where silts are common yet poorly characterised, and where current reliance on traditional sounding methods may compromise safety and cost-efficiency. More broadly, the study contributes to international research on silty soil behaviour and highlights the importance of developing region-specific correlations for in situ testing methods.

2. In situ testing in Finland

2.1. Weight Sounding Test (Painokairaus, PK)

The Weight Sounding Test (PK) is one of the most traditional geotechnical investigation methods in Finland. Originally developed in Sweden, it has been used since the 1930s and remains an inexpensive and practical method for preliminary soil profiling. The test consists of pushing or rotating a rod with a conical tip into the ground while applying a standard weight, typically 1 kN. If penetration under this load is insufficient, the rod is rotated manually or with a motorised rig, and the number of half-turns required for a penetration increment of 200 mm (L/0.2 m or pk/0.2 m) is recorded. In dense soils, hammering may be applied to advance the rod further [35,37].

The PK test provides a simple measure of soil resistance that can be plotted as penetration under weight and number of turns versus depth. Soil stratigraphy is inferred from changes in resistance and from the operator's field notes. PK is especially effective for detecting layer boundaries and identifying coarse-grained or stiff layers. However, the method has significant limitations in fine-grained soils, such as clays and silts, where penetration resistance cannot be easily linked to soil strength or stiffness. Interpretation is highly empirical, relying on long-standing experience and regional practice. Figure 1 illustrates the principal procedure historically used for PK. This schematic is included for conceptual clarity, as the traditional approach differs from current practice.

In Finnish design practice, PK data has historically been used to estimate strength from correlations that are based on studies from the 1960s–1980s and, based on the authors' experience, are regarded as conservative. Although widely performed because of its low cost and simplicity, PK is mainly used as an initial ground screening tool to target locations where to apply more advanced techniques such as CPTU. Overall, PK results contribute to the definition of the geotechnical ground model for a given project.

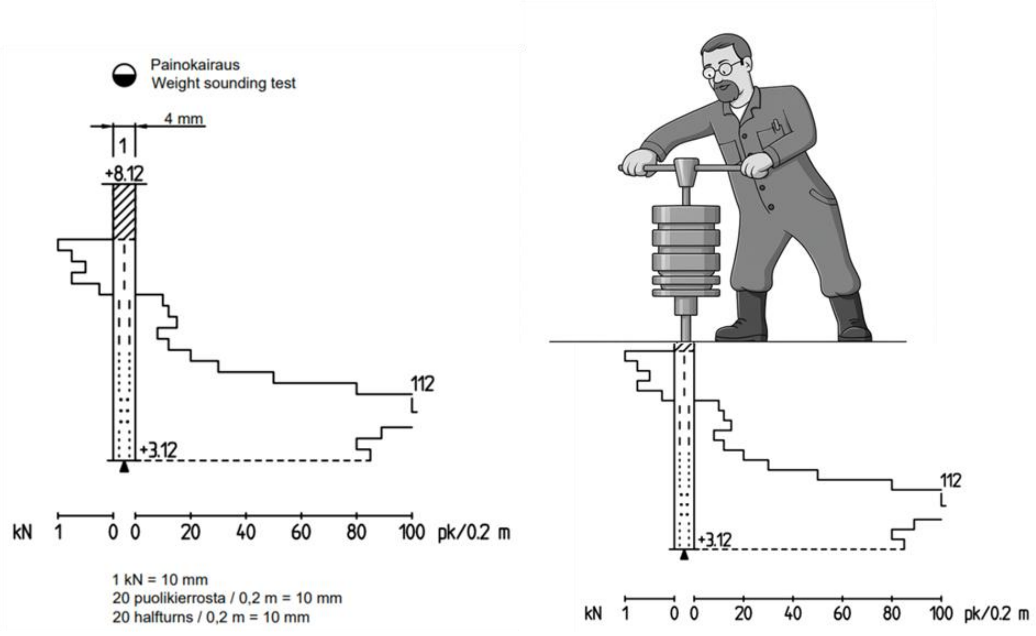

Figure 1. Weight Sounding (PK) principal procedure and interpretation (adapted from [35]; the human operator in the figure was AI-generated using ChatGPT 5.1).

2.2. Combined Static–Dynamic Penetration Testing (Puristinheijarikairaus, PH)

The Combined Static–Dynamic Penetration Test (PH) is a hybrid method that extends the range of soils that can be investigated compared to PK. The PH test begins with a static phase, where a cone penetrometer is pushed into the soil at a constant rate (20 ± 5 mm/s) up to a maximum static force, typically 30 kN. Measurements recorded during this phase include cone resistance, sleeve friction, and torque. When static penetration is no longer feasible, the test switches to a dynamic phase, in which a standardised hammer is used to drive the probe further. The number of blows per 200 mm $N20$ is recorded as the dynamic resistance. If penetration resumes easily after a few blows, the static phase may continue [36,37].

PH provides richer information than PK, especially because the static phase enables measurement of cone resistance and torque, which can be linked to soil type. For example, thin silt layers often appear as sharp peaks in resistance, whereas thicker silts show fluctuating but consistent torque behaviour. In practice, PH is widely applied in Finland for investigating a range of soils from clays to sands and gravels. Representative PH records showing torque and tip resistance variability with depth are presented in Figure 2.

As with PK, interpretation of PH results is strongly empirical. Finnish design guidelines (NCCI7 Annex 6) [34,41] provide correlations between PH results and geotechnical parameters such as friction angle, soil unit weight, and modulus number. However, these correlations are based on limited datasets and were developed several decades ago [41]. In silts, the interpretation is particularly uncertain: The transitional nature of the soil leads to conservative estimates of shear strength, which may underestimate bearing capacity or overestimate settlement potential.

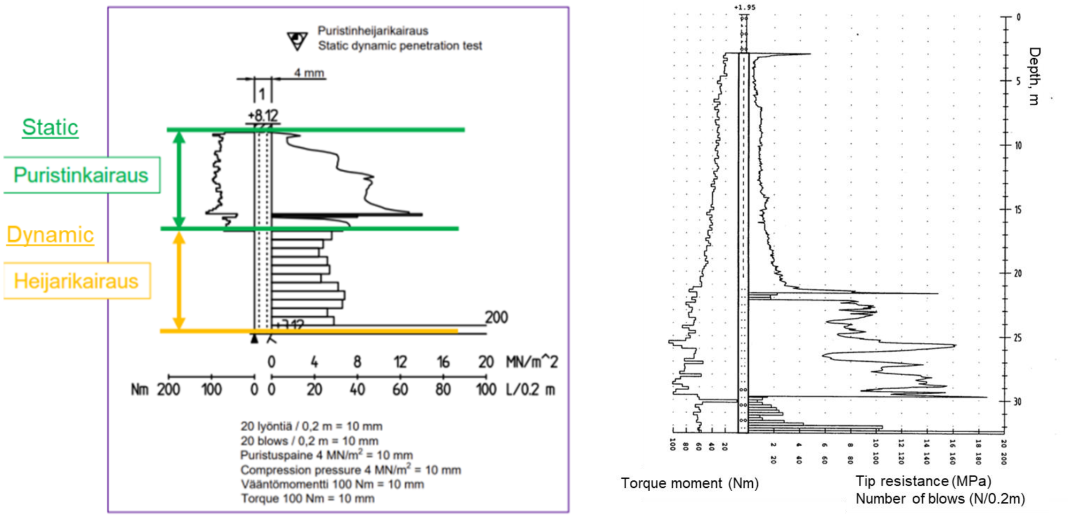

Figure 2. Example PH results; torque and tip resistance behaviour (adapted from [36]).

2.3. Cone Penetration Test with Pore Pressure Measurement (CPTU)

The Cone Penetration Test with pore pressure measurement (CPTU) is internationally recognised as one of the most reliable and repeatable methods for in situ soil characterisation [38]. CPTU involves pushing an instrumented cone penetrometer into the ground at a constant rate, measuring cone resistance q_c, sleeve friction f_s, and pore water pressure u_2. Compared to PK and PH, CPTU provides continuous profiles with high resolution and minimal operator influence.

In Finland, CPTU has gained popularity in recent decades, particularly for clay characterisation, where correlations between CPTU data and laboratory parameters have been extensively validated [15,17,19,22,24–27,29,42,43]. However, CPTU interpretation in silts remains challenging due to partial drainage during penetration, transitional behaviour, and lack of region-specific correlations. Nevertheless, CPTU offers clear advantages in terms of repeatability and parameter derivation [38].

2.4. Current guideline practice in Finland

The Finnish National Annex to Eurocode 7 (NCCI7) [34] provides guidance on deriving geotechnical parameters from traditional soundings, particularly PK and PH. The recommended correlations were developed from research conducted between the 1960s and 1990s, and while they have been widely adopted in practice, they do not reflect more recent advances in soil characterisation [41].

For silts, reliance on PK and PH data interpreted through NCCI7 may result in conservative parameter estimates [41]. This conservatism may be partly seen as beneficial, as it compensates for uncertainties, but it can also lead to uneconomical designs requiring ground replacement or stabilisation. Furthermore, the growing use of CPTU in Finland is not fully reflected in official guidelines for silts, creating a disconnect between practice and modern testing capabilities. A comparison of parameter derivation from PH versus CPTU, and the resulting implications for design, will be presented later in this paper (see Section 6).

Table 1 presents an extract from NCCI7 for coarse silts to sands. Notably, the table does not include soils finer than coarse silts.

Table 1. Extract from Finnish Eurocode 7 guidelines (NCCI 7, Annex 6) [34]; English translation [34].

Soil type		Unit weight (kN/m³)		Friction angle (°)	Janbu's tangent modulus parameters		Sounding resistance		
		Dry	Submerged		Modulus number *m*	Stress exponent *β*	Cone resistance from dynamic penetration test (puristinheijari) q_c (MPa)	Weight sounding Pk/0.2 m (Pk = half rotations)	Blow count from dynamic penetration test (puristinheijari) L/0.2 m (L = blows)
Coarse silt	Loose	14...16	9…	28	30…100	0.3	<7	<40	<8
	Medium-dense			30	70…150	0.3	7…15	40…100	8…25
	Dense	16…18	11	32	100…300	0.3	>15	>100	>25
Fine sand $d_{10} < 0.06$	Loose	15…17	9…	30	50…150	0.5	<10	20…50	5…15
	Medium-dense			33	100…200	0.5	10…20	50…100	15…30
	Dense	16…18	11	36	150…300	0.5	>20	>100	>30
Sand $d_{10} > 0.06$	Loose	16…18	10…	32	150…300	0.5	<6	10…30	5…12
	Medium-dense			35	200…400	0.5	6…14	30…60	12…25
	Dense	18…20	12	38	300…600	0.5	>14	>60	>25

3. Haistila test site and geological context

The Haistila test site [32] is in Ulvila, approximately 3 km from the coastal city of Pori in south-western Finland, on the left bank of the Kokemäki River (Figure 3). The area forms part of the coastal lowlands bordering the Gulf of Bothnia, which are characterised by extensive Quaternary deposits shaped by glacial and post-glacial processes.

The site stratigraphy is relatively homogeneous across the test area, which makes it particularly suitable for benchmarking studies. Based on borehole data and in situ investigations, the upper profile consists of approximately 3 m of sandy silt underlain by about 7 m of lightly overconsolidated silt [32]. These layers rest on stiffer glacial deposits, which form the geological basement for the Holocene sediments. The overlying silts were deposited in low-energy lacustrine and marine environments following the retreat of the last Ice Sheet, and their properties have been influenced by subsequent post-glacial land uplift and the evolving Baltic basin [44].

A broader geological context highlights the significance of these deposits. The west coast of Finland, including the Pori region, has been strongly shaped by alternating glacial advances and retreats during the last Ice Age. As the glaciers melted, fine sediments were deposited in sheltered basins such as estuaries, river deltas, and glacial lakes. In the Haistila area, silts accumulated particularly during the Ancylus Lake and Litorina Sea stages of the Baltic Sea. Today, the sediments are exposed to surface conditions due to continuous post-glacial rebound, which in this part of Finland is on the order of 6–7 mm per year [44].

The underlying bedrock is primarily Precambrian in age, dominated by Svecofennian granites and metamorphic rocks. In addition, the Satakunta sandstone, a distinct Proterozoic quartz-rich sedimentary formation, is found locally in the Pori region. Deep fracture zones within the bedrock have influenced the development of sedimentary basins and, therefore, the thickness of Quaternary deposits. Around the Kokemäki River delta, silts are particularly widespread, often interbedded with clays or organic-rich layers, and overlying moraine or glaciofluvial deposits [44].

The combination of homogeneous silt stratigraphy and accessibility makes Haistila a suitable natural laboratory for geotechnical research. Within the framework of FINCONE II, Haistila was selected for comparative in situ testing to investigate the variability of PK, PH, and CPTU methods when carried out by different operators.

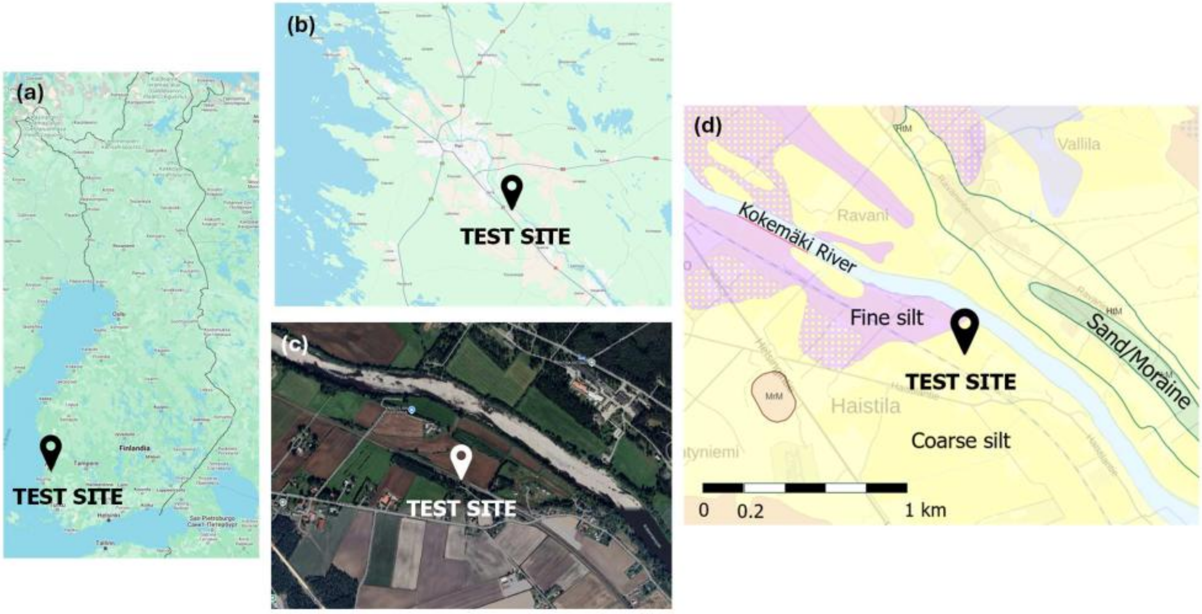

Figure 3. a-c) Location of Ulvila (Haistila) test site (Google Maps, coordinates 61.409080° N, 21.930159° E) and d) Surface geology (1 m depth) (GTK) (from [32]).

4. Methodology

4.1. Field campaign and scope

The benchmarking campaign at Haistila formed part of the FINCONE II project. Its major aims were to compare traditional Finnish in situ tests (PK and PH) with CPTU, and to assess the variability introduced by different operators. Tests were conducted independently by Tampere University (TAU) and Ramboll Finland Oy (RAM), one of the country's largest geotechnical engineering consultancies and the only operator to respond to Tampere University's invite.

The minimum amount of testing required from the operator was at least 1 PK, 1 PH, and 1 CPTU. Eventually, the resulting dataset from Haistila comprised the following:

- PK tests: 5 soundings by TAU and 1 sounding by RAM.
- PH tests: 2 soundings by TAU and 2 soundings by RAM.
- CPTU tests: 1 sounding by TAU and 2 soundings by RAM.

This setup provided a limited but valuable dataset for cross-comparison of methods and operator influence. It should be noted that TAU and RAM soundings were performed within a radius of 5 m from the benchmark TAU test locations. The close spacing minimises the influence of large-scale site heterogeneity, meaning that differences in results can be attributed mostly to method- and operator-related variability.

4.2. Equipment and specifications

For PK tests, TAU and RAM employed multi-purpose drill rigs equipped with standard PK rods and conical tips. The procedure followed Finnish practice [35]: Initial probing through surface layers, application of a 1 kN load, and subsequent rotation if penetration resistance exceeded threshold limits. Results were recorded as penetration depth under weight and half-turns per 200 mm.

PH tests followed the standard Finnish method [36], beginning with a static cone penetration phase at 20 ± 5 mm/s, up to a maximum static force of ~30 kN. Cone resistance, sleeve friction, and torque were measured. Upon reaching refusal in static mode, the dynamic phase commenced, with the number of hammer blows per 200 mm $N20$ recorded. TAU and RAM employed comparable equipment, although slight differences in torque measurement systems were noted, which may partly explain the variability observed later.

TAU and RAM used 50 mm² cones with pore pressure measurement at the u_2 position. Both systems had a maximum cone resistance capacity of 50 MPa, sleeve friction of 1.6 MPa, and pore pressure of 2.5 MPa. The accuracy of the TAU cone was within 0.01% for cone resistance, 0.0025% for sleeve friction, and 0.0015% for pore pressure, whereas the RAM system specified an accuracy better than 0.01% for cone resistance, 0.05% for sleeve friction, and 0.05% for pore pressure. The CPTU soundings were performed to depths of approximately 10 m.

4.3. Variability metrics

To evaluate the consistency of test results, three variability metrics were applied:

Relative Error (RE):

$$RE = \frac{|x_{RAM} - x_{TAU}|}{x_{TAU}} \times 100 \tag{1}$$

where x_{RAM} and x_{TAU} are the parameter values measured by Ramboll and Tampere University, respectively.

Coefficient of Variation (COV):

$$COV = \frac{\sigma}{\mu} \times 100 \tag{2}$$

where σ is the standard deviation and μ is the mean value of all repeated measurements at a given depth. It is important to note that, for COV, all measurements are considered equally.

Coefficient of determination (R^2):

$$R^2 = \frac{\left(\sum_{i=1}^{n} x_{TAU,i} x_{RAM,i}\right)^2}{\left(\sum_{i=1}^{n} x_{TAU,i}\right)\left(\sum_{i=1}^{n} x_{RAM,i}\right)} \tag{3}$$

To quantify the agreement between RAM and TAU measurements, a linear regression was performed with the intercept constrained to zero, ensuring direct comparability with the ideal 1:1 line. The resulting R^2 value was used as a goodness-of-fit measure, with values closer to one indicating higher consistency.

These metrics were applied to CPTU parameters and to selected PH and PK outputs, enabling quantification of repeatability across methods and between operators.

5. Results

The CPTU measured parameters q_t, f_s, and u_2 obtained by TAU and RAM are illustrated in Figure 4. The measurements showed generally good agreement (Figure 5).

The stratigraphy, interpreted according to the I_c method by [45], was consistently identified by both operators, with ~3 m of sandy silt overlying ~7 m of lightly overconsolidated silt. This was validated by the particle size distribution (PSD) analyses reported in [32].

Relative error analysis indicated the smallest deviations in q_t compared to other parameters (Figure 6). However, direct comparison is challenging for silts because thin layers do not align at exactly the same depths, as shown in Figure 5. The COV for q_t was also the lowest among the measured parameters (Figure 7), confirming the higher repeatability of cone resistance compared to sleeve friction and pore pressure. Sleeve friction and pore pressure showed greater scatter, reflecting their higher sensitivity to local heterogeneities and equipment effects [46].

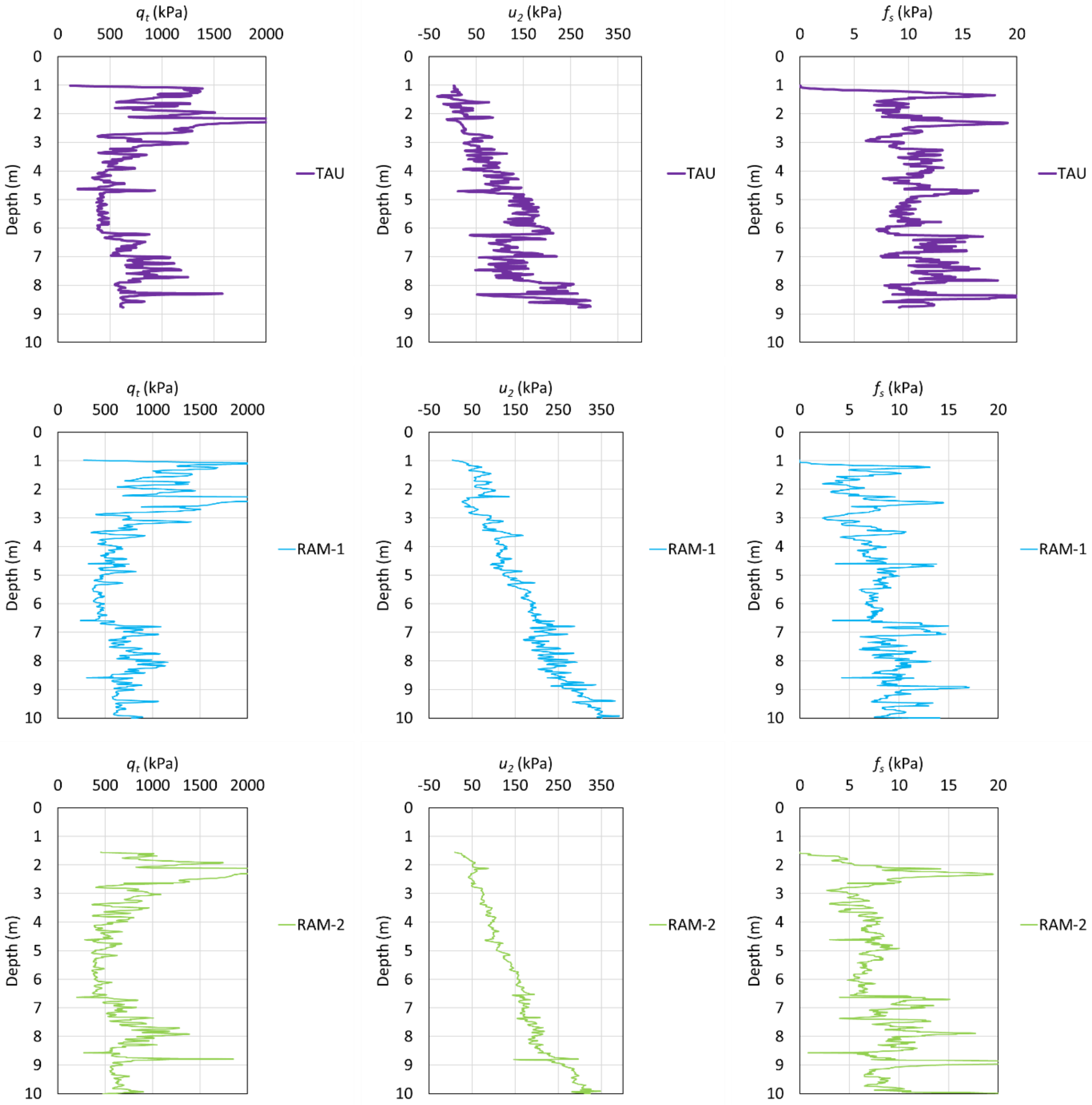

Figure 4. CPTU parameters q_t, u_2, and f_s from TAU and RAM measurements.

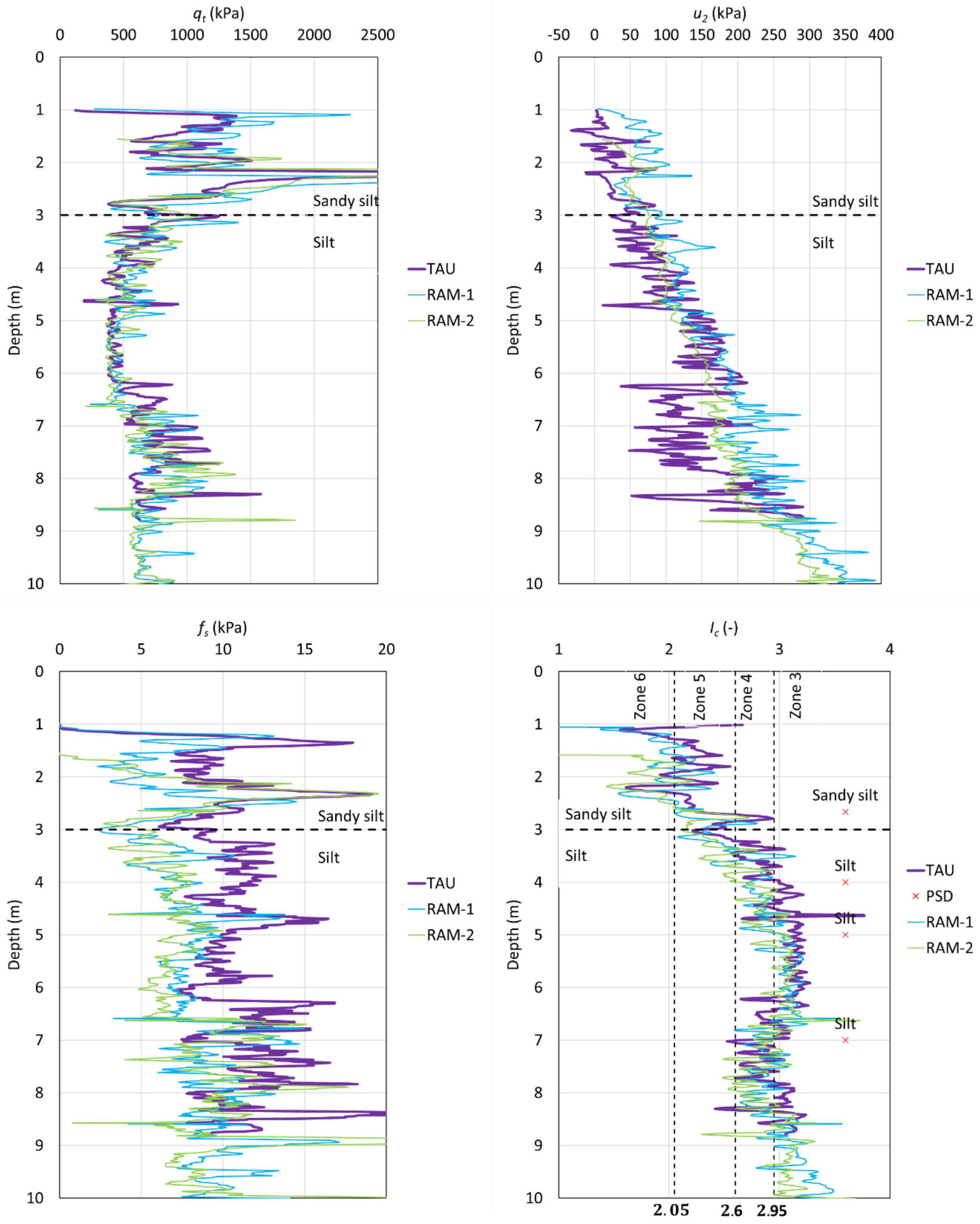

Figure 5. CPTU profiles from TAU and RAM.

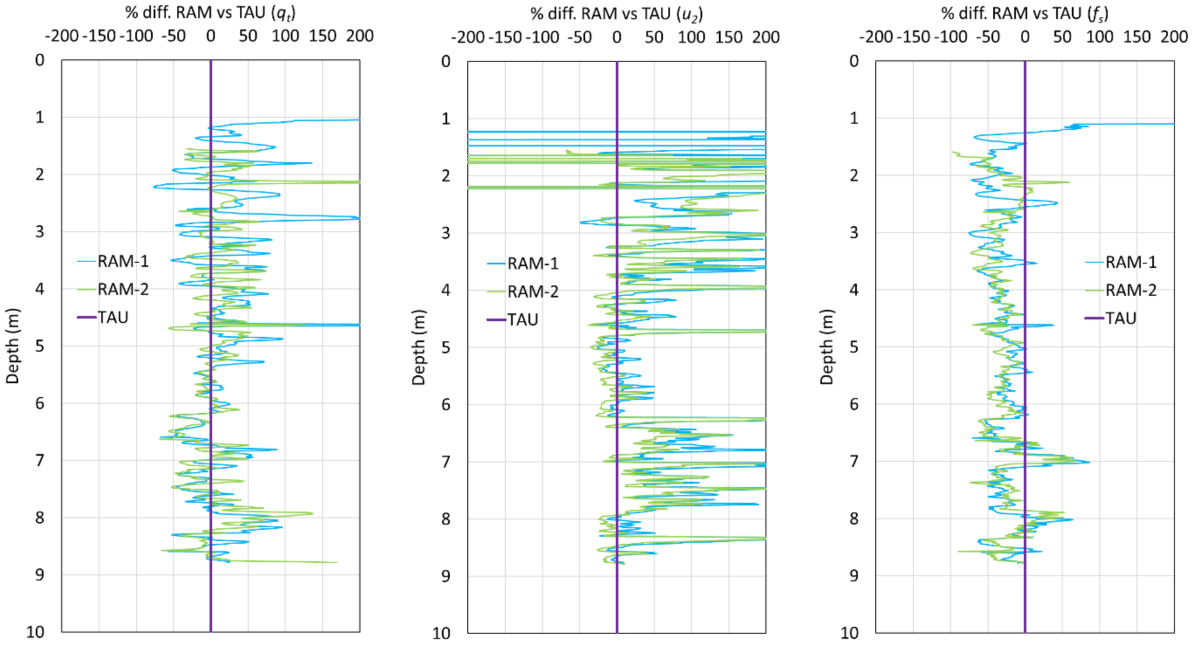

Figure 6. Relative error (RE) of CPTU parameters.

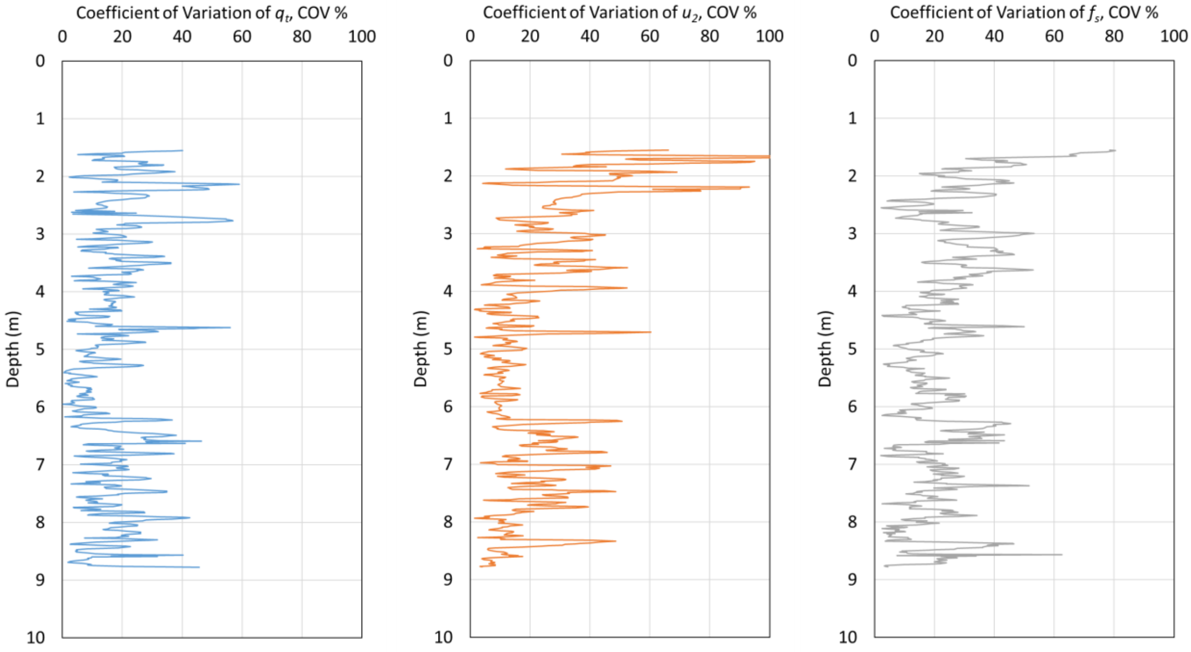

Figure 7. COV of CPTU parameters.

The coefficient of determination (R^2) values were consistently high across all parameters, indicating that the paired measurements follow the same overall trends despite local scatter (Figure 8). The slopes' deviation from the 1:1 line showed only modest systematic bias, which was minimal for q_t, and slightly more pronounced for u_2 and f_s, highlighting that most differences arise from random variability rather than systematic offset.

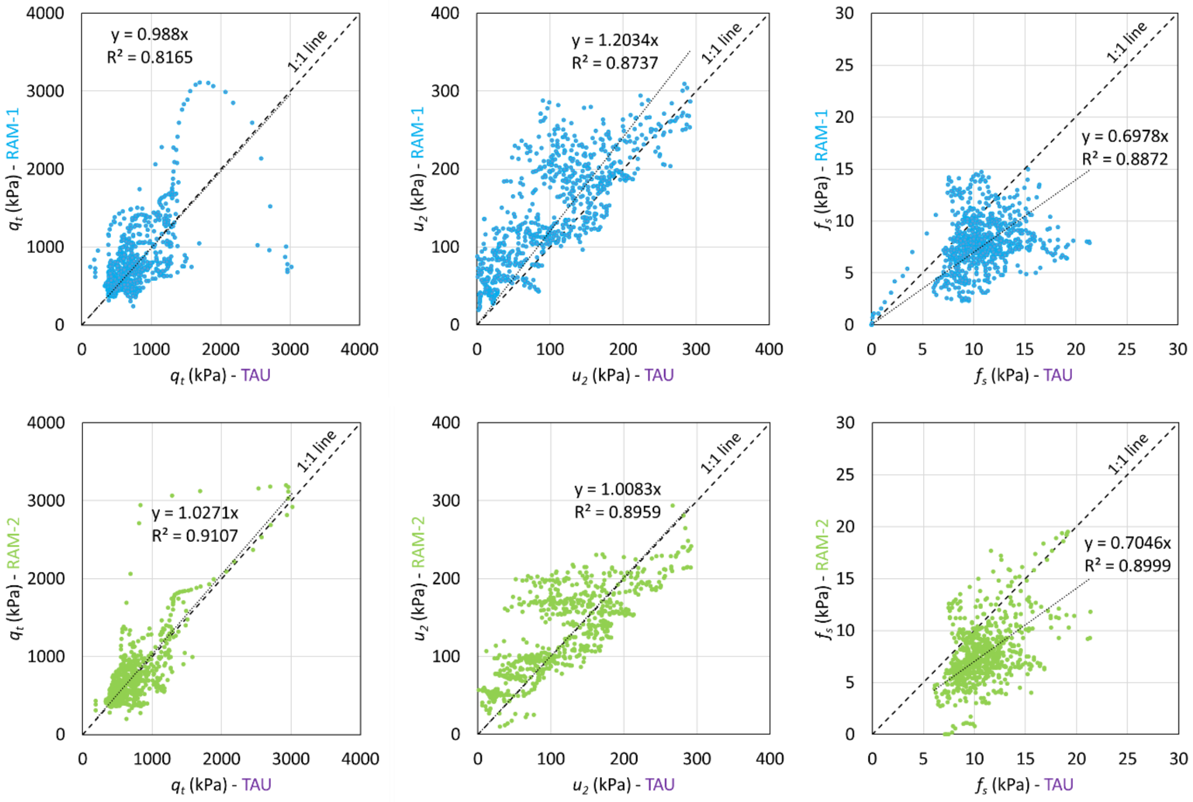

Figure 8. R^2 of CPTU parameters.

The PK soundings performed by TAU (five) and RAM (one) were consistent in detecting the main stratigraphy (Figure 9). Moreover, slightly stiffer behaviour was noted in the upper 2 m in the TAU profiles, while deeper layers showed similar resistance patterns. However, due to the empirical and operator-dependent nature of PK, the results could not be easily converted into quantitative soil parameters. This reinforces the method's role as a qualitative tool for stratigraphic identification rather than parameter derivation.

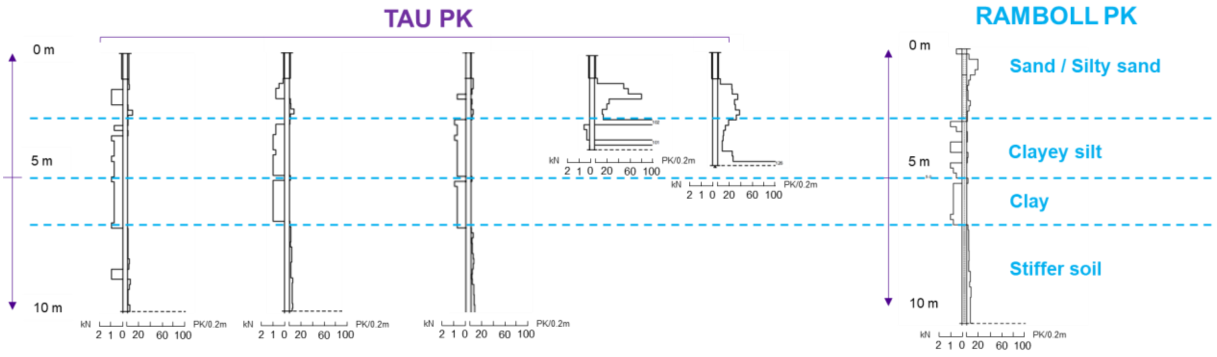

Figure 9. PK sounding comparison TAU vs RAM.

PH tests performed by TAU (two) and RAM (two) showed comparable tip resistance profiles, confirming broad agreement in identifying stratigraphy (Figure 10). However, torque (M) values measured by RAM were consistently higher than those obtained by TAU, particularly in the depth range of 2–7 m. This discrepancy may be linked to differences in equipment calibration or operator technique. For this reason, relative error between RAM and TAU measurement was not evaluated. The COV was used for comparison.

The variability of PH results was significantly higher than CPTU (Figures 11 and 12). Thin interlayers within the silt produced sharp peaks in resistance, while thicker silt zones exhibited fluctuating torque behaviour that was difficult to correlate consistently with soil properties. These issues highlight the sensitivity of PH to soil variability and operator/equipment factors.

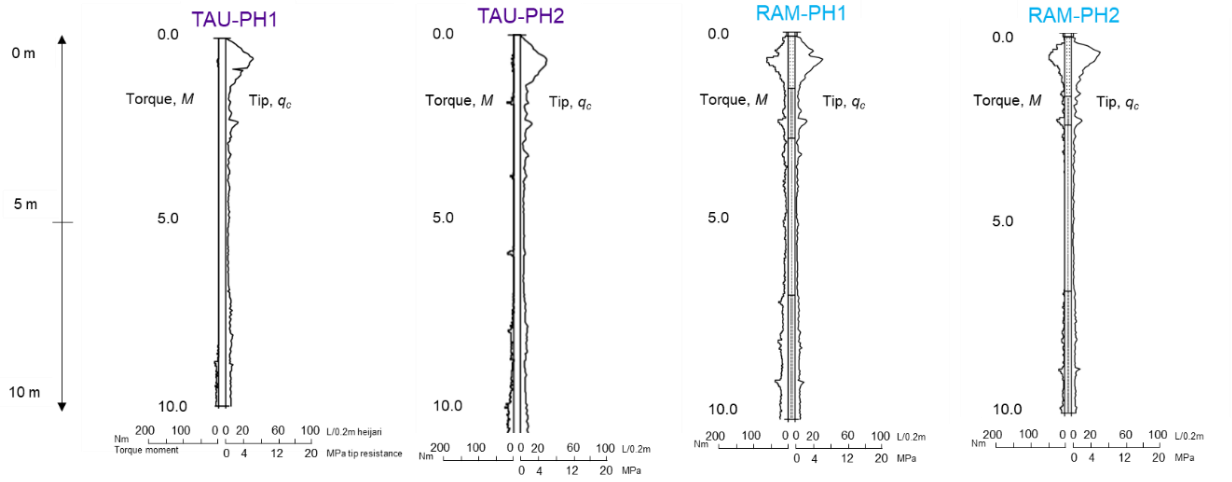

Figure 10. PH torque and tip resistance profiles TAU vs RAM.

When comparing CPTU and PH as methods, CPTU exhibited lower COV values, especially for q_t, as shown in Figure 12. This suggests that CPTU is inherently more repeatable and less operator-dependent than PH. However, the limited sample size (three CPTU and four PH tests) restricts the statistical robustness of these findings.

Moreover, it should be emphasised that COV and RE were calculated over very narrow (1–2 cm) depth intervals. Although the site was broadly homogeneous, thin interlayers and small shifts in stratigraphy between soundings were difficult to align precisely, as shown in Figure 5. These mismatches have artificially increased the apparent variability. Thus, averaging results over larger depth windows would likely reduce COV values and provide a more representative measure of consistency.

Despite this limitation, the observed trends point towards CPTU as the more reliable method for parameter derivation in silty soils, while PH results tended to show higher scatter and conservative estimates.

The R^2 values for tip resistance (q_c) were moderate to high, showing that both devices captured broadly similar trends, whereas the very low R^2 values for M indicated poor agreement and strong scatter between paired torque measurements (Figure 13). The pronounced deviations of the regression slopes from the 1:1 line, especially for M, highlight systematic differences between the PH devices in addition to the inherent variability of the method.

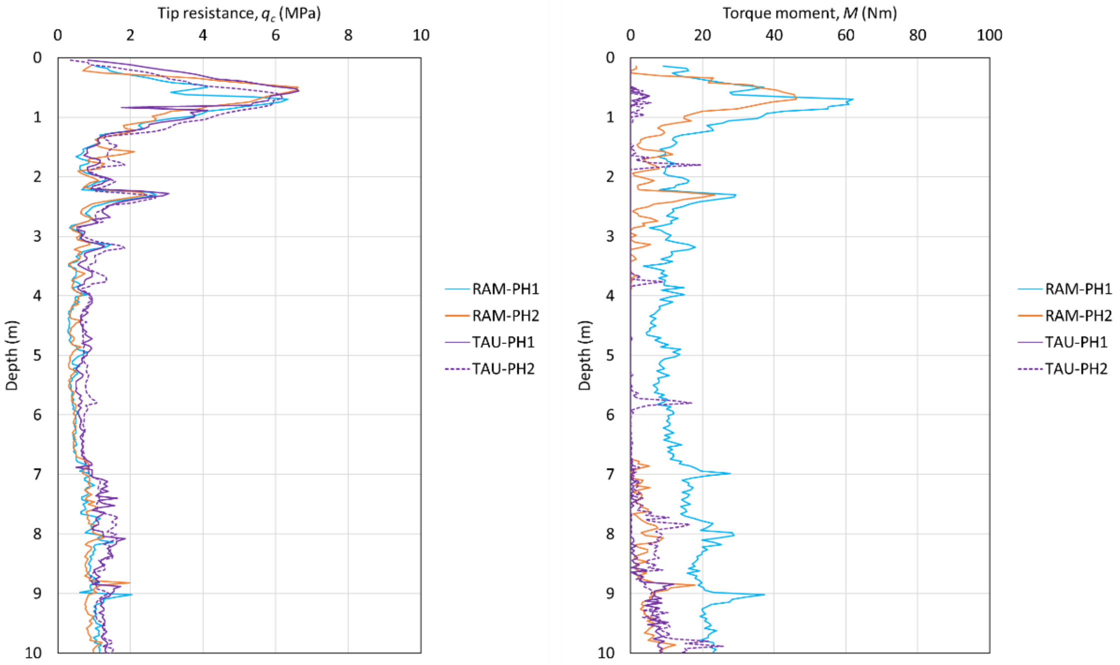

Figure 11. Variability comparison: CPTU vs PH.

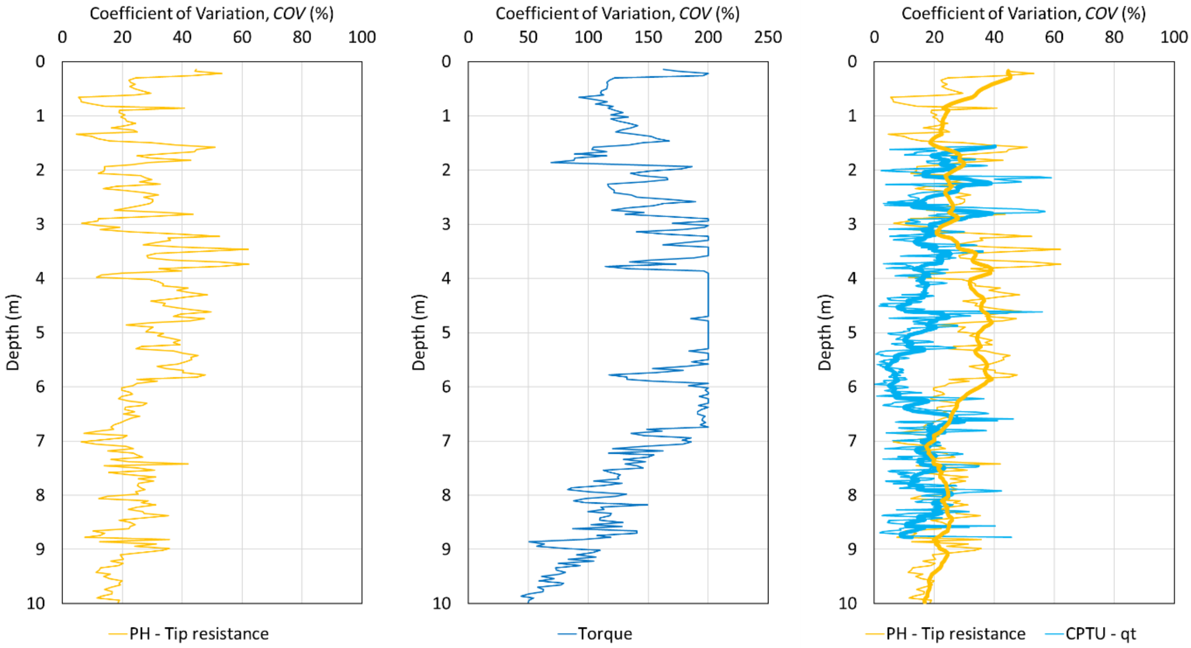

Figure 12. COV comparison: CPTU vs PH.

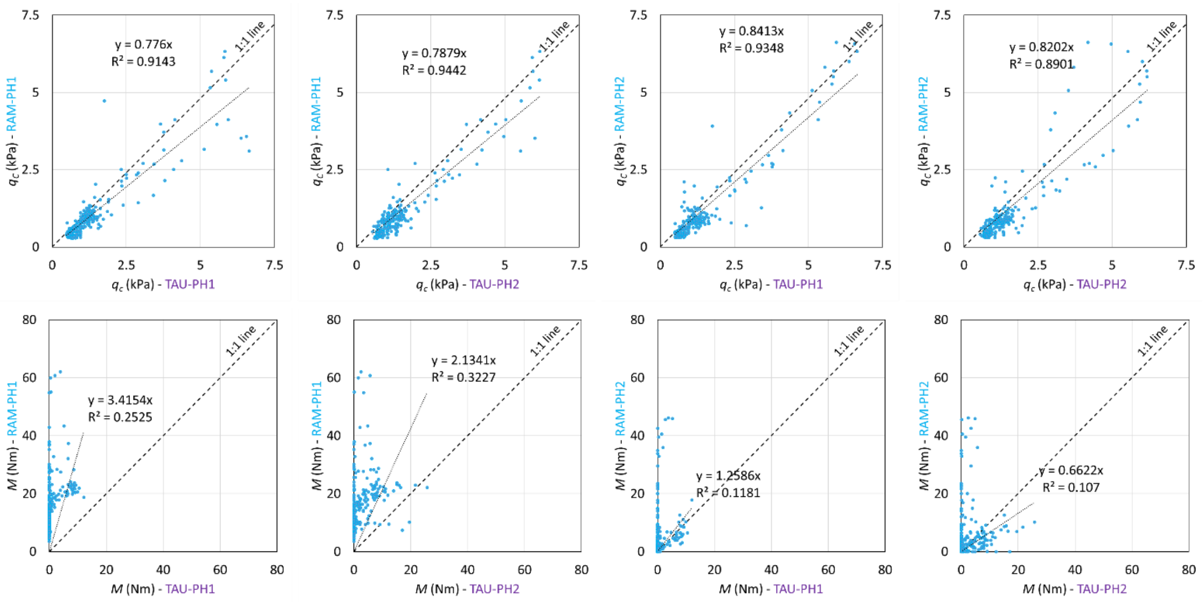

Figure 13. R^2 of PH parameters.

6. Discussion

6.1. Impact on geotechnical design parameters

According to Finnish guidelines [34], correlations between PH resistance and effective stress friction angle ϕ' can be applied. Based on the PH results from Haistila, where cone resistance values remained below 7 MPa, the derived friction angle was approximately $\phi' = 28°$ (see Table 1). This estimate classifies the soil as a loose coarse silt. Such a friction angle lies at the lower end of values typically reported for lightly overconsolidated silts [47,48], suggesting relatively weak shear strength. When applied in foundation design, this would translate into reduced bearing capacity and potentially large settlement estimates.

The PH-based estimate is likely to be overly conservative. Silts are transitional soils whose behaviour cannot be captured adequately by correlations developed for sands or clays, as for example demonstrated in the identification of permeability of coarse silts. In practice, this conservative interpretation could lead to uneconomical design choices, such as unnecessary soil replacement, stabilisation, or over-dimensioning of foundations. While conservatism in geotechnical design provides safety margins, excessive conservatism carries significant cost implications, particularly in infrastructure projects involving extensive silt deposits.

CPTU provides a more nuanced picture. Moreover, international frameworks for CPTU interpretation [48,49] suggest higher ϕ' values for silts ($\phi' \sim 30 - 32°$) with measurements in the observed range, but these correlations require calibration against local laboratory test data to ensure reliability. Laboratory tests on Haistila silt (not fully presented in this study) are needed to verify CPTU-derived parameters and to bridge the gap between empirical CPTU correlations and Finnish design practice. This calibration effort is ongoing within the FINCONE II project, which will provide the necessary laboratory–field linkages.

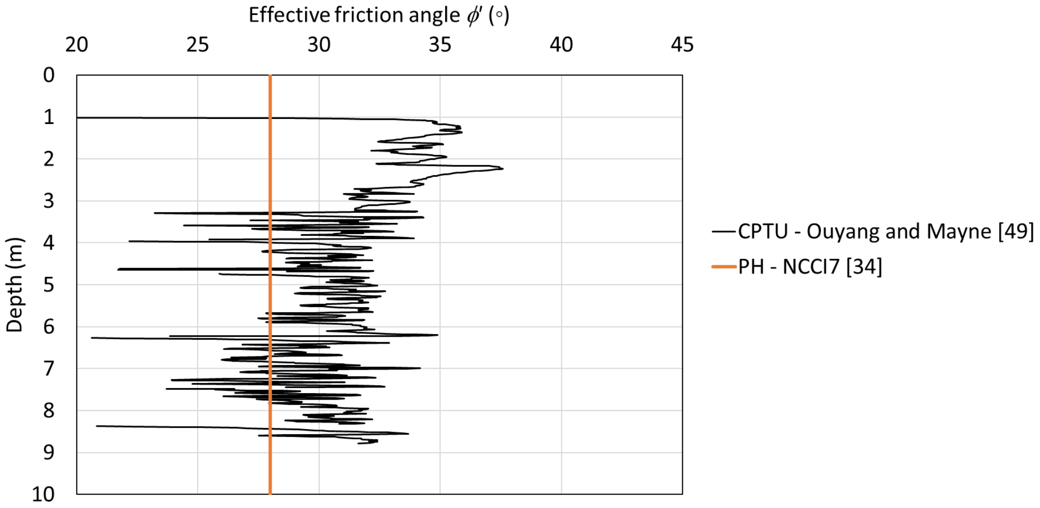

Figure 14. Friction angle interpretation from CPTU according to Ouyang and Mayne [49] and from PH based on [34].

The key advantage of CPTU is its repeatability and objectivity. Unlike PH, CPTU results are less dependent on operator judgement and equipment calibration, leading to more robust input for parameter derivation once appropriate correlations are developed.

6.2. Reliability of traditional methods

The results from Haistila confirm long-standing concerns about the reliability of traditional sounding methods in silts. PK and PH can identify stratigraphic boundaries, but their use for parameter derivation is problematic. PK, while inexpensive and rapid, showed limited ability to provide quantitative information beyond stratigraphy. Its results were broadly consistent between operators, but large uncertainty underlies the derivation strength or stiffness parameters. Thus, PK should be regarded primarily as a complementary method for preliminary profiling rather than as a tool for design parameter estimation in silts.

A major difficulty in evaluating soil parameters from PK and PH is that the NCCI7 tables (Table 1) start with coarse silts as the finest soil type, with relatively high resistance values for PK and PH. Consequently, engineers might interpret very low PK or PH values as indicative of clay or clayey silt and order field vane tests. However, vane tests in silty soils are highly problematic due to disturbance effects and often yield unrealistically low undrained shear strength values [30]. This limitation reinforces the need for caution when applying traditional methods in silts and highlights the importance of complementing them with more robust in situ or laboratory tests.

6.3. CPTU as a more reliable tool

CPTU demonstrated better repeatability than PH, with lower relative error and coefficient of variation, especially for cone resistance. This reinforces the international view that CPTU provides more reliable and objective measurements than operator-dependent sounding methods such as PH.

However, CPTU interpretation in silts is not straightforward. Partial drainage effects during penetration complicate the distinction between drained and undrained behaviour, and correlations derived for sands or clays may not apply directly.

The Haistila study highlights the need for further calibration of CPTU-based correlations against laboratory data. This calibration would enable CPTU to move from being a reliable profiling tool to a robust parameter derivation method for Finnish silts. Such work is being undertaken in the FINCONE II project, but broader datasets and multi-site campaigns will be required to establish confidence at the national scale.

6.4. Influence of operator and equipment

One of the unique aspects of the Haistila campaign was the comparison between two independent organisations, TAU and RAM. The results showed that while CPTU data were consistent across operators, PH torque measurements differed systematically, with RAM recording higher values. This suggests that equipment calibration, torque measurement systems, or operator techniques may introduce systematic biases in PH results. Such variability complicates the reliability of PH as a quantitative design tool.

The findings emphasise the importance of operator training, equipment calibration, and standardised procedures when using empirical methods such as PH. Without rigorous standardisation, variability between contractors can exceed the natural variability of the soil, undermining the reliability of the results.

6.5. Implications for guidelines and practice

The findings from Haistila highlight important implications for Finnish geotechnical practice. Current reliance on PK and PH in design reflects historical practice rather than technical reliability. While these methods will continue to serve as cost-effective tools for preliminary stratigraphic profiling, they should not be used as the main basis for parameter derivation in silts.

CPTU, by contrast, offers a more reliable foundation for parameter estimation, provided that silt-specific correlations are developed and calibrated with laboratory data. Updating the Finnish National Annex (NCCI7) to incorporate modern CPTU-based approaches would align design practice with current testing capabilities. Such updates should be supported by expanded field datasets and ongoing calibration efforts, including those within the FINCONE II project.

6.6. Broader relevance

Beyond Finland, the findings resonate with the international challenge of characterising transitional soils. Silts often fall between the domains of well-established clay and sand frameworks, making them difficult to interpret consistently. The Haistila study illustrates the risks of over-relying on outdated empirical correlations and underscores the need for site-specific calibration of in situ tests.

The study also demonstrates the value of collaborative benchmarking between academia and industry. By involving TAU and RAM, the results reflect real-world variability in practice and provide a basis for developing improved guidelines that can be widely adopted.

7. Conclusions

In this study, we have presented the results of a comparative field campaign at the Haistila test site in south-west Finland, aimed at benchmarking the performance of traditional sounding methods, Weight Sounding (Painokairaus, PK) and Combined Static–Dynamic Penetration Test (Puristinheijarikairaus, PH), against piezocone (CPTU) in silty soils. Tests were carried out independently by Tampere University (TAU) and Ramboll Finland Oy (RAM), enabling assessment of method variability and operator influence. Based on the results, the following conclusions can be drawn:

- PK and PH provide useful stratigraphic information but limited parameter reliability. PK soundings consistently identified layer boundaries but could not provide quantitative strength or stiffness estimates. PH results showed higher variability and tended to yield conservative design parameters.
- CPTU showed superior repeatability, as shown by the comparisons between TAU and RAM, which indicated smaller relative errors and lower coefficients of variation for CPTU, particularly for cone resistance. CPTU therefore offers a more reliable basis for parameter derivation, although interpretation in silts requires further calibration.
- Operator and equipment effects are non-negligible. Systematic differences in PH torque measurements between TAU and RAM suggest that equipment calibration and operator technique can strongly influence results. Such variability highlights the need for standardisation.
- Design implications are significant, as conservative PH-based parameters may lead to oversizing of foundations, unnecessary soil replacement or stabilisation, and increased project costs and carbon footprint. CPTU, when supported by laboratory calibration, provides a more robust pathway towards safer and more economical design outcomes.
- Current Finnish guidelines and practice rely on empirical correlations from the 1960s–1990s. The results demonstrate the need to establish silt-specific CPTU correlations supported by laboratory calibration and broader field datasets.

In summary, the Haistila benchmarking campaign demonstrates the need for a transition in Finnish geotechnical practice: PK and PH should continue to be used for preliminary stratigraphic profiling, but CPTU should be adopted as the primary tool for parameter derivation in silts. It should also be acknowledged that the comparative dataset, particularly for the PH soundings, is limited and therefore restricts the statistical confidence of some observations; however, the trends observed are consistent with the known behaviour of the methods and provide a coherent basis for the interpretations presented. Ongoing research, including the FINCONE II project, is essential to establish calibrated correlations and to modernise design practice for these challenging soils.

Use of AI tools declaration

The authors declare they have used Artificial Intelligence (AI) tools in the creation of part of Figure 1. In particular, the human operator in the figure was generated using ChatGPT 5.1.

Author contributions

Marco D’Ignazio: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft; Mohammad Sadegh Farhadi: Investigation, Data curation, Writing—review & editing; Tim Länsivaara: Supervision, Validation, Project administration, Funding acquisition, Writing—review & editing.

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Conflicts of interest

The authors declare no conflicts of interest. Marco D'Ignazio and Tim Länsivaara are guest editors for AIMS Geosciences and were not involved in the editorial review or the decision to publish this article.

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