Civil and Sustainable Urban Engineering

Research Article
Volume 6(2), 2026, 376–393
https://doi.org/10.53623/csue.v6i2.1434

Integrated Piezocone and Standard Penetration Testing for Geotechnical Site Characterization in Tangerang, Indonesia

Asriwiyanti Desiani*, Daud Rahmat Wiyono, Adrian Pramono

Civil Engineering Program, Faculty of Intelligent Technology and Engineering, Universitas Kristen Maranatha, Bandung, West Java 40164, Indonesia

*Correspondence: asriwiyanti@gmail.com

SUBMITTED: 22 September 2026; REVISED: 14 October 2026; ACCEPTED: 19 October 2026

ABSTRACT: Groundwater conditions, and the mechanical behavior of soil layers. This study evaluates the complementary application of piezocone penetration testing (CPTu) and standard penetration testing (SPT) to characterize subsurface conditions at a site in Kampung Sawah, BSD–Tangerang, Indonesia. The investigation included two CPTu soundings, CPTu-01 and CPTu-02, reaching depths of 5.58 m and 5.28 m, respectively, and three boreholes, BH-01, BH-02, and BH-03, extending to depths of 29.50 m, 29.50 m, and 33.50 m, respectively. The borehole records revealed heterogeneous subsurface strata consisting of silty clay, clayey silt, sand, gravelly sand, weathered sandstone, and siltstone. Groundwater levels were recorded at depths of 3.50 m, 1.50 m, and 4.70 m below ground level in BH-01, BH-02, and BH-03, respectively. SPT values varied with depth and soil type, with relatively high values observed in several sandy and weathered rock intervals. A preliminary correlation between CPTu and SPT results was established using data from CPTu-01 and BH-02, yielding a coefficient of determination of $R^2 = 0.8075$. However, the shallow CPTu penetration depths and the absence of a complete depth-matched dataset limit the reliability and broader applicability of this correlation. Consistent with limitations reported in previous CPT-based soil classification and correlation studies, these findings highlight the importance of integrating multiple geotechnical investigation methods while accounting for uncertainties associated with empirical correlations and spatial variability. Overall, this study provides site-specific insights into subsurface conditions and establishes a preliminary basis for further geotechnical investigations and foundation design assessments.

KEYWORDS: CPTu; standard penetration test; soil stratigraphy; groundwater; geotechnical site characterization; Tangerang.

1. Introduction

Geotechnical site characterization is essential for evaluating subsurface conditions and determining appropriate design parameters for foundations and other civil engineering structures. Soil deposits often exhibit considerable horizontal and vertical variability due to differences in depositional environments, material composition, weathering processes, and

groundwater conditions. Such variability can influence bearing capacity, settlement, excavation stability, and overall construction performance. Inadequate characterization of these conditions may introduce uncertainties into geotechnical design and increase the risk of foundation-related problems. Therefore, reliable site investigations require the integration of field measurements with geological observations and geotechnical descriptions to establish a comprehensive understanding of subsurface conditions [1–3].

The cone penetration test (CPT) and piezocone penetration test (CPTu) provide continuous or near-continuous penetration profiles that facilitate the identification of changes in soil behavior and stratigraphic boundaries. CPTu additionally measures pore-water pressure, providing valuable information for interpreting the behavior of fine-grained and saturated soils. In contrast, the standard penetration test (SPT) is conducted at discrete depths within boreholes, providing penetration resistance measurements together with soil samples and visual descriptions. The testing procedures and measurement principles are specified in ASTM D5778-20 and ASTM D1586/D1586M-18, respectively [1, 2]. These methods offer complementary advantages, as CPTu provides detailed penetration responses, whereas borehole investigations and SPT measurements provide direct stratigraphic information and discrete assessments of soil resistance. Integrating these methods can improve subsurface interpretation, particularly in geological settings characterized by heterogeneous soil deposits [4–7].

CPTu interpretation commonly involves corrected cone resistance, sleeve friction, pore-water pressure, normalized penetration parameters, and soil-behavior-type classification. Robertson [3, 5] developed widely adopted approaches for classifying soil behavior using cone penetration measurements and interpreting normalized CPT parameters. Subsequent studies have examined the effects of data variability, spatial cross-correlation, and measurement noise on soil classification and stratigraphic interpretation [8, 9]. These investigations demonstrate that the reliability of CPTu-based classification depends on appropriate parameter definitions, measurement quality, and geological conditions. Consequently, interpreting CPTu results without considering local stratigraphy and data limitations may lead to uncertainties in identifying soil boundaries and estimating geotechnical properties.

The estimation of overconsolidation ratio (OCR) and undrained shear strength from CPTu measurements introduces additional uncertainties because these parameters are generally derived from empirical relationships rather than measured directly. Their interpretation requires assumptions regarding soil behavior, stress history, and the applicability of selected correlation factors. Previous investigations have evaluated CPTu-based methods for estimating OCR and undrained shear strength, emphasizing the importance of selecting appropriate empirical relationships and understanding their limitations [4, 7, 10]. Accordingly, reliable quantitative interpretation requires complete penetration measurements, clearly defined calculation procedures, and independent validation through laboratory or in situ testing whenever possible.

CPTu–SPT correlations have also been widely investigated to facilitate comparisons between penetration testing methods and support preliminary geotechnical assessments. However, relationships developed for particular soil deposits or geological environments may not be directly transferable to other locations. Variations in soil composition, geological history, testing procedures, SPT energy corrections, groundwater conditions, and depth-matching methods can influence the resulting correlations. Recent investigations of region-

specific CPT–SPT relationships have highlighted the importance of incorporating geological variability and statistical uncertainty rather than applying universal empirical relationships [11–13]. Similarly, studies examining penetration resistance and soil properties have demonstrated that correlation performance depends on soil characteristics and the physical mechanisms governing penetration behavior [14–19].

Despite these developments, integrating shallow CPTu measurements with substantially deeper borehole and SPT records remains challenging, particularly in heterogeneous geological formations where investigation depths and measurement intervals differ considerably. Existing correlation approaches may provide useful preliminary relationships, but their application becomes uncertain when only a limited depth interval is shared between testing methods. Furthermore, incomplete depth-matched measurements and differences in soil stratigraphy can complicate the interpretation of penetration resistance and the estimation of geotechnical parameters. These limitations highlight a need for site-specific investigations that distinguish directly measured properties from empirical estimates while explicitly identifying the uncertainties associated with integrating different investigation methods [15–17].

The Kampung Sawah site in BSD–Tangerang, Indonesia, provides a relevant case for examining these challenges because its subsurface conditions comprise alternating layers of fine-grained soils, sand, gravelly sand, and weathered sedimentary materials. Variations in groundwater levels and stratigraphic sequences among the boreholes indicate considerable subsurface heterogeneity, suggesting that a single generalized soil profile may not adequately represent the entire investigation area. Moreover, the CPTu soundings extend to depths of approximately 5–6 m, whereas the boreholes reach approximately 30–34 m. This substantial difference in investigation depth creates difficulties in establishing direct CPTu–SPT relationships and evaluating soil behavior throughout the subsurface profile. An integrated interpretation is therefore necessary to identify the complementary contributions and limitations of these investigation methods [16–19].

The novelty of this study lies in its site-specific integration of shallow CPTu measurements with deeper borehole and SPT records in a heterogeneous subsurface environment, while explicitly distinguishing measured observations, empirical correlations, and interpretative uncertainties. Rather than assuming that penetration resistance relationships are universally applicable, the study evaluates the available CPTu–SPT correlation within the constraints of the investigation data and considers the implications of limited penetration depth, stratigraphic variability, and incomplete depth matching. This approach provides a more transparent basis for interpreting subsurface conditions and assessing the reliability of preliminary geotechnical estimates.

Therefore, this study aims to evaluate the complementary application of CPTu and SPT investigations for characterizing subsurface conditions at the Kampung Sawah site in BSD–Tangerang, Indonesia. Specifically, the study examines subsurface stratigraphy and groundwater conditions, evaluates variations in penetration resistance, investigates the preliminary relationship between CPTu and SPT measurements, and assesses the limitations of estimating OCR and undrained shear strength from the available data. The findings are expected to provide a site-specific geotechnical interpretation that supports preliminary foundation assessment, identifies uncertainties in the existing investigation records, and informs the planning of further subsurface investigations.

2. Materials and Methods

2.1. Site and Investigation Layout.

The investigation was conducted at Kampung Sawah, BSD–Tangerang, Indonesia. The investigation layout identifies three boreholes (BH-01, BH-02, and BH-03) and two CPTu soundings (CPTu-01 and CPTu-02). The layout provides the spatial context for comparing the field records; however, exact horizontal distances between individual investigation points were not calculated because a complete coordinate dataset and verified drawing scale were not available in the records used for this analysis. The locations of the five investigation points are presented in Figure 1. The layout provides the spatial context for the interpretation but does not establish a continuous subsurface section or prove that individual CPTu soundings are colocated with particular boreholes.

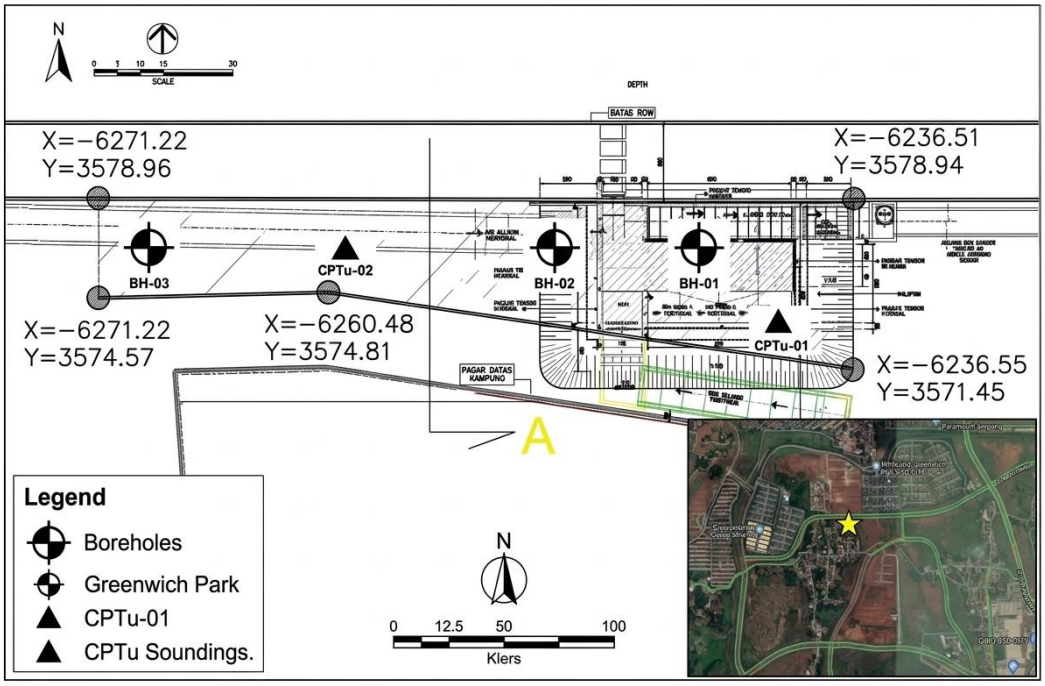


Figure 1. Site Investigation Layout Showing BH-01, BH-02, BH-03, CPTu-01, and CPTu-02 at Kampung Sawah, BSD–Tangerang.

2.2. Field Investigation Data.

The field dataset consists of the recorded depths of CPTu soundings, borehole depths, groundwater levels, soil descriptions, sample intervals, and SPT values. The investigation points and their reported depths are summarized in Table 1. The CPTu soundings provide information only over their achieved penetration depths. The borehole records provide a deeper stratigraphic description and discrete SPT values. The recorded groundwater levels are treated as observations at the time of investigation and are not assumed to represent seasonal maximum or minimum groundwater conditions. The SPT values reproduced in this study are those listed in the supplied drilling logs. In accordance with the distinction between recorded test results and corrected penetration resistance, the values are referred to as recorded SPT N-values rather than corrected N60-values [1]. Because the available records do not establish all correction factors, the values have not been converted to N60. Corrections for hammer energy, borehole

diameter, rod length, and sampler configuration must be documented before the values are treated as standardized N60 data.

Table 1. Summary of Field Investigation Points.

Investigation point	Investigation method	Final depth (m)	Recorded groundwater level (m below ground level)
CPTu-01	CPTu	5.58	Not provided
CPTu-02	CPTu	5.28	Not provided
BH-01	Borehole and SPT	29.5	3.5
BH-02	Borehole and SPT	29.5	1.5
BH-03	Borehole and SPT	33.5	4.7

2.3. Data Processing and Integrated Interpretation.

The interpretation procedure comprised five stages: (1) review of the investigation layout and field records; (2) compilation of borehole soil descriptions and SPT values; (3) review of the available CPTu profiles; (4) comparison of soil descriptions and penetration responses within the overlapping depth interval; and (5) assessment of the preliminary CPTu–SPT relationship and its limitations. The stages of the integrated interpretation are summarized in Figure 2. The workflow is intended to distinguish direct field observations from classifications and empirical estimates, consistent with the need to account for uncertainty in CPT-based stratification [8, 9].

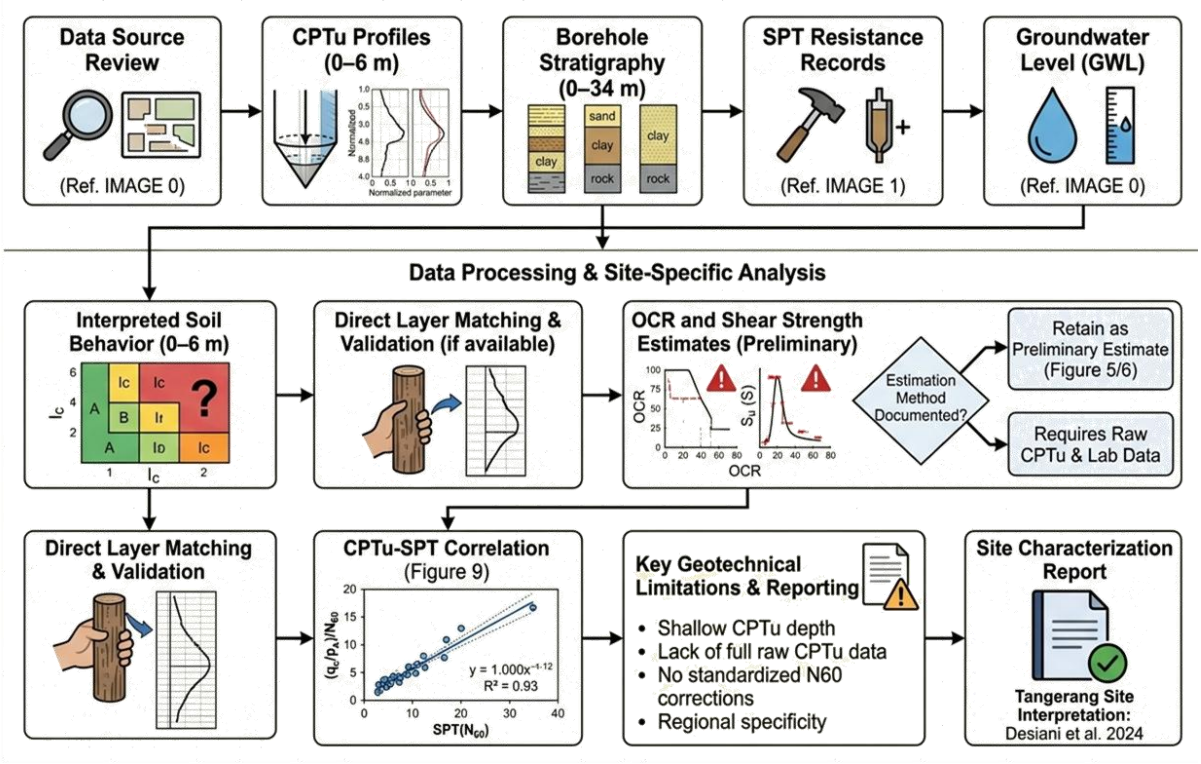


Figure 2. Workflow for Integrating Cptu Soundings, Borehole Descriptions, Groundwater Levels, SPT Values, and Preliminary Correlation Analysis.

The interpretation emphasizes agreement and disagreement among different data sources rather than assuming that each method identifies identical boundaries. Soil descriptions from boreholes are used to establish the documented stratigraphic framework. CPTu response is used to interpret shallow changes in soil behavior where the sounding depth permits. SPT values are used as discrete resistance indicators at their recorded sampling depths.

2.4. CPTu interpretation parameters.

CPTu interpretation commonly involves correcting measured cone resistance for pore-water pressure effects, evaluating effective stress, and calculating normalized penetration parameters. The correction used to obtain cone resistance is expressed in Equation (1), following established CPTu interpretation practice [2, 5]:

$$q_t = q_c + (1 - a)u_2 \tag{1}$$

where q_t is corrected cone resistance, q_c is measured cone resistance, a is the cone net-area ratio, and u_2 is pore-water pressure measured behind the cone. Equation (1) requires the applicable cone calibration information and measured u_2 values. It cannot be independently recalculated from the borehole logs alone.

The effective vertical stress is expressed in Equation (2), which distinguishes total vertical stress from the equilibrium pore-water pressure:

$$\sigma'_{v0} = \sigma_{v0} - u_0 \tag{2}$$

where σ_{v0} is total vertical stress and u_0 is equilibrium pore-water pressure at the depth of interest. Calculation requires an appropriate unit-weight profile and groundwater interpretation.

A normalized cone resistance may be expressed using the general form in Equation (3) [5]:

$$Q_{tn} = \frac{q_t - \sigma_{v0}}{p_a}\left(\frac{p_a}{\sigma'_{v0}}\right)^n \tag{3}$$

where p_a is the reference atmospheric pressure and n is the stress-normalization exponent selected according to the adopted CPTu interpretation procedure. The value of n must be selected and documented consistently. Equation (3) should not be evaluated without the necessary cone and stress data.

The normalized friction ratio is expressed in Equation (4):

$$F_r = \frac{f_s}{q_t - \sigma_{v0}} x100\% \tag{4}$$

where f_s is sleeve friction. A soil-behavior-type index can then be calculated using a compatible classification procedure. One commonly used expression for the index is shown in Equation (5) [3, 5]:

$$I_c = \sqrt{(3.47 - \log_{10} q_{tn})^2 + (\log_{10} f_r + 1.22)^2} \tag{5}$$

The classification chart and parameter definitions used in actual processing must be identified. In particular, the normalization method, friction-ratio definition, and classification procedure must be mutually compatible. Recent research emphasizes that CPT-based classification can be affected by cross-correlation between normalized parameters and noise in the measured profiles [9, 17].

Equations (1)–(5) document the interpretation framework; they do not imply that all parameters can be recalculated from the available drilling logs. Because the complete raw CPTu dataset was not available, no new numerical CPTu classification profile is claimed in this study.

2.5. OCR and undrained shear strength.

OCR is defined as the ratio between preconsolidation effective stress and current effective vertical stress, as shown in Equation (6):

$$OCR = \frac{\sigma'_p}{vo} \tag{6}$$

where σ'_p is the preconsolidation effective stress. A numerical OCR profile requires a documented method for estimating σ'_p, together with the relevant CPTu measurements or independent consolidation data. CPTu-based methods for estimating OCR continue to be investigated, but their applicability depends on the selected method and the characteristics of the soil [4, 7, 10].

The approximate OCR values available in the preliminary graphical summary were not used as verified quantitative results because the calculation procedure and scale could not be established from the records supplied.

For cohesive soils, an empirical CPTu estimate of undrained shear strength may be expressed as shown in Equation (7) [4, 5]:

$$S_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \tag{7}$$

where N_{kt} is an empirical cone factor selected for the soil and adopted interpretation procedure. The cone factor is not universal and should be justified using local calibration, laboratory results, or a suitable published basis. Without the raw CPTu measurements and documented cone factor, a definitive numerical S_u profile cannot be reproduced.

Consequently, this study discusses the preliminary shear-strength estimates only as reported estimates and does not use them as independently validated design parameters.

2.6. CPTu–SPT correlation.

The preliminary relationship reported for CPTu-01 and BH-02 is given in Equation (8):

$$y = -0.0555x + 2.6393 \tag{8}$$

The reported coefficient of determination is presented separately in Equation (9):

$$R^2 = 0.8075 \tag{9}$$

The plotted variables were described in the supplied material as x=N60 and y=qc/pa)/N60. These definitions must be checked against the original plot and calculation sheet before the equation is used quantitatively, particularly because the supplied borehole values are recorded SPT N-values and are not confirmed as corrected N60-values.

The coefficient of determination indicates the proportion of the observed response variance explained by the fitted linear relationship for the data used in the regression. It does not by itself establish statistical significance, predictive accuracy outside the sampled interval, or a causal relationship. Recent research on region-specific CPT–SPT relationships likewise indicates that the suitability of such correlations depends on the data and geological context [11]. Because the complete paired dataset and number of observations were not available, the correlation is treated as preliminary and site-specific. No new regression was performed from unverified or incomplete observations.

3. Results and Discussion

3.1. Borehole Stratigraphy and Variation Among Investigation Points.

The borehole logs indicate that the subsurface is heterogeneous and includes fine-grained soils, sandy materials, and weathered sedimentary layers. The major stratigraphic intervals and recorded SPT ranges are summarized in Table 2. The ranges summarize the values listed within each interval; they are not average values and do not represent corrected \(N_{60}\)-values unless independently confirmed.

Table 2. Summary of Principal Borehole Strata and Recorded SPT Values.

Borehole	Depth interval (m)	Principal description in drilling log	Recorded SPT \(N\)-value range
BH-01	0–5	Silty clay and clayey silt; stiff to very stiff	8–15
BH-01	5–14	Weathered sandstone, sand, and gravelly sand	20–31
BH-01	14–20	Clayey silt, siltstone, and sandy silt	11–31
BH-01	20–29.5	Clayey silt; stiff to hard, with light-green clayey silt at the base	12–34
BH-02	0–5	Silty clay and clayey silt	8–16
BH-02	5–14	Sand, gravelly sand, and weathered sandstone	18–31
BH-02	14–21	Core-loss interval, clayey silt, weathered siltstone, and sand	11–30
BH-02	21–29.5	Clayey silt; stiff to hard, with light-green clayey silt at depth	12–36
BH-03	0–5	Silty clay and clayey silt	10–11
BH-03	5–18.5	Weathered sandstone, sand, sandy silt, and weathered siltstone	18–42
BH-03	18.5–29	Clayey silt; very stiff to hard, then stiff	12–32
BH-03	29–33.5	Light-green clayey silt; stiff to hard	41–42

Note: SPT ranges are based on the supplied log entries. Intervals containing a change in lithology or consistency have been grouped for summary purposes; the original logs remain the authoritative source for exact layer boundaries. The core-loss interval at BH-02 is not assigned a specific soil type.

The upper sections of the boreholes are predominantly composed of silty clay and clayey silt. Sand and weathered sedimentary materials occur at intermediate depths, while clayey silt reappears in several deeper intervals. This stratigraphic sequence indicates alternating fine-grained, coarse-grained, and weathered materials rather than a homogeneous soil deposit. Such heterogeneity highlights the challenges associated with soil stratification based solely on penetration measurements, particularly in subsurface environments comprising multiple material types [8, 9, 20].

The borehole records reveal both similarities and differences in subsurface conditions. All three boreholes contain fine-grained materials near the ground surface, although the depths

and thicknesses of sandy and weathered rock intervals vary considerably. BH-03 exhibits relatively high SPT values in several sandy intervals, ranging from 18 to 42, whereas BH-01 and BH-02 display different stratigraphic sequences and penetration resistance values. These variations may be associated with local differences in depositional environments, weathering processes, and material composition. However, the available borehole records are insufficient to identify the specific geological processes responsible for these differences, and the interpretations should therefore remain descriptive. Figure 3 presents the borehole logs for BH-01, BH-02, and BH-03, illustrating variations in stratigraphic boundaries, sampling depths, and recorded SPT resistance. A comparison of these profiles highlights the spatial variability of subsurface conditions across the investigation site and emphasizes the importance of integrating stratigraphic observations with penetration resistance measurements for reliable geotechnical characterization.

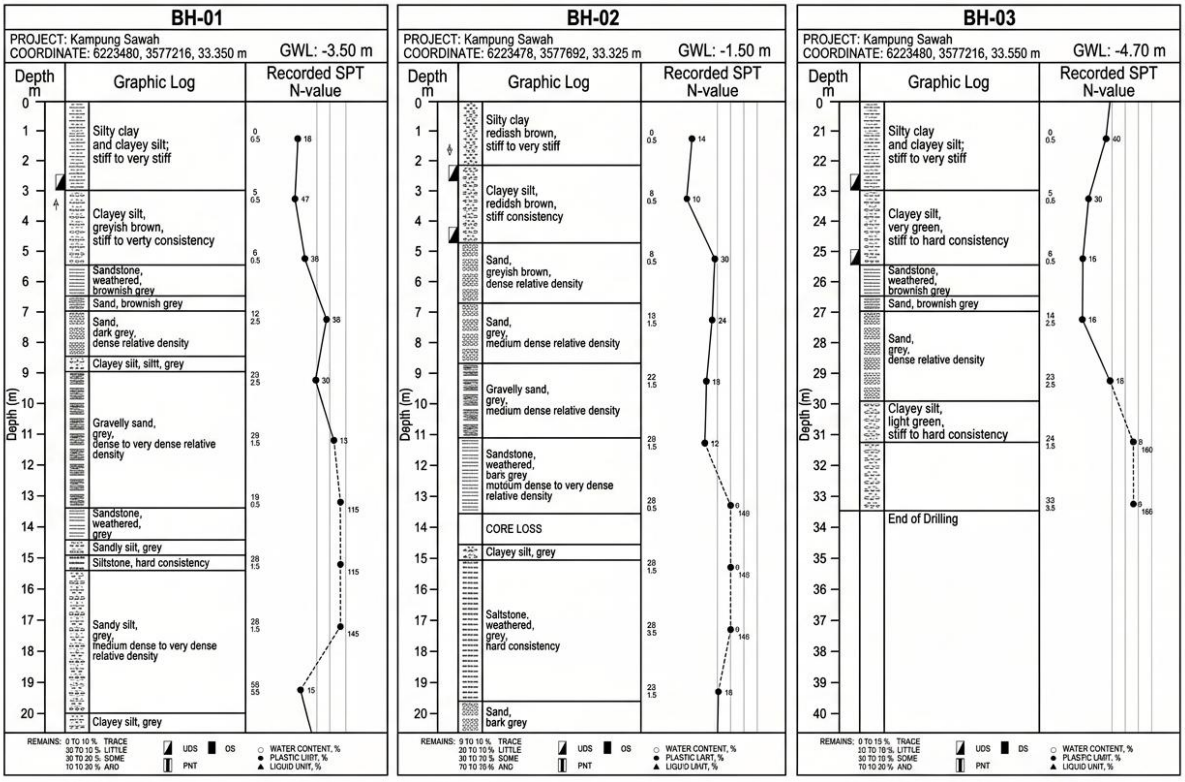


Figure 3. Borehole Logs For BH-01, BH-02, and BH-03 Showing Soil Descriptions, Sampling Depths, and Recorded SPT Values.

3.2. SPT Resistance and Soil Descriptions.

The recorded SPT values exhibit considerable variation with soil type and depth. Several sand and gravelly sand intervals display relatively high SPT values, indicating greater penetration resistance than typically observed in loose granular soils. In contrast, fine-grained layers exhibit a wider range of SPT values, suggesting variations in soil consistency and local stratigraphic conditions. However, these observations should not be interpreted as a universal relationship between soil type and penetration resistance, as SPT measurements are influenced by testing procedures, equipment characteristics, energy transfer efficiency, overburden pressure, and other site-specific factors. Although ASTM D1586/D1586M-18 establishes standardized testing procedures, reliable interpretation requires appropriate documentation of testing conditions and the application of relevant corrections [1]. Previous studies investigating

relationships between SPT resistance and soil properties have similarly emphasized the importance of considering material characteristics and the methods used to estimate geotechnical parameters [11, 16]. Furthermore, qualitative descriptions such as “stiff,” “dense,” and “hard” in borehole logs represent preliminary field assessments and should not be considered equivalent to standardized classifications derived from corrected SPT measurements.

The presence of weathered sandstone and siltstone introduces additional complexity into the interpretation of penetration resistance. In weathered or partially cemented materials, elevated SPT values may result from cementation, embedded rock fragments, or the inherent structure of the material rather than solely from soil density or consistency. Consequently, direct comparisons between penetration resistance in these materials and that in unconsolidated soil deposits may lead to misleading interpretations. Previous research examining the effects of soil layering and penetrometer diameter has demonstrated that penetration resistance can be influenced by stratigraphic boundaries, material heterogeneity, and testing geometry rather than exclusively by the mechanical properties of individual homogeneous layers [19]. Additionally, the core-loss interval identified in BH-02 introduces uncertainty into the subsurface interpretation because the absence of recovered material prevents reliable lithological identification within that interval. These findings highlight the importance of combining SPT measurements with borehole descriptions and geological observations while explicitly acknowledging uncertainties associated with weathered materials, incomplete core recovery, and variations in subsurface conditions.

3.3. Groundwater Conditions.

The recorded groundwater levels are 3.50 m below ground level at BH-01, 1.50 m at BH-02, and 4.70 m at BH-03. These differences are relevant to the interpretation of effective stress, the behavior of shallow fine-grained soils, and construction planning. The shallower recorded groundwater level at BH-02 indicates that groundwater may be encountered at a relatively shallow depth at that investigation point under the conditions observed during drilling. Excavation and foundation works may therefore require site-specific consideration of seepage, temporary groundwater control, and changes in soil behavior associated with groundwater conditions. Groundwater observations are also important inputs for stress calculations used in CPTu interpretation, as illustrated by Equation (2). However, groundwater levels measured during individual investigations may be affected by the timing and method of measurement, recent rainfall, and local drainage conditions. The three observations should not be treated as a long-term groundwater contour map. Additional monitoring would be needed to establish seasonal variation and design groundwater levels.

3.4. Integration of CPTu and Borehole Information.

The CPTu soundings reached depths of 5.58 m and 5.28 m, whereas the boreholes reached depths of 29.50–33.50 m. Consequently, direct CPTu interpretation is limited to the upper approximately 5–6 m. The deeper stratigraphic sequence must be established from the borehole logs, SPT records, and any additional investigation data. Within the overlapping shallow interval, the methods can be integrated by comparing CPTu response changes with the soil descriptions and SPT measurements at nearby depths. A close match between a change in cone response and a documented soil boundary would support the interpretation of a local transition.

A mismatch would not necessarily indicate an error: the tests sample different volumes of soil, and the boreholes and soundings may not be colocated. CPT-based soil classification is useful for identifying changes in soil behavior, but the resulting boundaries can be affected by measurement noise, parameter correlation, and geological variability [3, 5, 9]. Accordingly, the interpretation should distinguish between observed borehole boundaries and CPTu-based behavioral classifications. Figure 4 should present the integrated shallow interpretation while distinguishing observed borehole boundaries from CPTu-based interpretations. Deeper borehole layers should not be extended into the CPTu profile as though they were directly measured by the cone.

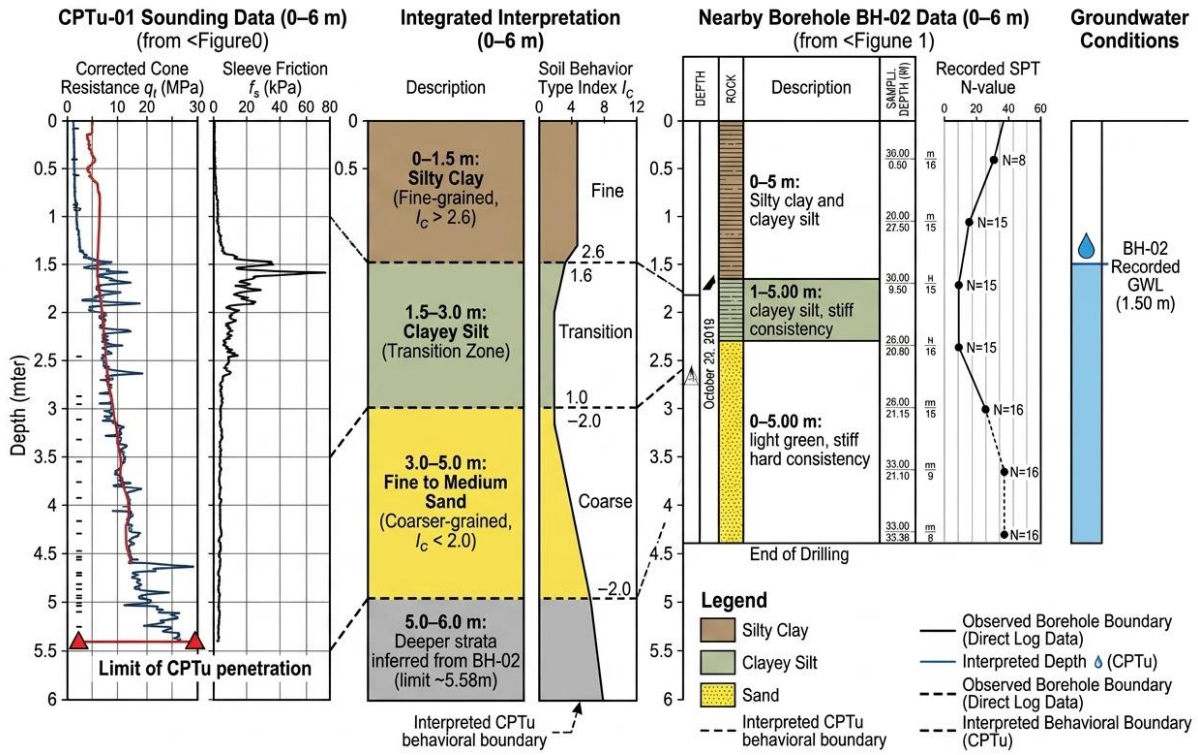


Figure 4. Integrated Shallow Stratigraphic Interpretation Comparing Cptu Response with Nearby Borehole Descriptions and SPT Observations within the Common Investigation Depth.

3.5. Preliminary OCR interpretation.

The OCR provides information about the stress history of cohesive soils and is relevant to evaluating compressibility and settlement behavior. OCR is defined as the ratio of preconsolidation effective stress to the current vertical effective stress, as expressed in Equation (6). Its determination therefore depends on accurate stress calculations and the adopted method for estimating preconsolidation stress. Previous studies have investigated OCR interpretation in stiff clays using CPT and SPT measurements, while more recent research has examined CPTu-based approaches for estimating OCR and undrained shear strength [4, 7, 10]. These methods require appropriate input measurements, clearly defined empirical relationships, and documented calculation procedures to ensure reliable interpretation.

Figure 5 presents the preliminary OCR profile obtained from the original investigation data, showing relatively low estimated OCR values at several depths. However, the calculation procedures, input parameters, and empirical relationships used to generate these values are not sufficiently documented. Consequently, the plotted values cannot be considered independently

verified estimates of soil stress history. In particular, OCR values substantially below unity require careful examination of parameter definitions, stress normalization, units, and the calculation methods employed. Although the preliminary profile illustrates variations in the reported OCR estimates with depth, these variations cannot be interpreted as a reliable quantitative trend without additional verification. Furthermore, the available borehole descriptions provide qualitative information about soil consistency but are insufficient to establish a validated numerical OCR profile. A more reliable assessment would require reprocessing the original CPTu measurements using an appropriate, documented estimation method and, where possible, validating the results against laboratory consolidation tests. Therefore, the OCR values presented in Figure 5 should be regarded as preliminary estimates rather than confirmed indicators of soil stress history.

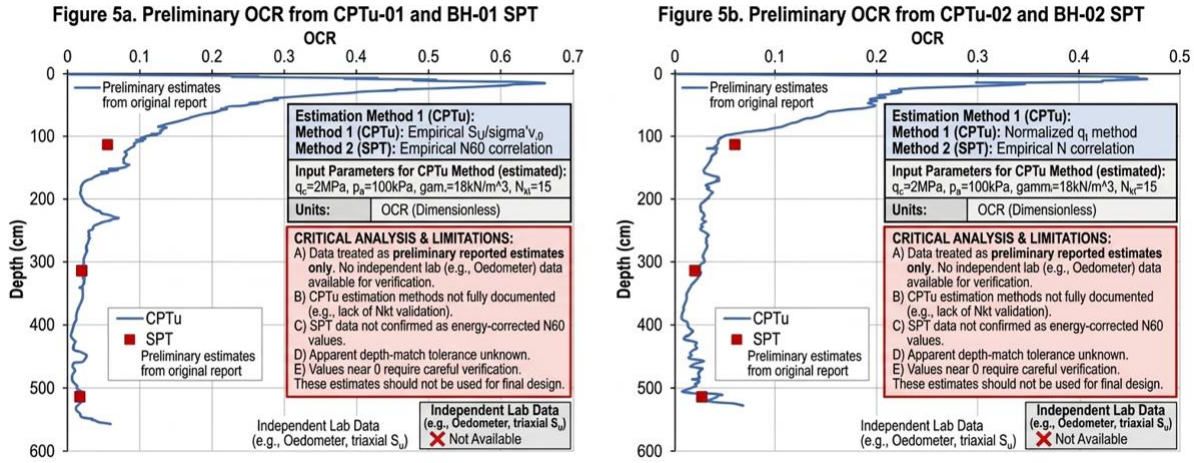


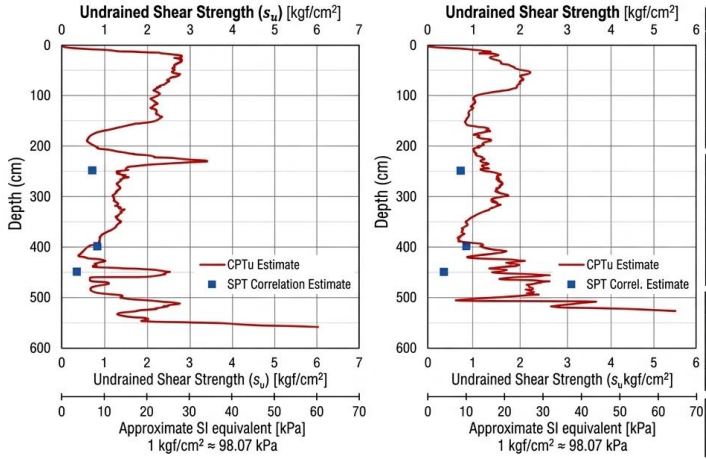
Figure 5. OCR Profile, if Retained from the Original Analysis, Should Identify the Adopted Estimation Method, Input Parameters, Units, and the Distinction Between Calculated Values and Independently Measured Values.

3.6. Undrained Shear-Strength Interpretation.

Undrained shear strength (s_u) is an important geotechnical parameter for evaluating the behavior of cohesive soils, particularly in short-term stability analyses, foundation design, and excavation assessments. Equation (7) presents an empirical approach for estimating undrained shear strength from CPTu measurements. The estimated values depend on corrected cone resistance, total vertical stress, and the selected empirical cone factor. Previous research has investigated CPTu-based estimation of undrained shear strength and overconsolidation ratio (OCR), emphasizing the importance of selecting appropriate estimation methods and accounting for assumptions associated with cone penetration measurements [4]. Similarly, numerical modeling and advanced CPT interpretation studies have demonstrated that deriving mechanical soil properties from penetration resistance requires a reliable relationship between measured responses and the geotechnical parameters being estimated [8, 15]. Consequently, the accuracy of CPTu-based shear-strength estimates depends on the quality of the input measurements, the suitability of the empirical correlations, and the geological characteristics of the investigated soils.

Figure 6 illustrates the preliminary undrained shear-strength estimates derived from CPTu-01, CPTu-02, and SPT measurements at selected depths. The graphical comparison provides an initial indication of variations in estimated shear strength with depth and differences between the investigation methods. However, the calculation procedures, selected

cone factors, conversion methods, and depth correspondence between CPTu and SPT measurements are not sufficiently documented. These limitations prevent the development of a validated continuous shear-strength profile and restrict direct quantitative comparisons between the two methods. Furthermore, the original graphical presentation expresses shear strength in kg/cm², which should be clarified as kgf/cm² when referring to kilogram-force per unit area. For consistency with international geotechnical practice, the values should preferably be expressed in kilopascals (kPa), using the conversion factor of 1 kgf/cm² ≈ 98.07 kPa. The CPTu- and SPT-derived estimates presented in Figure 6 should also be clearly distinguished according to their respective calculation methods, as these values cannot be considered directly equivalent without appropriate calibration and validation.



1. s_u from CPTu Estimation	
Estimation Method	Empirical $s_u = (q_t - \sigma_{v0})/N_{kt}$
Parameters Used (Estimated)	N_{kt} = 15 (empirical cone factor) σ_{v0} calculated from estimated density of 18 kN/m³ Input parameters are preliminary reported values; raw q_c data and explicit N_{kt} basis not documented in original reports
Data Source	Reports and interpreted graphs
2. s_u from SPT Correlation Estimation	
Estimation Method	Empirical correlation, typically based on $s_u = \alpha \cdot N_{60}$
Parameters Used (Estimated)	correlation coefficient α (unknown basis) Original reports do not document SPT hammer energy (energy-corrected N_{60}) or the specific correlation basis. Data treated as recorded SPT N-values
Data Source	Reports and interpreted graphs
3. s_u Estimate Depth-Matching	
Procedure	Discrete SPT values plotted at reported depths from boreholes BH-01 (for CPTu-01) and BH-02 (for CPTu-02). Data is not independently verified or re-matched
Matching Tolerance	Undefined in original records

CRITICAL LIMITATIONS NOTE: Estimates are based on reported preliminary figures. Lack of raw CPTu data, energy-corrected SPT values, and fully documented methodologies prevents their use as design parameters or validated measurements.

Figure 6. Preliminary Undrained Shear-Strength Estimates from Cptu and SPT. The Final Figure Should Identify the Estimation Method, Cone Factor Or SPT Correlation, Depth-Matching Procedure, and Units.

The borehole descriptions indicate variations in the consistency of fine-grained soil layers, suggesting that undrained shear strength may vary with depth and local stratigraphic conditions. However, qualitative field descriptions alone cannot independently verify the numerical shear-strength estimates obtained from empirical relationships. In addition, variations in soil composition, stress history, groundwater conditions, and penetration resistance may introduce further uncertainty into the estimated strength parameters. Establishing a reliable quantitative shear-strength profile therefore requires access to the original CPTu measurements, clearly documented empirical cone factors, and independent strength measurements obtained through appropriate laboratory or in situ testing. These findings emphasize that the available shear-strength estimates should be regarded as preliminary indicators of cohesive soil behavior rather than validated design parameters. Further investigation and calibration are necessary before these estimates can be confidently applied to foundation design, excavation stability assessment, or other geotechnical engineering applications.

3.7. CPTu–SPT Correlation.

The preliminary relationship between CPTu-01 and BH-02 is expressed in Equation (8), with a reported coefficient of determination of $R^2 = 0.8075$, as presented in Equation (9). This coefficient indicates that the fitted linear regression model explains a substantial proportion of the variation in the response variable within the original dataset. However, the strength, reliability, and generalizability of this relationship cannot be determined solely from the coefficient of determination. Additional statistical evaluation is necessary to establish whether

the observed relationship adequately represents the subsurface conditions and can be applied to predictive geotechnical assessments.

Figure 7 presents the preliminary CPTu–SPT correlation for CPTu-01 and BH-02, illustrating the relationship between the reported penetration resistance parameters. The available summary includes three representative data points, with N_{60} values of approximately 11, 15, and 36 and corresponding normalized response values of approximately 1.70, 2.20, and 0.60, respectively. A regression recalculated using these three rounded data pairs produces a relationship that is similar to, but not identical to, the originally reported equation. This discrepancy may be attributed to numerical rounding or the inclusion of additional observations in the original regression analysis. However, because the complete dataset and number of observations are unavailable, the reported equation cannot be independently verified. Therefore, the relationship illustrated in Figure 7 should be regarded as a preliminary empirical correlation rather than a fully validated regression model.

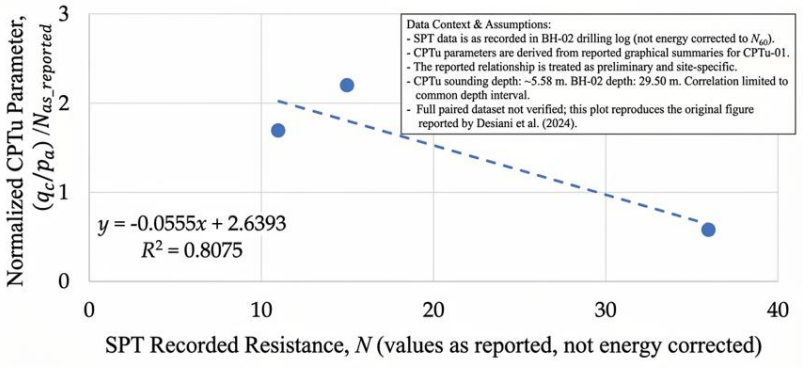


Figure 7. Preliminary CPTu–SPT correlation for CPTu-01 and BH-02.

Before the proposed correlation can be applied to predictive geotechnical assessments, several methodological aspects require further clarification, including the number of paired observations, the allowable depth-matching tolerance, the precise definitions of the regression variables, the application of energy corrections to obtain \(N_{60}\), and the statistical independence of the observations. These factors are essential for evaluating the reliability and reproducibility of the regression model. Furthermore, statistical significance, confidence intervals, and prediction errors cannot be established from the reported coefficient of determination alone. Previous research on region-specific CPT–SPT correlations has demonstrated that geological heterogeneity, soil characteristics, and statistical uncertainty can substantially influence the performance and applicability of empirical relationships [11]. Consequently, the correlation presented in Figure 7 should not be directly extrapolated to other geological settings or soil types without appropriate calibration and independent validation.

The selection of CPTu-01 and BH-02 as the strongest reported correlation may be associated with similarities in their spatial locations and stratigraphic characteristics. Nevertheless, the absence of verified investigation coordinates and complete depth-matched measurements prevents an objective assessment of whether this pairing provides a more reliable relationship than other possible CPTu–SPT combinations. Differences in soil layering, groundwater conditions, and penetration depths may also influence the observed correlation. Accordingly, the reported relationship should be interpreted as an exploratory, site-specific finding rather than a universally applicable predictive model. Further investigations involving additional CPTu soundings, borehole measurements, and statistically verified depth-matched

datasets are recommended to improve the reliability of the correlation and assess its potential application in geotechnical site characterization.

3.8. Comparison with Previous Research.

Previous CPTu research has examined the estimation of stress history and undrained shear strength from cone measurements [4, 7, 10]. Studies on CPT-based classification have investigated the influence of normalized parameters, data cross-correlation, and measurement noise on the identification of soil layers [8, 9, 17]. Other research has explored the use of soil-behavior-type indices in applications involving layered deposits and foundation performance [12, 13]. Recent work on region-specific CPT–SPT correlations highlights the importance of accounting for regional variability and uncertainty when relating penetration measurements to soil properties [11]. Studies of dynamic penetration, friction-angle estimation, and the influence of soil layering further demonstrate that penetration resistance is affected by the test method and the characteristics of the material being penetrated [14, 16, 19]. The present site illustrates why this caution is necessary. The borehole logs show alternating fine-grained and granular materials, weathered sedimentary intervals, and variation in groundwater level. A correlation calibrated in a uniform deposit may not represent all these materials equally. In addition, the CPTu soundings cover only the shallow portion of the borehole profiles, restricting the range of depths over which a direct comparison can be made. Accordingly, the principal contribution is not a universal CPTu–SPT conversion equation. It is a site-specific assessment of the benefits and limits of combining shallow CPTu measurements with deeper borehole descriptions and SPT records. Future work should test the preliminary relationship using a larger set of paired observations and report uncertainty as well as goodness of fit.

3.9. Engineering Implications.

The findings have several practical implications for preliminary geotechnical planning. First, the observed stratigraphic variability suggests that a single generalized soil profile should not be assumed to represent the entire site. Foundation selection should be based on the expected foundation loads, settlement criteria, verified soil parameters, and the depth and continuity of competent layers. CPT-based soil-behavior-type interpretation may support the identification of relevant layers, but the results should be considered alongside borehole observations and other geotechnical evidence [5, 12]. The current records are useful for preliminary planning but do not, by themselves, establish a final foundation type or design capacity. Second, the variation in recorded groundwater levels indicates that groundwater conditions should be considered in excavation planning and temporary works. Where excavations extend below the recorded groundwater level, the potential need for groundwater monitoring, drainage, or temporary dewatering should be assessed by the geotechnical designer. Third, the shallow CPTu penetration depth limits the use of CPTu alone for evaluating deeper bearing layers or settlement-sensitive strata. If the design depends on deeper soil conditions, additional CPTu soundings or other suitable in-situ and laboratory investigations should be considered. Finally, the reported CPTu–SPT relationship should be used only as a preliminary site-specific comparison until the paired data, variable definitions, and correction procedures have been verified. It should not be used as a substitute for direct design parameter assessment.

3.10. Limitations.

This study is subject to several limitations. The CPTu soundings terminate at depths of 5.58 m and 5.28 m, whereas the boreholes extend to 29.50–33.50 m. Consequently, direct CPTu–SPT comparison is limited to the shallow overlapping interval. Exact horizontal distances among investigation points could not be verified from the available records. The supplied borehole records contain SPT values, but complete correction information for deriving N60 is not available. The complete CPTu dataset, including raw cone resistance, sleeve friction, and pore-pressure measurements, was also not available for independent recalculation. The preliminary OCR and shear-strength plots do not provide sufficient methodological detail to validate their numerical values. In addition, the complete paired dataset and number of observations underlying the reported regression were not available. These limitations are important because CPTu-based classification and parameter estimation depend on the quality of the input data, the selected interpretation method, and the geological context [4, 8, 9]. Likewise, CPT–SPT correlations may be sensitive to regional conditions and the definition and correction of the variables used [11]. Consequently, the stratigraphic observations and recorded SPT values can be described, while the numerical OCR profile, shear-strength profile, and regression statistics should be interpreted cautiously. Further investigation and data verification are necessary before these estimates are adopted as design parameters..

4. Conclusions

This study evaluated the integration of CPTu and SPT measurements for geotechnical site characterization at Kampung Sawah, BSD–Tangerang, Indonesia. The results confirmed heterogeneous subsurface conditions comprising silty clay, clayey silt, sand, gravelly sand, weathered sandstone, and siltstone, with variations in layer thickness and stratigraphic sequences among the three boreholes. SPT measurements revealed relatively high penetration resistance in several sandy and weathered-material intervals, whereas fine-grained layers exhibited greater variability. Groundwater levels ranged from 1.50 to 4.70 m below ground level, indicating spatial differences that may influence preliminary geotechnical assessments. However, these measurements do not represent long-term groundwater fluctuations. CPTu soundings reached depths of approximately 5–6 m, limiting their application to shallow subsurface characterization, while deeper stratigraphic interpretation relied on borehole descriptions and SPT records. A preliminary CPTu–SPT correlation between CPTu-01 and BH-02 yielded a coefficient of determination of \(R^2 = 0.8075\), suggesting a potentially useful site-specific relationship. Nevertheless, its predictive reliability remains uncertain because the complete dataset, depth-matching procedures, and SPT correction factors have not been verified. Similarly, the available OCR and undrained shear-strength estimates cannot be considered validated quantitative profiles without documented calculation procedures and independent calibration. Overall, the findings demonstrate that integrating CPTu, SPT, borehole stratigraphy, and groundwater observations provides a more comprehensive characterization of heterogeneous subsurface conditions than relying on individual investigation methods. However, the available evidence is insufficient to establish a validated predictive CPTu–SPT relationship or definitive soil-strength parameters. Further investigations involving deeper CPTu soundings, standardized SPT corrections, verified depth-matched

measurements, and laboratory testing are recommended to improve the reliability of geotechnical assessments and support foundation design.

Data Availability Statement

The study uses field investigation information supplied for the project, including borehole logs, recorded SPT values, groundwater levels, CPTu investigation depths, and preliminary interpretation summaries. The complete raw CPTu dataset and the full paired dataset used for the preliminary regression were not available for independent reproduction.

Author Contribution

Asriwiyanti Desiani: Conceptualization, methodology, investigation, data analysis, writing—original draft, and supervision. Daud Rahmat Wiyono: Investigation, data collection, laboratory interpretation, and visualization. Adrian Pramono: Data analysis, validation, visualization, and writing—review and editing.

Competing Interest

The authors declare that they have no competing interests.

Funding

This research received no external funding.

Declaration of Generative AI Use

Generative AI tools (Gramarly/Quilbot/etc) were used solely to assist with language editing, grammar correction, and improving manuscript readability. The authors reviewed and verified the final content and take full responsibility for the accuracy, originality, and integrity of the manuscript.

References

[1] ASTM International. (2018). Standard Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils, ASTM D1586/D1586M-18; ASTM International: West Conshohocken, PA, USA. https://doi.org/10.1520/D1586_D1586M-18.

[2] ASTM International. (2020). Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils, ASTM D5778-20; ASTM International: West Conshohocken, PA, USA. https://doi.org/10.1520/D5778-20.

[3] Robertson, P.K. (1990). Soil classification using the cone penetration test. *Canadian Geotechnical Journal*, *27*, 151–158. https://doi.org/10.1139/t90-014.

[4] Wang, Z.-L.; Chen, H.-B.; Chen, F.-Q.; Liu, L.-Y. (2024). Determination of the overconsolidation ratio and undrained shear strength of cohesive soils by CPTu measurement. *Applied Ocean Research*, *146*, 103949. https://doi.org/10.1016/j.apor.2024.103949.

[5] Robertson, P.K. (2009). Interpretation of cone penetration tests—A unified approach. *Canadian Geotechnical Journal*, *46*, 1337–1355. https://doi.org/10.1139/T09-065.

[6] Robertson, P.K.; Wride, C.E. (1998). Evaluating cyclic liquefaction potential using the cone penetration test. *Canadian Geotechnical Journal*, *35*, 442–459. https://doi.org/10.1139/t98-052.

[7] Mayne, P.W.; Kemper, J.B. (1988). Profiling OCR in stiff clays by CPT and SPT. *Geotechnical Testing Journal*, *11*, 139–147. https://doi.org/10.1520/GTJ10960J.

[8] Marzouk, I.; Granitzer, A.-N.; Rauter, S.; Tschuchnigg, F. (2024). A case study on advanced CPT data interpretation: From stratification to soil parameters. *Geotechnical and Geological Engineering*, *42*, 4087–4113. https://doi.org/10.1007/s10706-024-02774-9.

[9] Yao, J.-C.; Wang, Y.; Guan, Z.; Senetakis, K. (2025). Cone penetration test (CPT)-based soil classification and stratification with consideration of data cross-correlation and noises. *Acta Geotechnica*, *20*, 6537–6555. https://doi.org/10.1007/s11440-025-02732-6.

[10] Gwak, D.; Ku, T. (2025). Data-driven machine learning approach for stress history evaluation in cohesive soils using cone penetration test data. *Engineering Geology*, *355*, 108246. https://doi.org/10.1016/j.enggeo.2025.108246.

[11] Sadik, L.; Khoshnevisan, S. (2025). Region-specific CPT-SPT correlations for cohesionless soils: A hierarchical Bayesian approach. *Geotechnical and Geological Engineering*, *43*, 430. https://doi.org/10.1007/s10706-025-03152-9.

[12] Khodayari, M.R.; Mousavizadeh, S.M.; Ahmadi, M.M. (2024). Analysis of pile end bearing capacity in Holocene interlayered silty deposits based on CPT soil behavior type index. *Engineering Geology*, *337*, 107597. https://doi.org/10.1016/j.enggeo.2024.107597.

[13] Hudson, K.S.; Ulmer, K.J.; Zimmaro, P.; Kramer, S.L.; Stewart, J.P.; Brandenberg, S.J. (2024). Relationship between fines content and soil behavior type index at liquefaction sites. *Journal of Geotechnical and Geoenvironmental Engineering*, *150*. https://doi.org/10.1061/JGGEFK.GTENG-12146.

[14] Oliveira, C.F.; Navarrete, M.A.B.; Breul, P.; Chevalier, B.; Tran, Q.A. (2025). Evaluation of different methods for cone resistance assessment from dynamic penetration tests. *Journal of Geotechnical and Geoenvironmental Engineering*, *151*. https://doi.org/10.1061/JGGEFK.GTENG-12272.

[15] Zhang, W.; Wang, D.; Zheng, J.; Fu, D. (2025). Numerical study of cone penetration tests to predict effective internal friction angles of cohesive soils. *Engineering Geology*, *345*, 107870. https://doi.org/10.1016/j.enggeo.2024.107870.

[16] Duque, J.; Acosta, C.; Canales, F.A.; Cárdenas, J. (2026). On the lookout for a general relationship between the friction angle of sandy soils and SPT. *Indian Geotechnical Journal*, *56*, 1543–1550. https://doi.org/10.1007/s40098-025-01201-x.

[17] Zheng, T.; Buckley, R.M.; Febrianto, E. (2026). A comprehensive approach for Bayesian soil classification using cone penetration test data. *Computers and Geotechnics*, *190*, 107671. https://doi.org/10.1016/j.compgeo.2025.107671.

[18] Jung, H.; Lin, J.; Stark, T.D. (2025). Sand state parameter from CPT. *Canadian Geotechnical Journal*, *62*, 1–16. https://doi.org/10.1139/cgj-2024-0076.

[19] Tian, Y.; Lehane, B. (2025). The influence of soil layering and penetrometer diameter on penetration resistance. *Canadian Geotechnical Journal*, *62*, 1–17. https://doi.org/10.1139/cgj-2024-0491.

[20] Dong, Y.; Wang, K.; Shen, K.; Cui, L. (2025). Understanding the scattering data from cone penetration tests based on sedimentary facies. *Journal of Rock Mechanics and Geotechnical Engineering*, *17*, 5282–5306. https://doi.org/10.1016/j.jrmge.2024.11.054.



© 2026 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).