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SPT–EFFECTIVE SHEAR PARAMETER CORRELATION FOR SOFT CLAY IN JAKARTA USING BIG DATA

Ali Iskandar[1*], Gregorius Sandjaja Sentosa[1], Aksan Kawanda[2], Felicia Yohana[1], Felicia Refalina Tantobudiono[1] dan Athena Callista[1]

[1]Program Studi Sarjana Teknik Sipil, Universitas Tarumanagara, Jl. Letjen S. Parman No. 1, Jakarta, Indonesia
[2]Program Studi Sarjana Teknik Sipil, Universitas Trisakti, Jl. Kyai Tapa No. 1 Grogol, Jakarta, Indonesia
[*]*aliiskandar@ft.untar.ac.id*

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ABSTRACT

This study aims to develop a practical model to estimate the shear strength parameters of clay soils, such as effective cohesion (c′), angle of internal friction (ϕ′), and elasticity modulus in a more efficient and economical, by using Standard Penetration Test (SPT) and index properties data (including grain size analysis and Atterberg test). This study focuses on fine-grained soils (especially in Jakarta) in two consistency groups, namely very soft clay (C01, SPT 0–2 blows/ft) and soft clay (C02, SPT 2–4 blows/ft). The analysis was conducted by establishing a linear relationship between mean effective stress (p′) and deviatoric stress (q), with an additional ±10% envelope to account for data variability. The results show that the linear regression of p′–q adequately represents soil behavior for both consistency groups. The ±10% envelope successfully accommodates variations including the effect of plasticity index (PI), indicating that this model can serve as a practical alternative in geotechnical design when triaxial test data and undistrurbed sampling test are not available.

Keywords: SPT; soft clay; linear regression; efective shear strength; Jakarta

ABSTRAK

Penelitian ini bertujuan untuk menyusun model praktis yang dapat memperkirakan parameter kuat geser tanah, seperti kohesi efektif (c'), sudut geser dalam efektif (ϕ'), dan modulus elastisitas secara lebih efisien dan ekonomis khususnya di Jakarta. Penelitian ini memanfaatkan data Standard Penetration Test (SPT) dan sifat indeks tanah (meliputi analisis ukuran butir dan batas Atterberg). Fokus penelitian ini adalah tanah lempung/berbutir halus pada dua kelompok konsistensi, yaitu very soft clay (C01, SPT 0–2 blows/ft) dan soft clay (C02, SPT 2–4 blows/ft). Analisis dilakukan dengan membangun hubungan linier antara tegangan rata-rata efektif (p') dan deviasi tegangan (q), kemudian ditambahkan envelope (batas atas–bawah) ±10% untuk mencakup variasi data. Hasil penelitian menunjukkan bahwa regresi linier p'–q cukup mewakili perilaku tanah pada kedua kelompok konsistensi. Envelope ±10% terbukti dapat mengakomodasi variasi data termasuk pengaruh indeks plastisitas (IP), sehingga model ini dapat dijadikan alternatif praktis dalam perencanaan geoteknik ketika data triaksial dan uji undisturbed sampling tidak tersedia.

Kata kunci: SPT; lempung lunak; regresi linier; kuat geser efektif; Jakarta

1. INTRODUCTION

Soft clay soils are widely found in Jakarta and are a major concern in foundation design. This type of soil is characterized by low bearing capacity and high compressibility. Shear strength parameters are commonly obtained from consolidated undrained (CU) triaxial tests, to provide insights of the strength and deformation characteristics of saturated soils under undrained conditions. A primary advantage of the CU triaxial tests is its ability to closely simulate field conditions, allowing for the evaluation of soil response at various stress levels, which is crucial for understanding stability in geotechnical designs. but these tests are costly and time-consuming.

However, these tests are costly and time-consuming, prompting the search for reliable empirical alternatives. While previous studies, such as Tanuwijaya et al. (2019) in Jakarta and Desiani et al. (2024) in Bandung, have explored correlations using cone penetration test (CPT) data. However, there is a lack of models based on the more commonly available standard penetration test (SPT) data that incorporate soil consistency.

Conversely, the SPT is a widely adopted in-situ testing procedure that provides information on soil density and stratification, and it is relatively quick and cost-effective to conduct. The primary advantage of the SPT lies in its efficiency, it allows for rapid data acquisition on soil properties across large areas (Watkins et al., 2021). Moreover, SPT results are often utilized for empirical correlations to estimate soil parameters, such as shear strength, thereby simplifying the design process for foundations and earth structures. However, a significant limitation of the SPT is its reliance on empirical correlations. Existing empirical methods usually rely only on plasticity index (PI) without considering soil consistency and local conditions.

In this study, the influence of the PI by performing sensitivity analyses to assess their contribution to the variation of the p′-q response, while the main model used simple linear regression as the main approach to map the p′-q′ relationship per soil consistency group (C01-C06). The line parameters (slope m = α and intercept a) were then used to derive design-relevant effective parameters. To anticipate data variations, an upper-lower bound of ±10% was applied to c′ and tan α to form a conservative envelope that is practical to use. Sensitivity analysis was optionally performed with MLR (q′~ p′+ PI) to assess ΔR^2 due to PI. If ΔR^2 is small, the influence of PI is considered adequately handled by the ±10% envelope without changing the main model.

The consistency of fine-grained soil based on SPT values is divided into 6 levels as shown in Table 1. This research aims to develop a simple correlation model that connect data from SPT and index properties test with CU triaxial test, by analyzing the relationship between p′ and q derived from field data, with a ±10% envelope applied to the regression results. The analysis focuses on very soft clay (C01, SPT 0–2) and soft clay (C02, SPT 2–4). Previous research has attempted to correlate soil parameters, but there are still gaps in accurate and reliable predictive models. Xie et al. (2024) conducted mechanical behaviour experiments on soft clay soil using true triaxial.

Table 1 Typical fine grained soil consistency based on SPT’s value (Terzaghi & Peck, 1967)

Consistency	N (blows/ft)
Very Soft (C01)	<2
Soft (C02)	2-4
Medium Stiff (C03)	4-8
Stiff (C04)	8-15
Very Stiff (C05)	15-30
Hard (C06)	>30

Effective internal friction angle correlation

Previous studies as shown in Figure 1-2, indicate that there is a significant correlation between plasticity index (PI) values and effective internal friction angle values. While the correlation of SPT and Undrained Shear strength is commonly based on SPT’s values. Effective cohesion values are generally close to 0, but under conditions such as over-consolidated or cemented soils, values may exceed 0, typical values are generally obtained using Table 2.

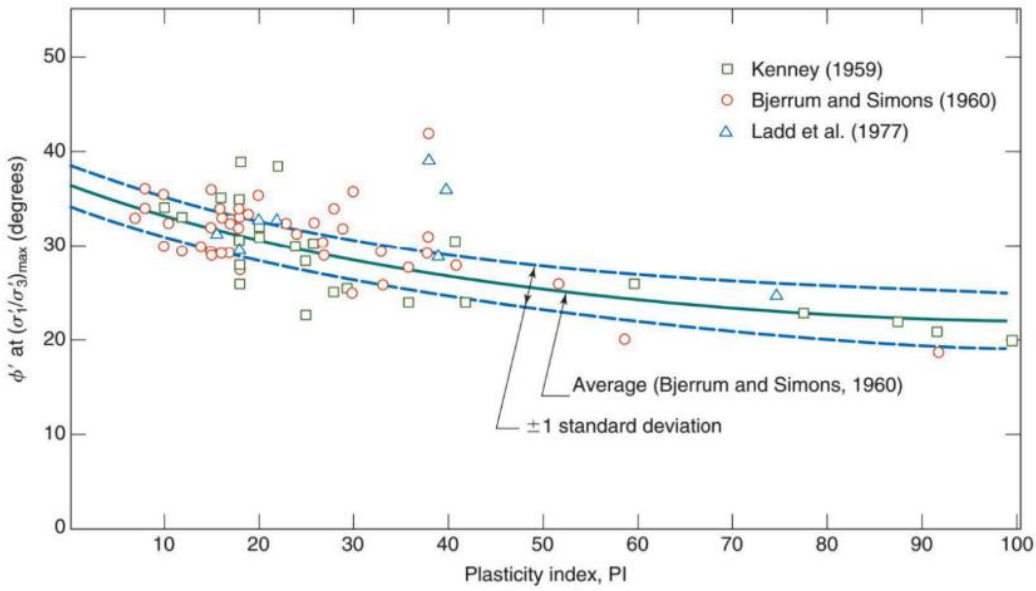

Figure 1. Empirical correlation between ϕ′ and PI from triaxial test on undisturbed normally consolidated soil (Ladd et al., 1977; Holtz et al., 2023)

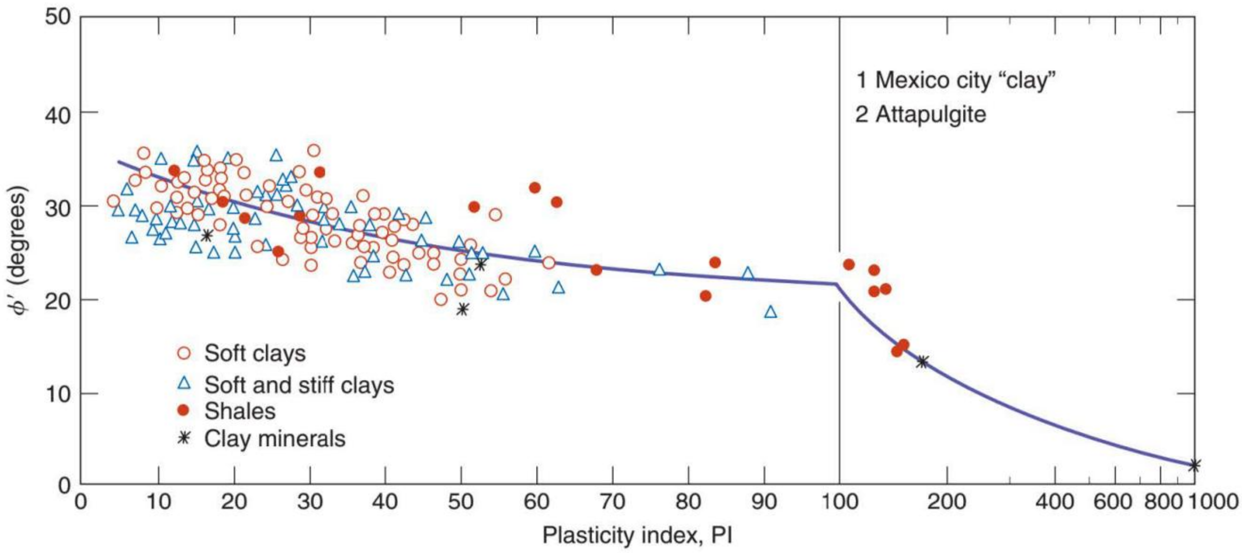

Figure 2. Empirical correlation between ϕ′ and PI of clay minerals over a wide range and other soils (Holtz et al., 2023)

Table 2 Typical values of effective cohession (Wesley, 2010)

Soil Type	Effective Cohession, c′,kPa
Normally consolidated soft clay	Generally close to 0, but can reach 10 kPa
Medium to stiff clay, including residual soil with Su range between 70-150 kPa	Around 10 to 25 kPa
Stiff to hard clay, especially over-consolidated clay	Around 25 to 100 kPa
Compacted clay	Generally, between 12 and 25 kPa

Table 2 is a typical correlation of c′ values, this correlation is often used in the absence of triaxial CU data, but the soil type can be known either through properties tests or field soil descriptions.

An understanding of stress paths in geotechnics

Stress-paths is a way to express a point coordinate on a Mohr circle in a coordinate system τ-σ, when there is a change in stress, the points at the apex of the circle will touch a stress path curve. Eq 1-2 can be used to express the coordinates of the peak of the circle.

$$q = \frac{\sigma_1 - \sigma_3}{2} \quad (1)$$

$$p = \frac{\sigma_1 + \sigma_3}{2} \quad (2)$$

Figure 3 shows how to express the coordinates of the apex of the Mohr circle where each loading condition is expressed as one stress point.

From the results of CU triaxial testing, generally three stress paths will be obtained as shown in Figure 4 and if each stress path peak is connected, it will form a K_f–line. By using the formula in Figure 4, the values of c′ and ϕ′ will be obtained. In geotechnical engineering, understanding the stress paths that occur in the field is fundamental to stability analysis. In embankments, the stress path is generally axial compression (AC) at the base of the embankment. However, at the edge of the embankment, the zone of axial compression changes to lateral extension and lateral compression, Wang and Luna (2012) characterised silt soils using triaxial testing in the Mississippi Valley. In its application, the use of stress paths can explain the phenomenon of soil when experiencing liquefaction (Fernando & Prihatiningsih, 2019)

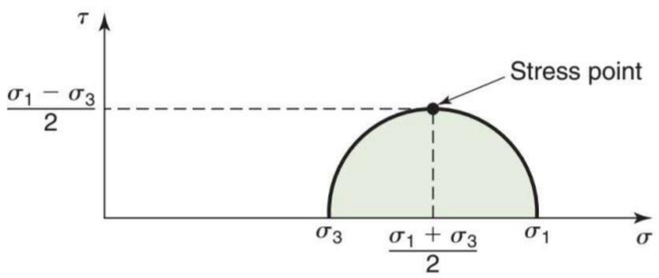

Figure 3. Expressing stress points on a Mohr circle (Holtz et al., 2023)

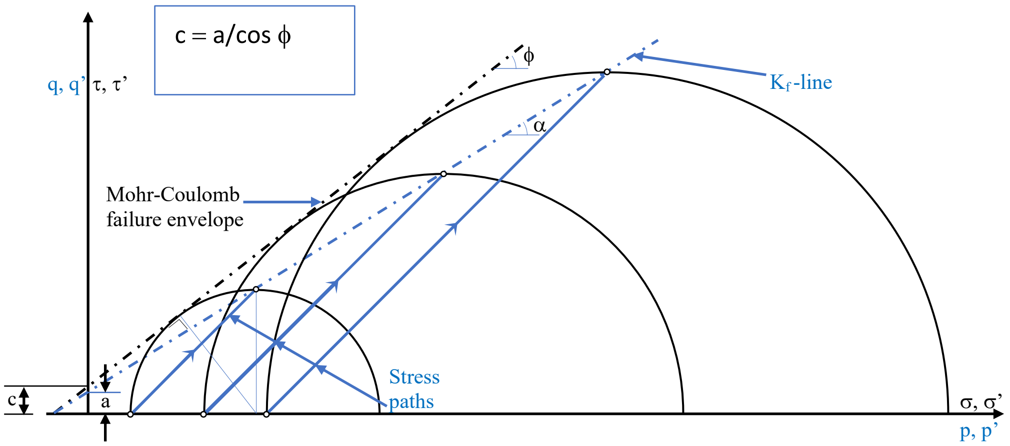

Figure 4. Mohr Coulomb envelope and K_f-line

Soil conditions in Jakarta tend to be dominated by alluvium fans and the result of weathering of weathered rocks originating from volcanoes in South Jakarta (Turkandi et al., 1992). Whereas in sub-tropical regions such as America and Europe, rock weathering generally occurs due to freezing and melting. The main differences in soils from rock weathering in Indonesia, America and Europe are caused by differences in climate, parent rock types, and weathering processes. Soils in Indonesia tend to be more acidic and more various in clay minerals due to intensive chemical weathering. American soils vary greatly depending on the region, while European soils tend to be more neutral to alkaline with high organic content. Figure 5 is a correlation of undrained shear strength (Su) values commonly used in design, especially for fine-grained soils where only SPT tests are performed without correction. Tan and Ramli (2023); Nassaji and Kalantari (2011) studied the correlation of corrected and uncorrected SPT values to obtain Su, with corrected SPT giving better results.

2. RESEARCH METHODOLOGY

Procedure description:

- The research data were collected from Standard Penetration Test (SPT) results and laboratory experiments, including index properties (water content, liquid limit, plastic limit, plasticity index, unit weight, and initial void ratio) and consolidated undrained (CU) triaxial tests. The SPT tests were conducted in accordance with SNI 4153:2008 and the ASTM D1586-08 protocol, while CU triaxial tests adhered to SNI 03-2455-1991Rev. 2004 and ASTM D4767-20. Atterberg limits were performed based on ASTM D4318-05, and grain size analysis was conducted based on ASTM D422-63(2007).
- Conversion of data into mean effective stress (p′) and deviatoric stress (q).
- Linear regression analysis of p′–q for each soil group.
- Determination of shear strength parameters (c′ and ϕ′). The collected data will be processed using statistical software such as Data Analysis Tools-Excel 2019 or Minitab or Python to perform multiple linear regression analysis (MLR) (SPT value, Atterberg limits, and particle size analysis) with dependent variables (cohesion and internal angle of repose).

- Application of ±10% envelope as a conservative boundary. The prediction model will be validated using CU triaxial test data as a reference. Validation is performed to ensure the accuracy and reliability of the prediction model.

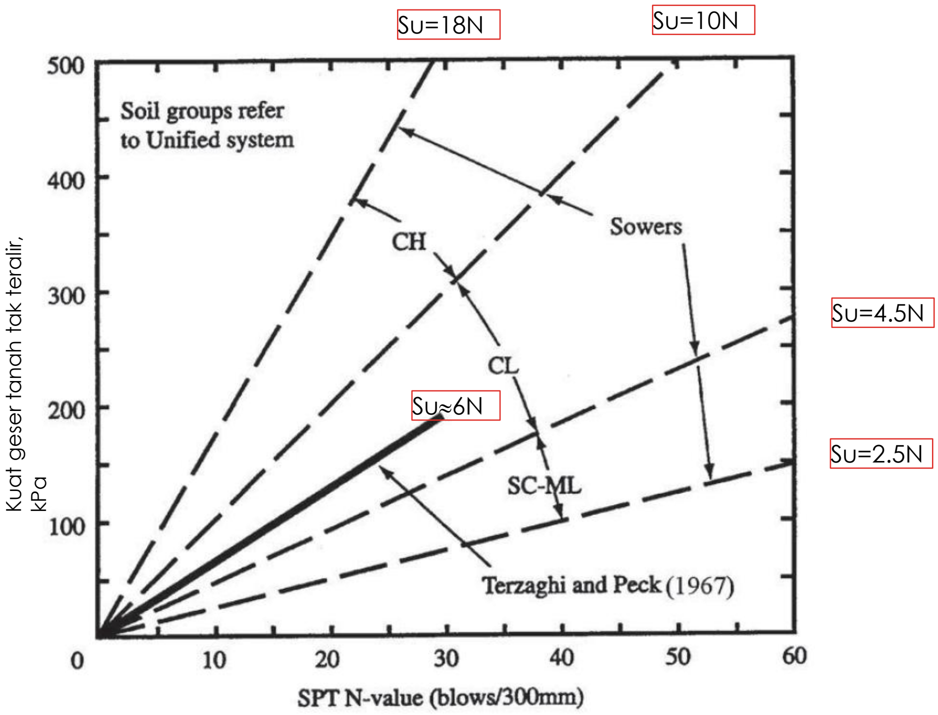

Figure 5. The correlation of undrained shear strength and SPT value adapted from (Terzaghi & Peck, 1967)

Data collection tools and techniques:

- Standard Penetration Test (SPT): Used to measure N-SPT values in the field, in accordance with SNI 4153:2008.
- CU Triaxial Test: Conducted in the laboratory to determine soil strength parameters such as cohesion (c′) and internal friction angle (ϕ′), in accordance with SNI 03-2455-1991 Rev.2004 and ASTM D4767-20.
- Atterberg Limits Test: Conducted to determine the liquid limit (LL), plastic limit (PL), and plasticity index (PI), in accordance with ASTM D4318-05.
- Grain Size Analysis: Conducted to determine the grain size distribution of soil, in accordance with ASTM D422-63(2007).
- Statistical Software: Data Analysis-Excel or SPSS or Python will be used for multiple linear regression (MLR) analysis.

Equation and formula

Multiple Linear Regression is a statistical method used to predict a dependent variable based on several independent variables. In the context of the load-bearing capacity of bored piles, this method analyzes the linear relationship between various soil parameters, pile characteristics, and on-site implementation factors with their load-bearing capacity.

The multiple regression formula expresses a linear relationship between several independent variables (X_1, X_2, ..., X_n) and a dependent variable (Y). Its purpose is to find the value of β_i (Eq. 3) that minimizes residual error.

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+\ldots+\beta_nX_n+\epsilon \quad (3)$$

where Y: dependent variable (cohesion or internal angle of repose), β_0: intercept, β_1, β_2,…, β_n: regression coefficients, X_1, X_2,…, X_n: independent variables (SPT values, Atterberg limits, etc.), and ϵ: error term.

A previous study was the prediction of undrained shear strength values using the Long Short Term Memory (LSTM) machine learning model Aqib et al. (2025) with inputs in the form of moisture content, liquid limit (LL), plastic limit

(PL) and fine grain content obtained quite good results compared to several training models such as Artificial Neural Networks (ANNs) and Support Vector Regression (SVR).

Figure 6 illustrates the methodology flowchart of the research as explained below:

- Gather the following data: N-SPT, index properties (LL, PL, PI, w, γ, e_0), and selected CU results from several locations in Jakarta.
- Divide data per consistency (C01–C06) based on N-SPT.
- Plot p′–qlinear regression per group to obtain mmm and aaa; fixed intercept option provided if technically necessary.
- Calculate upper–lower bound ±10% on c′ and tan α for each group.
- Sensitivity analysis (optional): MLR q ~ p′ + PI → report base R^2 vs. R^2+PI and ΔR^2; no formal model validation is performed at this stage because the objective is operational correlation, not full predictive modelling.
- The output would be equations per group, p′–q + envelope graphs, and ΔR^2 summary.

3. RESULT AND DISCUSSION

The analysis focused on very soft clay (C01, SPT 0–2 blows/ft) and soft clay (C02, SPT 2–4 blows/ft). The results demonstrated a consistent linear relationship between mean effective stress (p′) and deviatoric stress (q) for both soil groups. The slope (m) and intercept (a) from regression were used to calculate cohesion (c′) and internal friction angle (ϕ′). The ±10% envelope was applied to ensure that the results covered the variability of the data.

Plot q vs p′ on very soft (C01) and soft (C02) soils shows a good linear relationship, with a slope close to 0.41 and a high R^2 (>0.8).

- The nearly uniform slope indicates uniformity of the deviation ratio to p′ in this range.
- The lower intercept in C01 compared to C02 reflects a lower stress-bearing capacity due to loose soil structure and high-water content.

Figure 7 illustrates the mapping of p′–q on very soft clay (C01) using 40 CU triaxial tests. While Figure 8 illustrates the mapping of p′–q on soft clay (C02) using 217 CU triaxial tests.

The values of c' and φ' can be derived from the p' and q diagrams as shown in Table 3.

Using a deviation of ±10%, the shear strength parameters for very soft clay and soft clay after superimposition, as shown in Figure 9, with ±10% deviation the influence of PI can still be well-adapted. Summary of sensitivity analysis using MLR as shown in Table 4.

4. CONCLUSION

This study successfully developed a practical and efficient model for estimating the effective shear strength parameters (c′ and ϕ′) of fine-grained soils in Jakarta by leveraging big data from SPT and index properties tests. The analysis focused on very soft (C01) and soft (C02) clays, leading to the following key conclusions:

- A strong linear relationship exists between mean effective stress (p′) and deviatoric stress (q) for both consistency groups. The high coefficients of determination (R^2 > 0.8) confirm that linear regression provides a robust representation of the stress-strain behavior for these soils.
- The derived model parameters resulted in consistent effective friction angles (ϕ′≈ 24°) for both groups, while the effective cohesion (c′) showed a logical increase from 18 kPa for very soft clay (C01) to 20 kPa for soft clay (C02), reflecting the increase in soil strength with consistency.
- The application of a ±10% envelope around the regression line effectively captured the natural variability in the data, including the influence of factors like the Plasticity Index (PI). This was supported by the sensitivity analysis, which showed that adding PI only marginally improved the model fit (ΔR^2 was small), justifying the use of the simpler envelope method for practical design purposes.
- This model presents a significant advantage for preliminary design stages, offering a reliable and economical alternative to expensive and time-consuming CU triaxial tests when they are not available.

The primary limitation of this study is its focus on normally consolidated, very soft to soft clays. Future work will expand this big data analysis to include medium stiff to hard clays (C03 to C06) to create a comprehensive correlation model encompassing the full range of soil consistencies encountered in Jakarta and similar sedimentary environments. Validation of the model against independent case studies is also recommended to further reinforce its reliability.

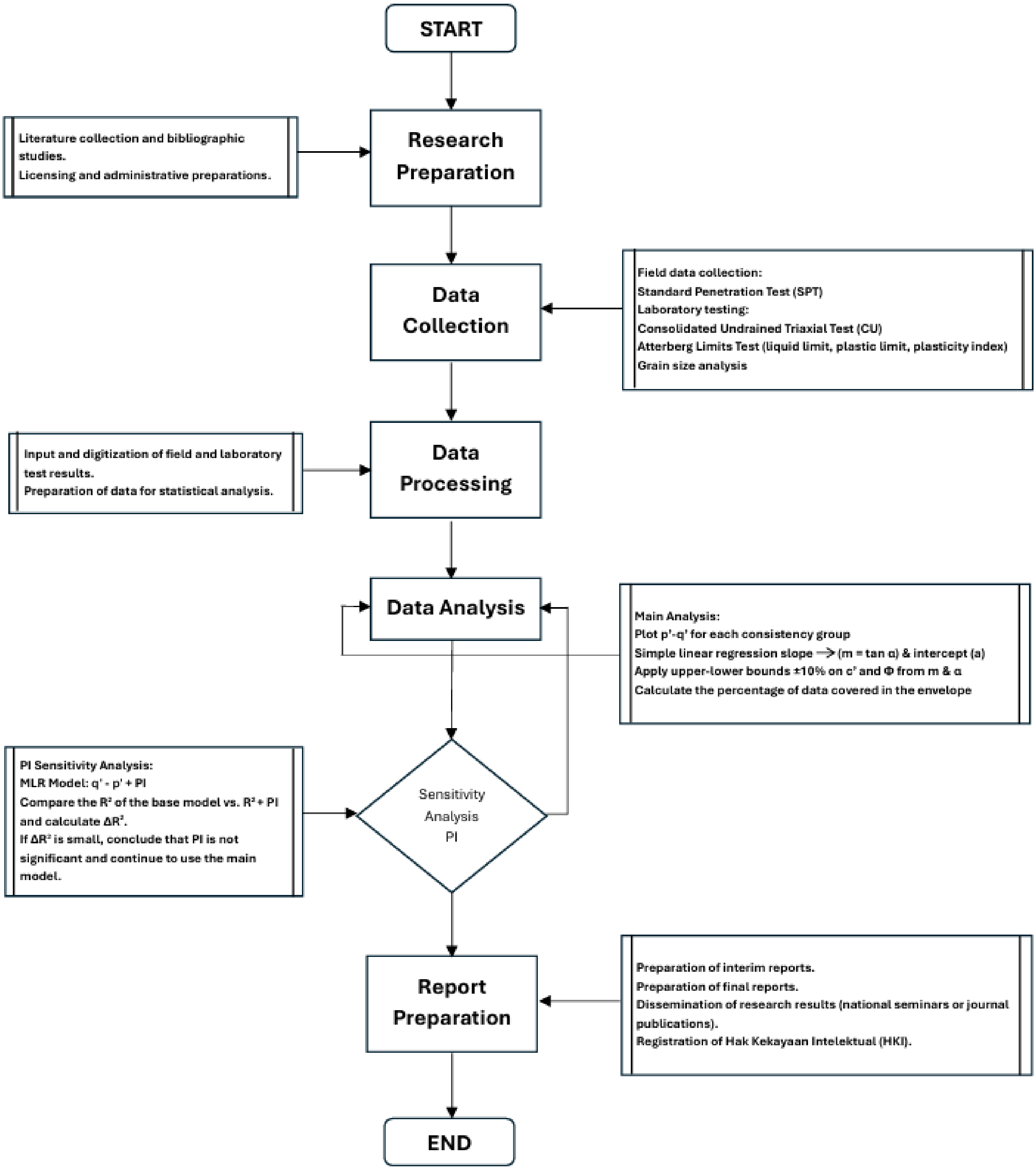

Figure 6. Research methodology flowchart

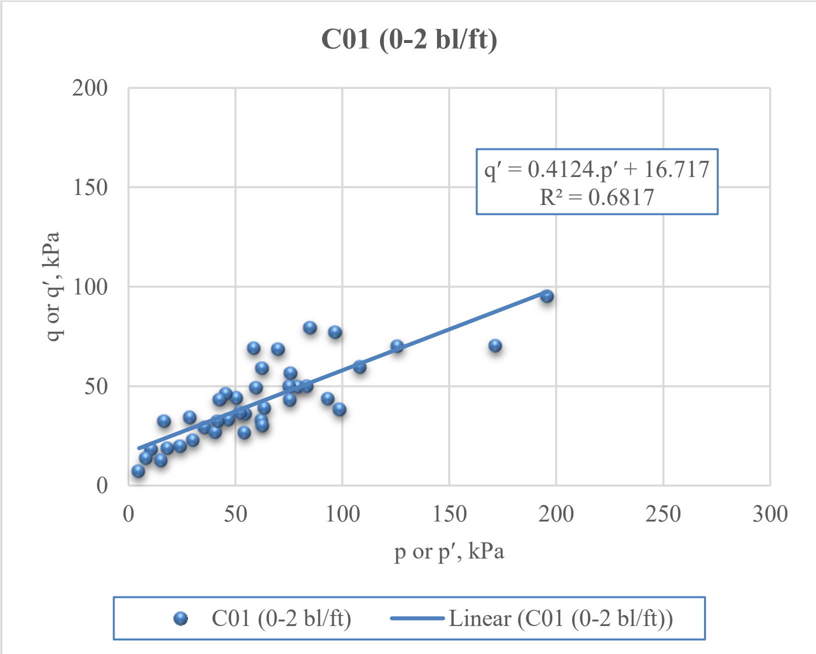

Figure 7. Relationship of p′–q′ for very soft clay (CO1*)*

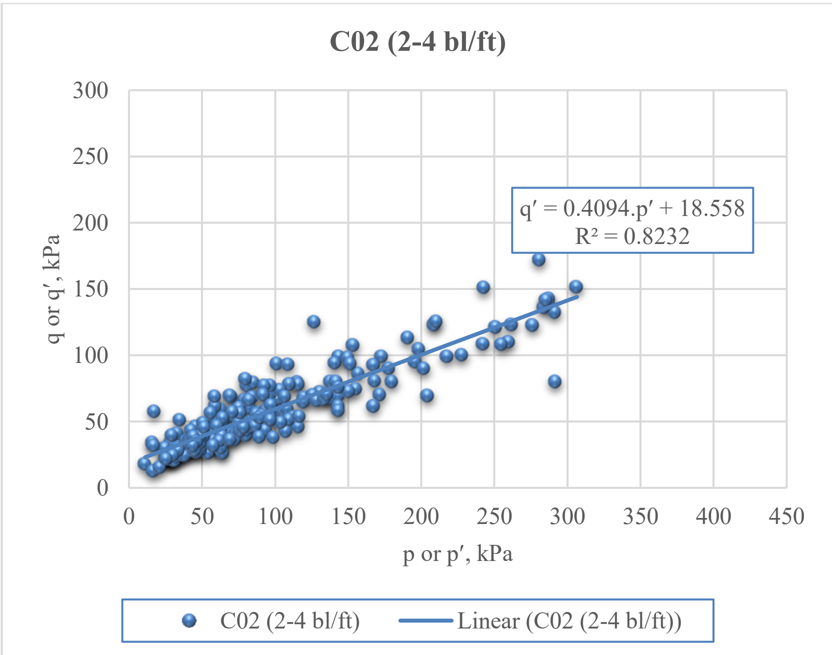

Figure 8. Relationship of p′–q for soft clay (CO2*)*

Table 3. Linear regression results of p′-q

Soil consistency	a, kPa	m = tan α	c′, kPa	ϕ′, kPa
Very Soft Clay (C01)	16,72	0,41	18	24
Soft Clay (C02)	18,56	0,41	20	24

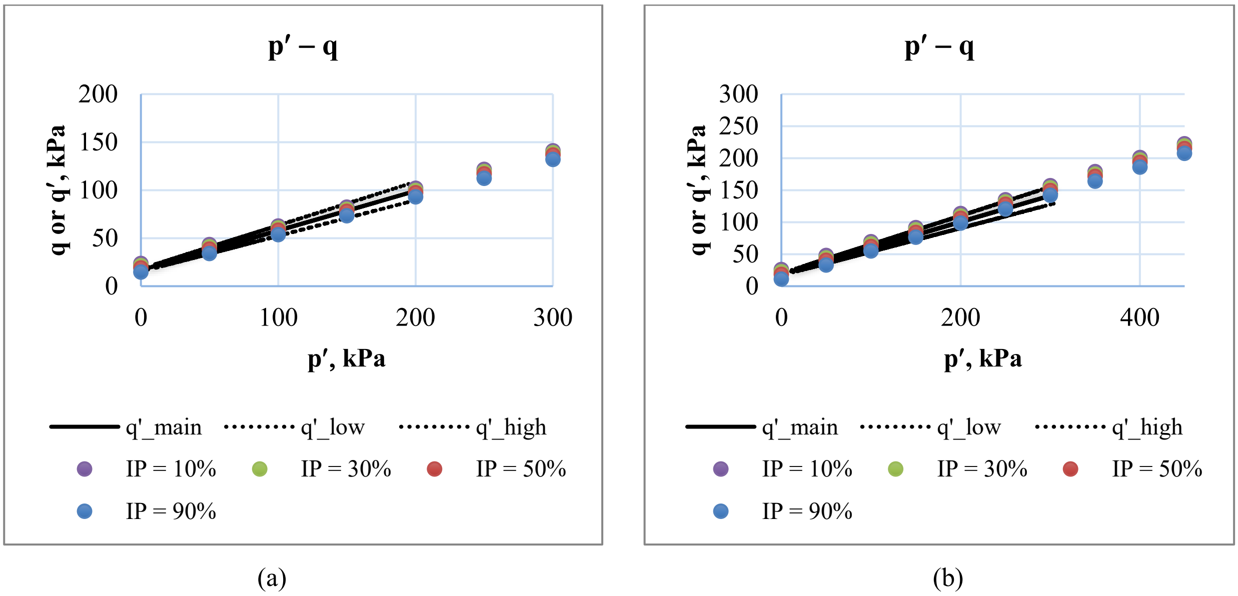

Figure 9. Superimposed data with ±10% envelope

Table 4. Shear strength parameters with ±10% envelope

Soil consistency	c′, kPa	ϕ′, (°)
Very Soft Clay (C01)	16 ~ 20	21 ~ 26
Soft Clay (C02)	18 ~ 22	21 ~ 26

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