A Novel Cross-Pile Calibration Approach for Deriving Local Skin Friction Correlations of Bored Piles

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Received: 16 December 2025 | Revised: 4 January 2026 | Accepted: 10 January 2026

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ABSTRACT

The design of bored piles in Jakarta is often conservative due to reliance on general empirical methods that fail to capture the high shaft friction characteristic of prevalent cemented soils in the area. This study introduces a Cross-Pile Calibration (CPC) strategy that develops site-specific correlations between Standard Penetration Test (SPT) N-values and maximum skin friction. This method uses a combination of load test data from multiple projects and fully mobilized piles to calibrate predictions for those with partial mobilization data in similar soil strata. The study proposes new linear correlations for key soil groups, including skin friction equal to 3.33 times the N-value for cemented sand, capped at 300 kPa, and skin friction equal to 4.0 times the N-value for clay-silt, capped at 160 kPa. Validation against 27 independent piles shows that, on average, applying the CPC-derived correlations within a rational framework yields shaft capacity projections that are 29% higher than those predicted by the classical Reese and Wright method, quantifying a significant reduction in design conservatism. This work provides a practical, data-driven framework for optimizing bored pile design in Jakarta's complex geology.

Keywords-skin friction; Standard Penetration Test (SPT) correlation; Cross-Pile Calibration (CPC); cemented soil; instrumented pile

I. INTRODUCTION

The rapid development of high-rise structures in Jakarta requires reliable deep foundation solutions. Bored piles are commonly used, but the city's unique subsurface profile, including interbedded layers of cemented sands, silts, and clays [1, 2], complicates their design. Standard practice relies on empirical correlations derived from the SPT, the primary and most accessible source of field data for foundation design. SPT underlies both conventional methods and modern, data-driven approaches, such as machine learning [3-8]. However, correlations, such as the Reese and Wright method [3, 9, 10], are inaccurate for locally cemented soils, often resulting in overly conservative designs and unnecessary construction costs [2, 11, 12]. Authors in [13] highlighted the sensitivity of bored pile capacity to geometric parameters, such as the Diameter-to-Depth Ratio (D/L), particularly in cohesive soils. Model 4200 Vibrating Wire Strain Gauges (VWSG) [14] were used for testing. These gauges were fixed to the rebar cage to ensure bonding with the concrete, enabling direct measurement of strain for load-transfer analysis in the CPC framework. The core challenge in developing better local correlations is data scarcity. Although instrumented static load tests with VWSG [14], provide direct load transfer measurements [3, 15-17], a single test rarely achieves full shaft friction mobilization in all soil layers, leaving the maximum skin friction ($f_{s\text{-}max}$), a critical design parameter, unknown for many soil layers across the pile depth. Consequently, deriving a robust $f_{s\text{-}NSPT}$ (or N_{SPT}) correlation from fragmented field data is a significant gap in current practice. Recent advances have focused on improving the interpretation of individual load-settlement curves [18], yet a systematic method to integrate incomplete data from multiple pile tests is lacking. In order to address this issue, the CPC strategy was proposed. CPC is a data fusion methodology that synthesizes information from multiple instrumented piles across different sites. Its central concept involves using $f_{s\text{-}max}$ values from one pile as a calibration reference to estimate the same parameter in other piles with similar soil conditions and only partial mobilization data. This study aims to demonstrate how the CPC framework can overcome data limitations, develop and present a new set of $f_{s\text{-}NSPT}$ correlations for Jakarta's dominant soil groups, and validate the accuracy of these correlations using independent field axial static tests [19]. Building upon the authors' prior work in pile instrumentation, this study develops a novel CPC strategy [3, 15, 16].

II. METHODOLOGY

A. *Data Source and Instrumentation*

The conducted analysis is based on a proprietary database of 35 fully reconstructed and instrumented bored pile load tests from various Jakarta projects. Each pile was equipped with multiple VWSGs and tell-tales, and borehole logs and NSPT data were collected from the same location [20-25]. Shaft friction (f_s) values at different depths were calculated from strain data based on fundamental load-transfer principles. This study uses 35 static load tests conducted on bored piles at 12 construction sites across Jakarta. The piles have diameters of 1.0 m (18 piles), 1.2 m (13 piles), 1.5 m (two piles), and 1.8 m (two piles), with lengths varying from 26 m to 78 m, with an average length of approximately 50 m, and concrete strengths ($f_{c'}$) ranging from 25 MPa to 50 MPa, representing standard concrete grades used in local foundation work. Thus, the collected data span the practical design range for bored piles in Jakarta and provide a solid basis for developing site-specific correlations.

B. *The Cross-Pile Calibration Workflow*

The CPC process involves two key steps, shown in Figure 1:

- Identification of Calibration Reference: For each unified soil classification (e.g., cemented silt or sand), the piles that achieved full friction mobilization in that layer are identified. The measured f_s value of these piles is taken as the representative $f_{s\text{-}max}$ for that soil type and SPT range.
- Calibration of Partial Data: For piles in the same soil layer that achieved only partial mobilization, the unknown f_{s_max} is estimated by calibrating the partial data against the reference f_{s_max} from Step 1. This calibration is based on a comparable soil type and an average NSPT value within the layer.

This process transforms a collection of incomplete tests into a complete, layer-specific database of f_{s_max} values, enabling reliable statistical analysis.

This two-step calibration is based on a fundamental geotechnical principle: the amount of f_s mobilized at a given displacement primarily depends on the soil's shear strength and the condition of the pile-soil interface. These factors are characterized by soil type and N_{SPT}. Therefore, in similar soil strata with comparable N_{SPT} values, the ratio of mobilized f_s to ultimate f_{s_max} can be reasonably assumed to be consistent across different piles. The CPC strategy operationalizes this principle by using data from a "donor" pile with full mobilization to calibrate and complete the load-mobilization curve of a "receiver" pile with partial data.

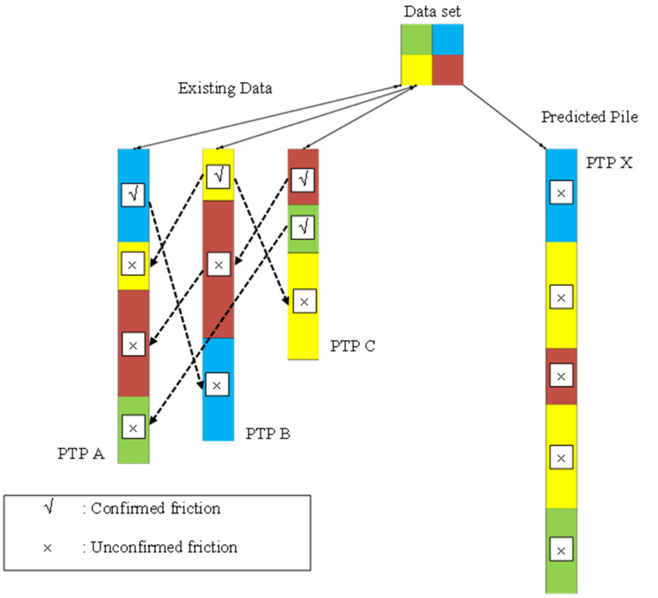

Fig. 1. Schematic of the CPC workflow.

C. *Derivation of Skin Friction-SPT Correlations*

The curated $f_{s\text{-}max}$ database was organized by soil type and cementation condition. A linear regression analysis ($f_{s\text{-max}} = m \times N_{SPT}$) was performed for each group. Figure 2 depicts the coefficient of determination (R^2) from these regressions for key soil classifications.

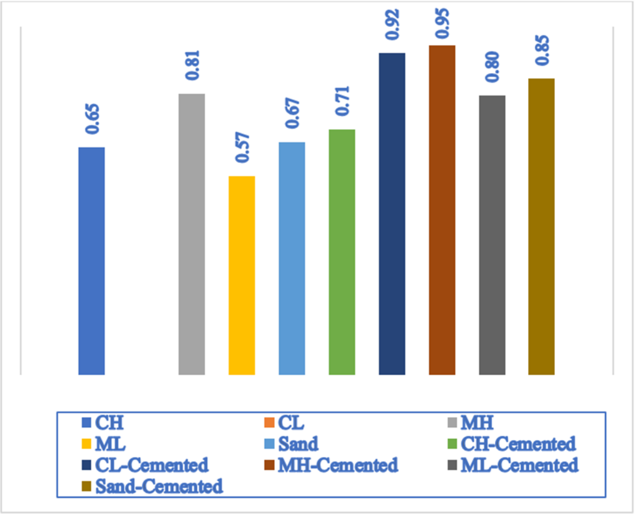

Fig. 2. Goodness-of-fit for soil-specific f_s - N_{SPT} regressions. Soil-type USCS: CH/CL = High/Low-Plasticity Clay, MH/ML = High/Low-Plasticity Silt, Sand = Sand (non-cemented); "-cemented" suffix indicates naturally cemented strata.

A notable finding is that the R^2 values are consistently higher for cemented soil groups (e.g., $R^2 > 0.90$ for cemented sand and silt) than for their non-cemented counterparts. This difference provides statistical justification for treating cemented strata separately in the proposed correlations and confirms the existence of a strong and reliable linear trend, suitable for design purposes. Based on data trends, practical upper limits (capped values) were applied, where data indicated that friction does not increase indefinitely with the N_{SPT} value. The proposed CPC method correlates skin friction directly with uncorrected N_{SPT} values. This approach is intentional, as the N_{SPT} value inherently reflects the soil's intrinsic shear strength and the confining pressure at the test depth. The calibration database includes piles embedded within the typical depth range for bored piles in Jakarta (approximately 15 m-45 m), which ensures that the effect of increasing vertical stress with depth is implicitly incorporated into the derived $f_{s\text{–}NSPT}$ relationships. Consequently, normalization of N_{SPT} values for overburden pressure (N_1) is not required, and the correlations can be applied directly to field N_{SPT} values within the depth range covered by the database.

III. RESULTS AND DISCUSSION

A. Proposed Design Correlations and Their Validation

The CPC strategy produced a set of practical, site-specific design equations, representing the primary outcome of this research. Table I summarizes these correlations for the dominant soil groups in Jakarta. A key feature of these correlations is their incorporation of upper limits, or capped values, which reflect the observed plateau in skin friction mobilization within high-strength layers, a critical advancement over simple, unbounded linear models.

TABLE I. CPC-DERIVED DESIGN CORRELATIONS FOR MAXIMUM SKIN FRICTION IN JAKARTA

Soil group	Proposed correlation (f_s in kPa)	Upper limit (kPa)	Applicability (N_{SPT} range)
Clay-silt (CH, MH, etc.)	$4.0 \times N$	160	$N < 40$
Sand (SP)	$3.0 \times N$	180	$N < 60$
Cemented clay	$3.0 \times N$	250	$N < 100$
Cemented silt	$2.5 \times N$	250	$N < 100$
Cemented sand	$3.33 \times N$	300	$N < 90$

The proposed correlations focus on mobilized shaft friction (f_s) because it is the dominant component of axial capacity in the investigated bored piles. In contrast, base resistance (q_p) contributes relatively little, typically less than 15% of the ultimate load. This is characteristic of long bored piles installed in Jakarta's soil profile. Full mobilization of q_p would require settlement levels that are structurally unacceptable for design purposes. In contrast, f_s can be mobilized at significantly smaller displacements. From a data perspective, each pile provides multiple independent measurements of the shaft's response across several soil layers, which enhances the reliability of the f_s-derived correlations. Conversely, q_p is represented by a single measurement at the pile base, which may be affected by construction disturbances, imperfect cleaning, or localized anomalies. This increases the uncertainty of q_p estimation compared to the distributed nature of f_s. Furthermore, the nonlinear and often softening load-displacement behavior of q_p [26] makes predicting it from basic in situ tests (e.g., SPT) highly uncertain without supplemental, high-resolution tests (e.g., CPT and PMT). Considering these factors, the q_p was treated using a conservative supplemental model following [27], while the CPC framework was developed to optimize the more reliably measurable f_s component, which governs the performance of long bored piles in Jakarta.

B. Comparative Analysis of Projected Pile Capacity

The practical application of the CPC framework was evaluated through a comparative analysis of a separate set of 27 instrumented bored piles. The load tests on these piles ended before geotechnical failure (full shaft friction mobilization) occurred, so their ultimate shaft capacity (Q_s) could not be directly measured. This scenario is common in practice and represents the exact data limitation that the CPC strategy is designed to address. For each pile, the ultimate shaft capacity was estimated via two analytical approaches:

- Proposed CPC + T-Z Analysis: The partially mobilized skin friction profiles were used as input. The CPC-derived $f_{s\text{-}max}$ correlations were applied within a load-transfer (t-z) analysis to project the pile's behavior to failure. In this model, the concrete shaft stiffness (E_c) was reduced from its theoretical value ($4{,}700\sqrt{f_{c'}}$ MPa) by 0-50% to account for realistic degradation in submerged conditions. This reduction served as the primary calibration parameter. This yielded the CPC-projected ultimate shaft capacity, $Q_{s(CPC)}$.
- Classical Reese and Wright Method: The ultimate capacity was calculated directly using the general $f_{s\text{-}NSPT}$ correlations from Reese and Wright, yielding the classically predicted ultimate shaft capacity ($Q_{s(Classic\ R\&W)}$).

The core of this comparison is the divergence between the failure loads projected by the two methods using the same incomplete field data. Figure 3 provides a direct comparison of the two projection methods by plotting $Q_{s(CPC)}$ against the validation piles. The data points cluster closely around a trendline with a slope of 1.29, which quantitatively confirms the CPC framework's projected average uplift of 29%. The proximity of these points to the 1:1 parity line further illustrates the strong linear correlation ($R^2 = 0.97$) and consistent, low-scatter nature of this capacity increase across different pile geometries and soil profiles. Table II quantifies this comparison, showing a low Coefficient of Variation (CoV) (9.8%) for the projection ratio, indicating consistent uplift across the independent pile set. This systematic difference quantifies the potential economic benefits and reduction in conservatism that can be achieved by adopting site-specific CPC correlations. The high R^2 and low scatter (CoV <10%) suggest that the CPC method reliably and rationally scales the output of the classical method, effectively calibrating it to local cemented soil behavior. This comparative analysis confirms that the CPC framework offers a systematic, data-driven approach to deriving higher yet justifiable shaft capacity estimates from incomplete load test data. The CPC strategy is a key methodological advancement that significantly improves practical applicability and economic potential, offering a reliable, systematic approach to the widespread issue of partially mobilized field data. By calibrating fragmented data across multiple tests, CPC maximizes the informational value extracted from costly instrumented load tests. A comparative analysis of 27 independent piles shows that using these correlations in a rational analytical framework, results in projected shaft capacities that are consistently and significantly higher (a mean ratio of 1.29) than those from the classical Reese and Wright method. This uplift, characterized by low scatter (CoV = 9.8%), quantifies the contribution of natural cementation to strength and bridges the identified research gap. CPC offers a data-driven pathway to more economical and reliable foundation design in Jakarta.

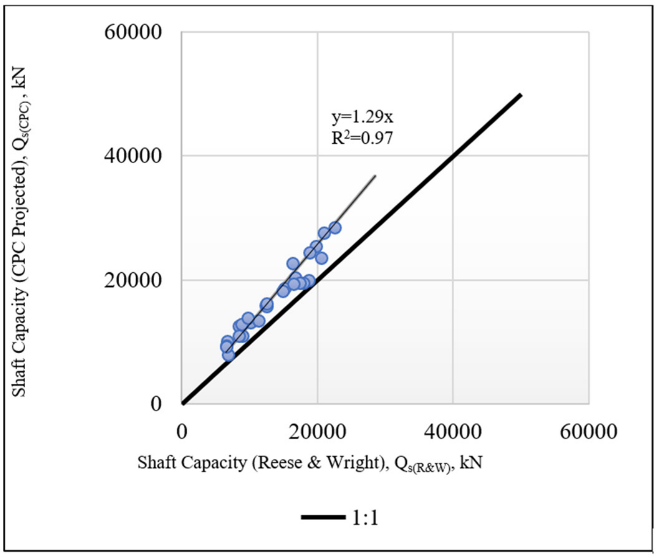

Fig. 3. Comparison of projected ultimate shaft capacities.

TABLE II. COMPARISON OF PROJECTED ULTIMATE SHAFT CAPACITIES FROM CPC AND CLASSICAL METHODS

Parameter	Description	Value
Mean Projection Ratio (MPR)	Average of the ratio across the 27 independent piles. An MPR > 1.0 indicates that the CPC method projects higher capacities than the Reese and Wright method.	1.29
Standard Deviation (SD)	Scatter (dispersion) of the individual ratios around the mean.	0.13
CoV	Normalized measure of scatter, calculated as SD/MPR. A lower CoV indicates more consistent performance of the CPC uplift.	9.8%
Implied design impact	The CPC framework projects shaft capacities that are, on average, 29% higher than the classical method, with low scatter (CoV < 10%), demonstrating a systematic and reliable reduction in design conservatism.	

C. Limitation and Future Work

The proposed CPC correlations are derived from rotary-bored piles constructed with polymer or bentonite slurry. They focus on cemented sands, clays, and silts within typical Jakarta design ranges (diameters of 0.8-1.5 m). This method uses uncorrected N_{SPT} values and has not been validated for other construction techniques, such as wash boring, or for clay, shale, rock, or gravelly sand formations. Future studies could integrate high-resolution in situ tests (e.g., CPT and PMT), extend the approach to pile groups and alternative drilling methods, and validate the correlations in other regions with similar cemented soil profiles.

IV. CONCLUSIONS

This study successfully developed a new set of SPT-based correlations to predict the skin friction of bored piles in Jakarta using a novel Cross-Pile Calibration (CPC) strategy. The main conclusions are:

- The CPC framework effectively overcomes the limitation of partially mobilized field data by integrating and calibrating skin friction information from multiple instrumented pile tests. This transforms fragmented data into a complete database for correlation development.
- New, site-specific linear correlations with defined upper limits were established for Jakarta's key soil groups (e.g., f_s = 3.33 N for cemented sand, capped at 300 kPa). The high coefficients of determination ($R^2 > 0.90$) for cemented soils demonstrate the reliability of these correlations.
- A comparative analysis of 27 independent piles with capacities projected via a *t-z* model using CPC correlations demonstrates a systematic and significant increase. On average, the proposed method projects shaft capacities that are 29% higher than those calculated using the conventional Reese and Wright method, with low variability Coefficient of Variation (CoV) = 9.8%. This quantifies the potential reduction in design conservatism.

The CPC-derived correlations offer foundation engineers a practical, data-driven tool. This work offers validated, site-specific design equations that capture the strength of cemented soils. These equations enable more economical and confident design of bored piles in Jakarta, potentially reducing conservatism by around 29%, as quantified in this study. Beyond these local correlations, the CPC framework establishes a transferable methodology. The systematic process of cross-calibrating multiple pile tests provides a solution that can be applied in other regions worldwide to transform incomplete field data into reliable foundation design criteria for similar geotechnical challenges.

ACKNOWLEDGEMENT

The authors' sincere gratitude is extended to the academic leadership of Universitas Tarumanagara: to Dr. Ir. Daniel Christianto, M.T., Head of the Civil Engineering Department, and to Dr. Eng. Oei Fuk Jin S.T., M.Eng., Interim Head of the Doctoral Program in Civil Engineering. The authors thank them for their invaluable support and for fostering an enriching academic environment conducive to this work.

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