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CORRELATING PILE DRIVING ANALYZER (PDA) AND CASE PILE WAVE ANALYSIS PROGRAM (CAPWAP) RESULTS TO INFER SUBSURFACE SOIL VARIABILITY: A CASE STUDY ON DRIVEN SPUN PILES

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ABSTRACT: Dynamic pile testing using the Pile Driving Analyzer (PDA) combined with Case Pile Wave Analysis Program (CAPWAP) signal-matching analysis provides a rapid method for evaluating pile capacity while offering insight into subsurface behavior. This study investigates 25 driven spun piles (Ø400 mm, L = 40 m) installed in layered clay–sand stratigraphy in Dumai, Indonesia. PDA tests were performed during restrike and refined using CAPWAP analysis to obtain resistance distribution and ultimate capacity. Energy transfer efficiencies ranged from 17.24% to 26.02% (average 20.9%). Statistical evaluation indicates that energy efficiency does not strongly correlate with ultimate capacity, confirming that capacity variability is primarily governed by soil resistance rather than hammer performance. Linear regression between PDA and CAPWAP capacities shows very strong agreement ($R^2 \approx 0.98$) with low prediction error. CAPWAP capacities varied from 139 to 218 tons. Shaft resistance contributed 85–94% of total capacity, confirming friction-dominated behavior, while toe resistance remained minor. Distribution and correlation analyses reveal a bimodal capacity pattern (140–170 tons and 190–220 tons), corresponding to localized soft clay pockets identified in CPT data. Measured capacities generally align with design predictions (180–220 tons), producing safety factors between 1.2 and 1.8. The findings demonstrate that dynamic testing, when integrated with statistical analysis and site investigation data, can function not only as a capacity verification tool but also as an indicator of subsurface heterogeneity in large-scale foundation projects.

Keywords: PDA, CAPWAP, Pile Capacity, Shaft Resistance, Dynamic Testing

1. INTRODUCTION

The evaluation of axial pile bearing capacity is essential to ensure structural safety and long-term performance in large-scale industrial and infrastructure projects. Although static load testing (SLT) is widely recognized as the most reliable method for determining ultimate pile capacity, its implementation is often constrained by high cost, extended testing duration, and logistical challenges—particularly when a large number of piles must be verified within strict construction schedules [1,2]. These constraints have led to the widespread adoption of high-strain dynamic testing using the Pile Driving Analyzer (PDA), which enables rapid capacity estimation during driving or restrike conditions. Dynamic testing has become a common quality-control method in recent Indonesian projects due to its efficiency and adaptability in the field [3–5].

Dynamic testing of pile (PDA test) is based on the analysis of one dimensional waves generated when the piles was hit by a suitable hammer. Therefore, for the purpose of testing, the pile must be hit (re-strike if the pile has been driven) by a hammer capable to transfer sufficient impact energy to mobilize the pile capacity. Two types of instrument are required for the sake of dynamic testing of piles. One set of accelerometer and one set of strain transducer. They need to be installed at the upper part of the pile. To obtain a reliable ultimate capacity from dynamic testing, some guideline must be followed, such as hammer weight, impact factor, a few of them are mentioned, to mobilize the full soil strength. The minimum suggested hammer weight 1% of the required ultimate pile capacity to be proved for shafts installed in soils, and for the piles with larger expected end bearing contributions, the recommended percentage increases to at least 2% of the ultimate pile capacity to be tested. The accuracy degree of PDA data is subjected to uncertainties with respect to the energy transmitted to the pile during testing. The measurement were recorded by PDA test and analyzed with the well known “Case Method” using the Case Pile Wave Analysis Program (CAPWAP) software.

The Case Method interprets these signals to estimate capacity, although its accuracy depends significantly on signal quality, pile integrity, and energy transfer characteristics. Recent studies demonstrate that PDA is increasingly used in layered and soft-clay environments, including for PHC pipe piles and driven precast piles. Li (2023) [6] showed that PDA combined with CAPWAP signal-matching analysis yields capacity estimates consistent with static load tests, provided the recorded waveforms are stable and well-matched. Similarly, Qiu [7] highlighted that high-strain dynamic testing can reliably characterize pile behavior when hammer energy, damping, and soil–pile interaction are modeled correctly.

CAPWAP performs iterative signal matching between measured and simulated waveforms, allowing separation of shaft resistance (Rs) and toe resistance (Rb), as well as estimation of resistance distribution and predicted settlement. Several studies have demonstrated that CAPWAP-interpreted dynamic results can closely match static load capacities across multiple project sites with varying soil profiles [8–10]. Recent research also emphasizes the importance of using CAPWAP to overcome the limitations of the Case Method, especially in heterogeneous soils. Zhussupbekov [11] demonstrated that dynamic signal-matching can identify changes in stiffness along the pile shaft in non-uniform deposits, while Salem [12] used CAPWAP to validate large-diameter bored pile capacities in dense sand and carbonate formations.

In layered soil conditions where transitions between soft cohesive and denser granular layers occur, both static and dynamic pile testing reveal important insights into pile behavior that are not evident from single-method assessments. For instance, Elsakhawy (2024) [13] conducted a comprehensive evaluation of long bored piles in interbedded intermediate geomaterials and demonstrated that dynamic load testing calibrated against static load tests can reveal variations in skin friction and tip resistance across soil layers, and that dynamic tests often show higher estimated capacities in the presence of cohesive–granular interfaces due to the mobilization mechanisms captured under transient impact loads. In addition, recent efforts to enhance the quality management of driven piles through statistical evaluation of dynamic tests emphasize the sensitivity of dynamic capacity predictions to hammer energy, pile geometry, and soil resistance parameters, reinforcing the importance of careful signal interpretation and calibration when assessing capacity in heterogeneous subsurface profiles [14].

Collectively, these studies illustrate that dynamic testing methods such as PDA and CAPWAP not only estimate bearing capacity but also provide deeper understanding of soil–pile interactions in stratified conditions, which is particularly relevant when evaluating spun piles in deep clay–sand stratigraphy typical of many coastal and industrial sites. However, most available studies focus primarily on validating total pile capacity against static load tests rather than systematically analyzing resistance distribution and spatial variability. There remains limited documented case evidence regarding long driven spun piles embedded in deep clay–sand stratigraphy typical of eastern Sumatera industrial zones.

Dynamic testing should therefore not be viewed solely as a verification tool, but also as a potential indirect geotechnical investigation method. Differences between PDA and CAPWAP may reflect subsurface variability; however, such differences can also arise from modeling assumptions, damping parameters, and energy transfer uncertainties in dynamic testing interpretation. Furthermore, differences between PDA-estimated capacity and CAPWAP-interpreted resistance distribution may reflect localized soft pockets, variable consolidation states, or embedment differences into dense layers. When supported by CPT and borehole data, these discrepancies can provide meaningful insight into subsurface variability.

This study investigates 25 driven spun piles (Ø400 mm, L = 40 m) installed in an industrial zone in Dumai, Indonesia. PDA tests were conducted during restrike in accordance with ASTM D4945 [15], followed by CAPWAP signal-matching analysis. The objectives of this study are: (1) to evaluate the statistical agreement between PDA and CAPWAP capacities; (2) to analyze the relative contribution of shaft and toe resistance; (3) to examine the influence of hammer energy transfer; and (4) to interpret capacity variability as an indicator of subsurface heterogeneity. Unlike previous validation-focused studies, this paper integrates correlation analysis, resistance distribution assessment, and statistical interpretation to demonstrate how dynamic testing can provide geotechnical insight beyond capacity confirmation.

The following sections describe the context of the study, the procedures used to obtain and process the field data, and the key findings from the dynamic testing program. The paper concludes with a discussion of how these results relate to design assumptions and what they imply for practical foundation engineering.

2. RESEARCH SIGNIFICANCE

This research highlights the dual function of PDA and CAPWAP as both a structural verification tool and an indirect method for identifying subsurface variability. By statistically evaluating 25 driven piles and integrating CPT and borehole information, the study demonstrates that capacity clustering and resistance distribution patterns correspond to localized variations in clay strength identified in site investigation data. The findings contribute to practical foundation engineering by showing that dynamic testing programs can enhance design validation, detect anomalous soil zones, and improve reliability assessment in large-scale projects where extensive static load testing is impractical.

3. METHODOLOGY

3.1 Project Location and Scope

This study was conducted in Bangsal Aceh, Dumai, Riau Province, Indonesia, within a heavy industrial development zone requiring deep foundation systems with high axial capacity and long-term serviceability performance. The project consists of driven spun piles supporting industrial structures subjected primarily to axial compression loads.

Fig. 1 Multiple Pile Test on Site

A total of 25 driven spun piles with identical nominal geometry (diameter 400 mm, total length 40 m) were evaluated. The scope of this research is limited to high-strain dynamic testing (PDA) performed during restrike and subsequent CAPWAP signal-matching analysis. Static load testing was not included in this investigation; therefore, interpretation focuses on dynamic capacity evaluation and comparative statistical assessment.

3.2 Pile Specifications and Data Collection

All piles were prestressed spun concrete piles with a nominal diameter of 400 mm and total length of 40 m. Embedded lengths varied between 34.7 m and 38.5 m depending on soil resistance encountered during driving. Pile driving was performed using a free-fall diesel hammer (DD type) with two hammer weight configurations: 4.5 tons and 5.5 tons. Pile material properties assumed uniform variability acknowledged as limitation.

For each pile, the following parameters were recorded: total length, embedded depth, hammer type, driving date, restrike date, penetration depth, and blow count. These installation parameters were later used to evaluate energy transfer efficiency and to examine potential correlations between hammer configuration and interpreted capacity. Details of each pile driven can be seen on Table 1. Additional geotechnical data were incorporated from borehole logs, CPT profiles, and laboratory testing. The soil stratigraphy at the site as seen in Table 2.

Table 1. Pile Test Data

Pile ID	Embedded Length (m)	Penetration Depth (m)	Hammer Type
T1	37.0	36.0	DD 5.5 ton
T2	36.7	35.7	DD 5.5 ton
T3	39.0	38.5	DD 5.5 ton
T4	38.8	38.2	DD 5.5 ton
T5	38.9	38.4	DD 4.5 ton
T6	35.6	34.7	DD 4.5 ton
T7	37.5	36.8	DD 5.5 ton
T8	38.1	37.6	DD 5.5 ton
T9	36.4	35.9	DD 4.5 ton
T10	39.2	38.7	DD 5.5 ton
T11	37.9	37.3	DD 4.5 ton
T12	36.5	35.8	DD 5.5 ton
T13	39.1	38.5	DD 5.5 ton
T14	38.4	37.9	DD 5.5 ton
T15	39.5	38.9	DD 5.5 ton
T16	36.2	35.5	DD 4.5 ton
T17	38.0	37.2	DD 5.5 ton
T18	38.6	38.0	DD 5.5 ton
T19	35.8	35.2	DD 4.5 ton
T20	39.4	38.8	DD 5.5 ton
T21	37.7	37.0	DD 5.5 ton
T22	38.3	37.7	DD 5.5 ton
T23	39.0	38.5	DD 5.5 ton
T24	37.2	36.6	DD 4.5 ton
T25	36.8	36.2	DD 5.5 ton

It consists of fill material (0–2 m), soft to medium clay (2–15 m), stiff clay (15–25 m), and dense sand layers below 25 m depth with soil classification followed ASTM D2487. Groundwater was encountered at approximately 1.8 m below the surface. Cone penetration test (CPT) results confirm the variability of soil strength with depth. These data are used to validate PDA and CAPWAP interpretations of shaft and toe resistance distributions.

Table 2. Soil Descriptions

Depth (m)	qc (MPa)	Soil Description
2	1.2	Soft Clay
15	2.5	Medium Clay
25	6.8	Stiff Clay
35	12.4	Dense Sand
40	15.3	Dense Sand/Gravel

3.3 PDA Testing Procedure

PDA testing was conducted in accordance with ASTM D4945 [15]. Two strain transducers and two accelerometers were installed diametrically opposite at approximately 1.5 pile diameters below the pile head as seen in Figure 2. Signals were recorded at a sampling frequency of 40 kHz with standard low-pass filtering to minimize noise and aliasing. For heterogeneous sites, dynamic testing of at least 10–15% of total piles is recommended.

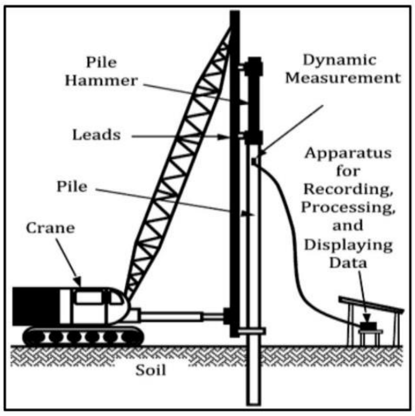

Fig 2. PDA Test Schematic

Force (F) and velocity (V) signals generated by hammer impact were processed using the Case Method to obtain initial estimates of total capacity. Signal quality was evaluated by examining waveform symmetry, force–velocity consistency, and Blow Transfer Area (BTA).

3.4 Energy Calculation and Efficiency Assessment

Hammer potential energy (Ep) was calculated using:

$$\boldsymbol{E_p = W \cdot h}$$

where W is hammer weight (ton) and h is drop height (m). Transferred energy (Et) was obtained directly from PDA measurements. Energy efficiency (η) was computed as:

$$\boldsymbol{\eta = (E_t/E_p)\ \cdot 100\%}$$

For each pile, multiple hammer blows were recorded during restrike. The record with the highest energy transfer (EMX) was selected for CAPWAP analysis. The highest EMX record was selected to ensure sufficient impact energy and signal clarity for reliable CAPWAP interpretation. Repeatability was verified by comparing the two highest-energy blows, ensuring that interpreted capacities differed by less than ±5%.

Hammer type, cushion condition, and pile head preparation were kept consistent throughout testing to minimize variability in energy transfer efficiency.

3.5 CAPWAP Analysis Procedure

CAPWAP analysis was performed through iterative signal matching between measured PDA waveforms and simulated stress-wave responses. The procedure allows separation of the total ultimate capacity (Ru) into shaft resistance (Rs) and toe resistance (Rb), while also estimating resistance distribution along the pile shaft.

Soil parameters used in the CAPWAP model were defined based on CPT-derived stratigraphy. Because CAPWAP interpretation is sensitive to modeling assumptions, a sensitivity check was performed by varying toe quake and damping parameters within reasonable engineering limits. The analysis indicated that a variation of approximately ±1 mm in toe quake could alter interpreted toe resistance by approximately 5–8%, highlighting the importance of parameter calibration in dynamic signal-matching analysis.

3.6 Data Validation and Interpretation

Prior to statistical interpretation, waveform quality was verified by examining the recorded force–velocity curves to identify potential indications of pile damage or abnormal signal behavior. The signals exhibited stable and symmetrical characteristics without abrupt force drops or velocity spikes. In addition, Blow Transfer Area (BTA) values approached 100% for all piles, indicating effective energy transfer and confirming that the tested piles remained structurally intact during restrike testing.

After signal validation, statistical analysis was performed to evaluate the relationships among key parameters obtained from PDA measurements and CAPWAP interpretations. The analysis included linear regression between PDA-estimated and CAPWAP-interpreted capacities, resistance ratio evaluation between shaft and toe components, distribution analysis to identify clustering patterns, and correlation matrix analysis among ultimate capacity, shaft resistance, toe resistance, design capacity, and safety factor.

This statistical framework enables the dynamic testing results to be interpreted not only as a verification of pile capacity but also as an indicator of possible subsurface variability across the investigated site.

4. Results and Discussion

4.1 Energy Transfer Evaluation

Energy efficiency values ranged from 17.24% to 26.02%, with an average of approximately 20.9%. Piles tested within softer clay layers generally exhibited lower efficiency values, whereas piles terminating in stiffer clay or dense sand showed improved energy transfer. This behavior is consistent with wave propagation theory, where softer soils dissipate a greater portion of impact energy through plastic deformation and damping mechanisms [16].

No strong linear correlation was observed between energy efficiency and ultimate capacity. This suggests that variations in interpreted capacity are governed primarily by soil resistance characteristics rather than hammer performance alone. In this dataset, efficiency values around 20% were commonly associated with stable PDA–CAPWAP agreement; however, capacities below this value were not automatically unreliable and required waveform quality verification. The 20% value is therefore not proposed as a universal threshold but represents an empirical observation specific to the soil profile and hammer configuration investigated in this study.

The observed variability in efficiency reflects the interaction between stress wave transmission and layered soil stiffness. In denser strata, stress waves are transmitted more effectively, promoting higher resistance mobilization, whereas in softer layers greater energy attenuation occurs. Previous studies on dynamic testing parameters similarly indicate that energy transfer, driving resistance, and wave impedance are strongly influenced by surrounding soil conditions and should be considered in capacity interpretation [17].

4.2 Statistical Properties and Correlation Analysis of Dynamic Capacity

To comprehensively evaluate the dynamic testing results, regression analysis, resistance ratio statistics, distribution assessment, and correlation matrix evaluation were integrated within a unified statistical framework.

Linear regression between PDA-estimated capacity and CAPWAP-interpreted ultimate capacity produced a coefficient of determination of $R^2 \approx 0.98$, with a regression slope close to unity and RMSE below 2% of the average measured capacity as seen in Figure 3. This strong agreement confirms the internal consistency of field measurements and signal-matching interpretation.

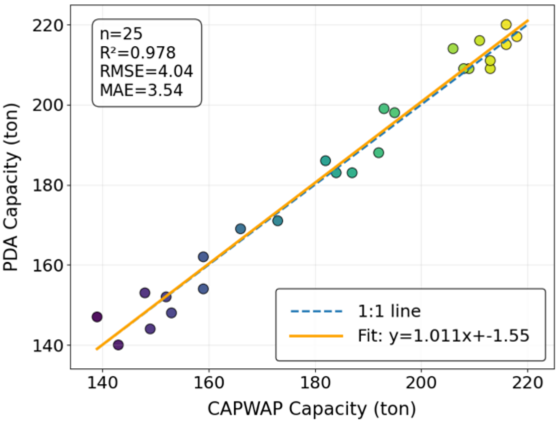

Fig 3. PDA-Estimated vs CAPWAP-Interpreted Pile Capacity.

When analyzed separately by hammer configuration (DD 4.5 ton and DD 5.5 ton), both subsets maintained similarly high coefficients of determination ($R^2 > 0.95$), indicating that hammer magnitude did not significantly influence interpreted capacity trends. Correlation graph can be seen in Fig. 4.

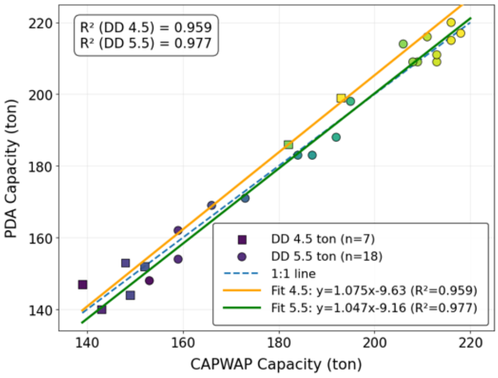

Fig 4. PDA vs CAPWAP Pile Capacity by Hammer Type

Beyond total capacity agreement, resistance distribution analysis provides deeper insight into pile behavior. Statistical evaluation of the shaft resistance ratio (Rs/Ru) for all 25 piles yielded values ranging from 0.86 to 0.94, with a mean of 0.90 and a standard deviation of 0.021, corresponding to a low coefficient of variation (2.3%). In contrast, the toe resistance ratio (Rb/Ru) ranged from 0.06 to 0.14, with comparatively higher relative variability. These results confirm that the piles consistently exhibit friction-dominated behavior within the investigated clay–sand stratigraphy. The observed dominance of Rs aligns with studies highlighting that dynamic load tests analyzed with CAPWAP capture resistance distribution along the pile shaft and tip more reliably by calibrating stress wave data against an assumed soil–pile model, thus isolating the relative contributions of skin friction and end bearing [18–20].

The histogram distribution of CAPWAP ultimate capacity reveals a bimodal pattern, with clusters approximately between 140–170 tons and 190–220 tons (Figure 5). This clustering indicates localized variability within the tested area. The distribution of shaft resistance closely follows the total capacity pattern, whereas toe resistance shows limited spread and lower magnitude. Although embedded lengths varied between 34.7 m and 38.5 m, most pile tips terminated within similar stratigraphic horizons. A normalization review of capacity relative to embedded length did not significantly modify the clustering trend, suggesting that capacity variability is primarily associated with soil resistance differences rather than embedment depth alone. Pearson correlation analysis further clarifies the statistical structure of the dataset, as shown in Figure 6. The correlation matrix indicates an almost perfect relationship between PDA capacity and CAPWAP capacity (r = 0.99), confirming that the field-estimated dynamic capacity is highly consistent with the signal-matching interpretation. From a practical standpoint, this suggests that the measured impact response at the pile head was sufficiently stable and that the CAPWAP back-analysis did not introduce significant deviation from the original PDA-based capacity trend. In other words, the dynamic testing program was internally consistent, and the variations observed among piles are unlikely to be caused solely by measurement noise or random testing error.

A similarly very high correlation is observed between CAPWAP capacity and shaft resistance, as well as between PDA capacity and shaft resistance (both approximately r = 0.99). Mathematically, this is expected because the total ultimate capacity is composed of shaft resistance and toe resistance. However, from a geotechnical perspective, the importance of this result lies in the dominance of shaft resistance over toe resistance in the tested piles. Since the piles are embedded primarily in layered clay deposits before reaching dense sand, most of the mobilized resistance develops along the pile shaft through skin friction. Therefore, when shaft resistance varies from one pile to another, the total capacity also changes almost proportionally.

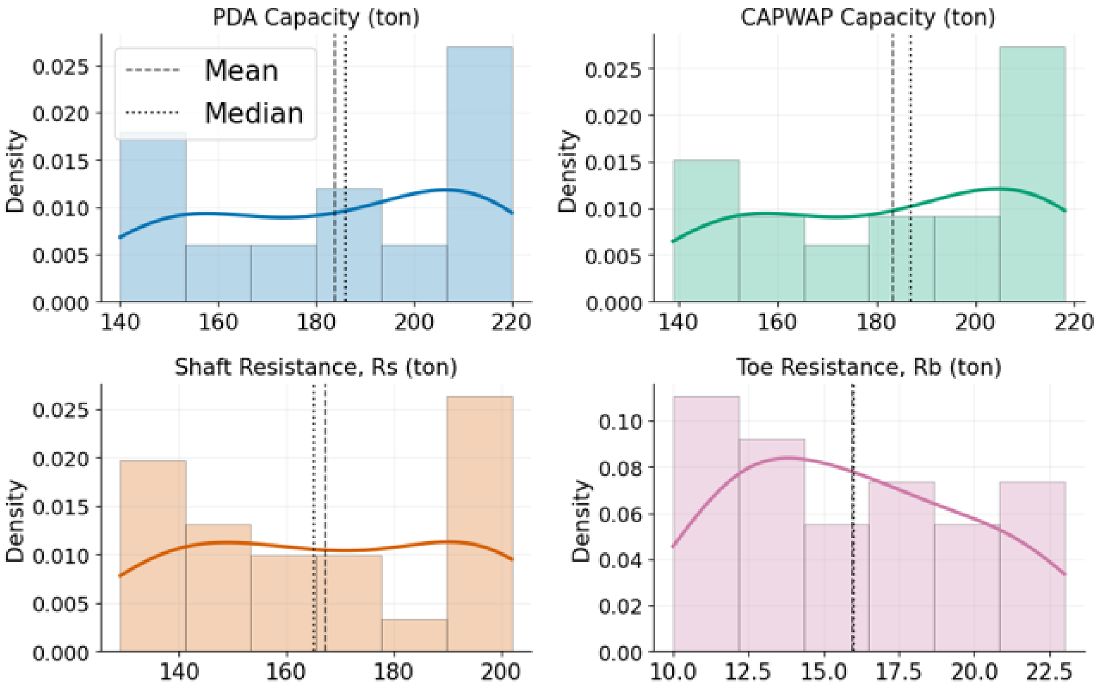

Fig 5. Histogram Distributions of PDA and CAPWAP Pile Capacity

This means that the observed pile-to-pile capacity variability is essentially a reflection of variability in the surrounding soil strength along the embedded shaft rather than variability at the pile toe.

In contrast, the correlation involving toe resistance is only moderate. Toe resistance shows correlation values of about 0.39 with PDA capacity, 0.44 with CAPWAP capacity, and 0.32 with shaft resistance. This indicates that toe resistance contributes to total capacity, but its contribution is much less dominant and less systematic than shaft resistance. Geotechnically, this suggests that the pile tips likely terminate within relatively similar bearing strata, so the toe contribution remains comparatively limited and does not control the overall variation in capacity. In this soil profile, the transition into denser material at depth appears to provide some end-bearing support, but not enough to override the influence of shaft resistance mobilized through the clay layers above. In other words, the pile behaves predominantly as a friction pile rather than an end-bearing pile.

The correlation between design capacity and measured dynamic capacities is also high (r = 0.93 for both PDA and CAPWAP), indicating that the Meyerhof-based design approach captures the general trend of pile performance reasonably well. However, the correlation is still lower than that between measured capacity and shaft resistance. This implies that the design method is adequate for estimating the average capacity level, but it cannot fully capture localized variations in soil conditions from pile to pile.

Geotechnically, this is reasonable because conventional design calculations are based on simplified soil layering and representative soil parameters, whereas dynamic testing reflects the actual resistance mobilized at the specific pile location. Thus, the difference between design capacity and measured capacity may be interpreted as evidence that local stratigraphic variation still plays an important role even when the overall design profile is acceptable.

The very high correlation between safety factor and the measured capacities (r = 0.98–0.99) is also expected, since safety factor in this study is directly derived from the ratio between ultimate capacity and the service load. Although this relationship is mathematically inherent, it still confirms that lower-capacity piles correspond directly to lower reliability margins. From a geotechnical standpoint, this indicates that weaker zones within the site are not only reducing mobilized resistance, but also narrowing the design reserve against the working load. Therefore, localized capacity reduction should not be viewed as a minor fluctuation, but as a potential indicator of weaker subsurface conditions requiring closer engineering attention.

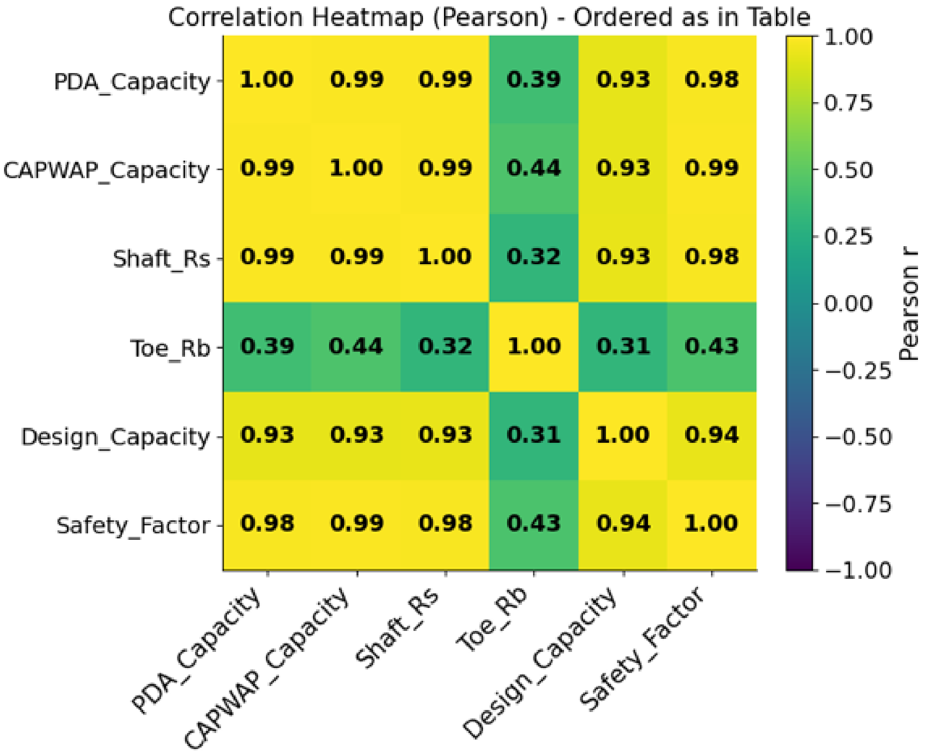

Fig 6. Pearson Correlation Analysis Heatmap

Taken together, the correlation structure supports a clear geotechnical interpretation of the tested site. The strong dependence of total capacity on shaft resistance indicates that the piles derive most of their resistance from interaction with the surrounding clay layers. As a result, any local variation in clay consistency, consolidation state, or thickness directly affects the mobilized pile capacity. The weaker and more scattered role of toe resistance indicates that differences at the pile base are comparatively less significant than the variability along the shaft. Therefore, the correlation matrix is not merely a statistical summary; it reflects the actual load-transfer mechanism of the piles in the investigated ground. For this particular site, the results suggest that localized variability in clay strength is the main driver of capacity clustering, and dynamic testing is able to capture this variability more sensitively than simplified design assumptions alone.

4.3 Comparison with Design Assumptions

Design capacity was estimated using the classical Meyerhof approach. For cohesive soils, the α-method was applied using adhesion factors representative of medium to stiff clay conditions, while for granular layers conventional end-bearing factors (Nq) were adopted for dense sand. These parameters were applied consistently across the site to allow comparison between design predictions and dynamically interpreted capacities.

The calculated design capacities ranged between 180 and 220 tons, whereas CAPWAP-interpreted ultimate capacities varied from 139 to 218 tons. When compared with the service load of 120 tons, the resulting safety factors ranged from approximately 1.2 to 1.8. In general, the design method produced capacity estimates that are reasonably consistent with measured dynamic capacities, indicating that the adopted design assumptions provide realistic predictions for the investigated soil profile.

However, several piles exhibited safety factors close to the lower bound of approximately 1.2. These piles correspond to locations where CPT data indicated the presence of softer clay zones at depths between approximately 35 and 38 m. This observation suggests that while the adopted design method provides generally conservative estimates, localized soil anomalies may reduce the available performance margin in certain areas.

Overall, the combined statistical and comparative analyses demonstrate that the variability of interpreted pile capacity is primarily governed by shaft resistance mobilization along the pile length rather than by hammer configuration or energy transfer variations. The results also show that dynamic testing can effectively detect localized soil heterogeneity that may not be fully captured by simplified design assumptions. Consequently, integrating dynamic testing with site investigation data can improve reliability assessment and provide valuable feedback for foundation design verification in large-scale industrial projects.

5. CONCLUSION

This study evaluated the performance of 25 driven spun piles (Ø400 mm) using high-strain dynamic testing (PDA) combined with CAPWAP signal-matching analysis. The conclusions are presented in the same structured format as the original manuscript, with strengthened quantitative and statistical interpretation.

1. Energy Transfer Efficiency ranged from 17.24% to 26.02%, with an average of approximately 20.9%. A practical threshold of about 20% efficiency was observed to provide stable PDA–CAPWAP agreement. However, statistical analysis confirmed that energy efficiency does not exhibit strong correlation with ultimate capacity, indicating that capacity variability is governed primarily by soil resistance rather than hammer performance.
2. Pile Integrity was confirmed for all tested piles. Force–velocity signals were symmetrical and stable, and Blow Transfer Area (BTA) values approached 100%, with no indication of structural cracking or damage during restrike. This eliminates installation damage or hammer inefficiency as primary explanations for low-capacity results.
3. Capacity Analysis showed CAPWAP capacities ranging from 139 to 218 tons, with very strong linear agreement with PDA capacities ($R^2 \approx 0.98$). The RMSE between methods was less than 2% of average capacity, confirming measurement reliability and modeling consistency. Shaft resistance contributed approximately 85–94% of total capacity, while toe resistance contributed only 6–12%, confirming friction-dominated behavior in cohesive strata.
4. Geotechnical Interpretation revealed a bimodal distribution of measured capacities (140–170 tons and 190–220 tons), indicating lateral subsurface heterogeneity. Piles with lower capacities (<160 tons) correspond to CPT-identified soft clay pockets at depths between 35–38 m, whereas higher-capacity piles were associated with embedment into stiffer or

denser layers. These findings demonstrate that dynamic testing can function as an indirect method for identifying localized soil variability beyond simple capacity verification.

5. Design Validation showed that measured capacities generally align with design predictions (180–220 tons), with calculated safety factors ranging from 1.2 to 1.8. While the adopted design method (Meyerhof and ASTM D2487) provides realistic and generally conservative estimates, piles with safety factors close to 1.2 highlight the influence of local soil anomalies and the importance of dynamic verification.

Overall, the integration of PDA and CAPWAP not only provides reliable capacity evaluation but also enhances geotechnical interpretation in layered clay–sand stratigraphy. The study confirms that discrepancies between dynamic test outputs should not be viewed solely as technical variation but may serve as indicators of subsurface heterogeneity. When combined with CPT and borehole data, dynamic testing becomes a cost-effective and statistically robust tool for quality assurance and foundation reliability assessment in large-scale industrial projects. Because static load testing was not conducted in this project, the conclusions are based on internal consistency between PDA measurements, CAPWAP interpretation, and site investigation data.

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