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# Comparison of Pile Capacity using The Meyerhof Method and Pile Driving Analyzer (PDA)

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## ABSTRACT

*Estimating the axial capacity of piles using the direct method is still a challenging task. This estimation is primarily carried out after the completion of construction, using field methods such as static load tests or Pile Driving Analyzer (PDA) to calculate the axial capacity of piles in actual field settings. This study will focus on the estimating process of pile capacity using data from 5 building projects in Klang Valley. The data includes SPT test data which becomes the input for indirect calculations using the Meyerhof method and field measurement using the PDA test. The primary goal is to establish a correlation between the data obtained from direct and field methods. The Meyerhof method, known for its reliability and widely used by consulting geotechnical engineers, is the direct method employed in this study. The calculation findings indicate a strong correlation ($R^2$ = 0.9434) between (Max Resistance) RMX values from the PDA test and Meyerhof pile capacities, validating the reliability of the Meyerhof method and its potential for accurate pile capacity estimation. The slope of 1.0925 indicates that Meyerhof is slightly higher than RMX values for bored piles. For the spun pile, the $R^2$ value is 0.936, demonstrating a strong connection between RMX values and calculated pile capacities. As a recommendation, it is suggested that relying solely on traditional testing like Standard Penetration Tests (SPT) and Pile Driving Analyzer (PDA) tests may overlook critical insights into soil behaviour. Therefore, exploring advanced soil investigation techniques is essential. Techniques such as Cone Penetration Tests (CPT) provide continuous soil profiles and detailed stratigraphy, allowing for a more accurate assessment of soil strength and layering. Additionally, shear wave velocity measurements offer valuable data on soil stiffness and can enhance dynamic analysis capabilities.*

*Keywords: PDA test; meyerhof method; pile capacity; RMX*

## INTRODUCTION

The soft ground conditions prevalent in the Klang Valley present formidable challenges for the design and implementation of pile foundations, which are crucial in supporting various structures, from high-rise buildings to infrastructure projects. Traditional reliance on SPT values has frequently proven inadequate for accurately predicting the behaviour of piles in these complex soil environments. The limitations of the SPT arise primarily from its inability to capture the dynamic responses of piles during the installation process, as well as the intricate nature of soil-structure interactions that characterize the region's soft, compressible soils (Fattahi et al. 2024). By exclusively depending on SPT data, researchers risk developing overly conservative designs, potentially inflating construction costs due to the necessity of larger pile dimensions or deeper embedment than may be required. Conversely, an insufficient understanding of the soil's inherent weaknesses can lead to under-designed foundations, which pose significant risks to the structural stability and long-term durability of buildings in this rapidly evolving urban landscape. As urbanization accelerates in the Klang Valley, there is a pressing imperative for a more sophisticated and precise approach to foundation design that can effectively navigate the complexities of soft soil conditions. This research aims to assess the pile capacity using analytical methods such as the Meyerhof method and to compare the pile capacity from analytical methods with the PDA test. The PDA test, recognized for its dynamic testing capabilities, plays a pivotal role in elucidating the load transfer mechanisms and assessing the performance parameters of piles during the driving process. The results from PDA testing often afford a more understanding of pile performance compared to SPT alone (Wang et al. 2021). This study aspires to develop an understanding of pile behaviour in soft soils by integrating dynamic PDA data with traditional SPT-N values, thereby fostering an approach that enhances the accuracy of pile configurations. The anticipated outcome is the establishment of safer, more reliable, and cost-effective construction practices tailored to the region's distinct challenges. An overestimation of the pile's load capacity could result in catastrophic failures; while underestimating it may force unnecessary over-engineering, leading to inflated costs and complexities during construction (Henrina et al. 2019). The research will pave the way for robust correlations between these diverse parameters, ultimately leading to the formation of predictive models that accurately estimate pile capacity and settlement, contributing to innovative and sustainable foundation design practices in the Klang Valley. In conventional engineering practice, designs for pile foundations often hinge upon the values derived from SPT-N tests, which may fall short of accurately forecasting the actual behaviour of piles once they are installed. Although the SPT remains a widely adopted and cost-effective method for estimating soil strength, it provides only a limited and indirect depiction of actual soil behaviour under dynamic loading conditions experienced during pile installation. The SPT-N values reflect the soil resistance encountered when a standardized hammer strikes the ground, yet they do not adequately capture the dynamic behaviour of soil during the ongoing process of pile driving. Primarily focused on measuring the soil's resistance under static conditions, the SPT contrasts sharply with the inherently dynamic processes that govern pile installation. This disparity may lead to significant inconsistencies between anticipated and actual pile behaviour, especially in complex and heterogeneous soil strata, which can vary greatly in composition and mechanical properties. Such discrepancies can culminate in inaccurate projections of pile capacity, potentially resulting in costly over-designs, project delays, or more critically, serious structural risks due to inadequate design standards. Researchers often resort to conservative design assumptions when relying solely on potentially misleading SPT-N values, resulting in excessively robust pile foundations that necessitate greater quantities of materials, prolong construction timelines, and escalate overall project costs. Unforeseen ground conditions encountered during pile driving, whether due to variations in soil composition or unexpected subterranean features, may not be accurately reflected in SPT-N values, leading to the necessity for on-the-fly design revisions that can incur both time and financial burdens. Additionally, an over-reliance on SPT-N values for determining pile capacity can lead to under-design scenarios, where the actual structural demands significantly exceed the designed capacity. This presents serious risks, including foundation subsidence, structural failures, and in extreme cases, catastrophic collapses that jeopardize both safety and investment.

Nowadays, prediction of pile capacity using Artificial Neural Networks (ANN) and machine learning is commonly adopted (Benbouras et al. 2021; Bong et al. 2020; Pham et al. 2020; Zi Xun & Abdullah 2023; Chen et al. 2023; Mohd-Saim & Kasa 2024). However, due to the knowledge limitation among engineers, this method is experiencing slow adaptation. The conventional method has become the preferred method because of its reliability, and easy and fast analysis. Another option for pile capacity estimation is using CPT data. Cone penetration testing (CPT) is expensive and requires multiple in-situ tests to determine the pile's characteristics. To predict the pile set-up parameter "A" from CPT for the project's design goal, two new hybrid learning models—PSO-RF and HHO-RF—that combine random forest (RF) with particle swarm optimization (PSO) and Harris Hawks optimization (HHO) were created (Dawei et al. 2023).

Investigating the behaviour of pile foundations through the analysis of SPT values and PDA tests has profound implications that extend across multiple sectors, particularly in infrastructure engineering. (Handley et al. 2006). Another method that can give a good field measurement of pile capacity is using an Osterberg load test (O-cell) (Patino & Galindo, 2024). The significance of pile foundations in the construction industry cannot be overstated. Yet, there remains a notable lack of comprehensive studies that thoroughly investigate the complex dynamics of pile foundation performance. Pile testing stands as a fundamental practice in construction, serving not only to enhance the safety and reliability of structures but also to ensure their overall quality. This practice is particularly crucial for the welfare of individuals and communities that depend on robust and resilient infrastructure systems. Pile testing refers to a series of assessments that play a vital role in determining the maximum load-bearing capacity of piles. This assessment is critical, as the ability of a pile to support a structure is paramount to maintaining its stability and structural integrity. Ensuring these factors is essential for various construction projects, including high-rise buildings, bridges, and other significant infrastructure developments. The consequences of inadequate pile performance can be severe, potentially leading to structural failure and risks to safety and property. (Jarushi et al. 2023). Moreover, understanding the performance of piles under various conditions such as soil type, environmental influences, and load variations can provide invaluable insights into improving design methodologies and construction practices. Thus, advancing research in this area is not just an academic exercise but a necessary endeavour to improve civil engineering and public safety standards (Paul, 2023). Integrating SPT-N data with PDA offers a powerful strategy from a construction standpoint, significantly boosting operational efficiency and resulting in considerable cost savings (Henson, 2023). By effectively leveraging these data sets, construction teams can analyze the soil's geotechnical characteristics in real time, allowing them to make informed adjustments during the pile installation process. This synergy between SPT-N and PDA not only improves the accuracy of the pile driving method but also minimizes the risk of overdriving or under-driving piles, which can result in costly delays and rework. With the ability to adapt to immediate site conditions, construction teams can optimize their strategies, ensuring that projects stay on schedule and within budget while maintaining safety and structural integrity. This proactive approach minimizes the likelihood of expensive delays caused by unexpected subsurface conditions allowing for the optimization of pile lengths and minimizing material waste. Furthermore, conducting a precise evaluation of pile capacity during the initial stages of the construction process is crucial for enhancing overall safety outcomes. This early assessment identifies potential issues related to pile performance or structural integrity well before they can escalate into serious problems. By anticipating these challenges, construction teams can implement appropriate mitigation strategies, significantly reducing the risks associated with pile failures. This proactive approach not only ensures a safer working environment for construction crews but also minimizes the likelihood of accidents and the development of structural inadequacies that could arise later in the project. Overall, thorough early assessments play a vital role in safeguarding both personnel and the integrity of the construction project as this is connected to SDG 11, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable.

On a societal level, the implications of this research are profoundly significant. Enhancing safety and reliability within infrastructure is vital in promoting public safety and overall welfare. When it comes to pile foundations, accurate and carefully engineered designs that are founded on reliable and comprehensive data are essential. These designs enable crucial structures such as bridges, high-rise buildings, and roadways to withstand the test of time and maintain their stability and durability under various environmental conditions and loads. The research underscores the importance of adhering to stringent engineering standards and best practices, ensuring that each foundation is tailored to the site's specific conditions and the structure's expected usage. Moreover, by prioritizing the integrity of these foundational systems, we foster greater trust within communities regarding the safety of their surrounding infrastructure. This results in a ripple effect that enhances economic productivity, as reliable transportation networks and secure buildings can attract investment and promote social mobility. Ultimately, the insights derived from this research are poised to inform policy decisions and engineering practices, pushing the boundaries of what is possible in modern-day construction and design. This vigilance helps safeguard the public and minimizes the likelihood of costly infrastructural failures that can lead to significant socioeconomic disruptions. In addition, the implementation of optimized designs alongside innovative installation techniques plays a crucial role in minimizing soil disturbance during the construction process. By carefully planning and executing these strategies, construction projects can significantly reduce the need for excessive materials, which conserves not only natural resources but also alleviates environmental impact. This approach fosters a more sustainable construction practice that is mindful of the surrounding ecosystem and contributes to preserving local habitats. Furthermore, the economic advantages of employing reliable construction practices cannot be understated. These efficiencies can deliver substantial cost savings that benefit society as a whole (Jackmartin 2025). By reducing the resources required for construction and extending the lifespan of infrastructure, we enable projects to be more financially accessible for communities. Additionally, decreased long-term maintenance expenses arise from using high-quality materials and precision in design, ensuring that infrastructure remains safe and functional for many years. This holistic benefit results in a stronger foundation for society, encouraging investment in infrastructure that supports economic growth and enhances the quality of life for residents as this is connected to SDG 9, which aims to Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

This study aims to significantly improve the accuracy and reliability of pile capacity predictions by strategically integrating SPT-N data with cutting-edge, real-time measurements derived from advanced PDA testing (Kothuri et al. 2024). Integrating these two comprehensive data sources is designed to provide a more precise and dependable foundation for engineering design decisions. The PDA captures real-time, high-resolution measurements of pile behaviour during the driving process, detailing the complex and dynamic interactions between the pile and surrounding soil layers. This rich dataset provides critical insights into driving stresses, soil resistance characteristics, and overall pile integrity, enabling researchers to make informed decisions based on actual conditions observed during construction (Jain et al. 2018). By systematically converging PDA data with SPT-N values, the research aims to transition from overly cautious design assumptions to precise, reliable predictions of pile performance. The application of data-driven methodologies will facilitate the optimization of pile design, ensuring that adequate capacity is achieved while minimizing excess material use. Furthermore, this integrated approach enables the early identification of potential issues throughout the installation process, thus significantly reducing risks and enhancing overall safety in construction practices within the challenging landscape of the Klang Valley.

## METHODS

The SPT N-value is utilized to compute the pile capacity. The details of Meyerhof method is given in Meyerhof (1976). It was employed to ascertain the bearing capability of the piles. The method is selected because it is widely used by the practicing engineer. However, the limitations of this method are that it does not consider complex soil behaviour such as the effective stress reduction, remolding effect due to pile installation and consolidation effect. The axial capacity of each test is evaluated by comparing it to the measured results obtained from the PDA test. The details about PDA test are given in ASTM D4945-17 (2017). The Meyerhof method correlates with PDA test results from five different construction sites around Klang Valley. The piles consist of bored, spun and Reinforced Concrete (RC) piles with varying sizes ranging from 250mm to 1800mm. Statistical analysis was conducted to analyse the correlation between the measured (PDA) and calculated (Meyerhof) methods. Figure 1 shows the flow chart of the study. The construction sites for data collection are located at Seksyen 23 (Shah Alam), Cybersouth (Cyberjaya), Westport (Klang), Pulau Indah (Klang) and Puchong, as depicted in Figure 2.

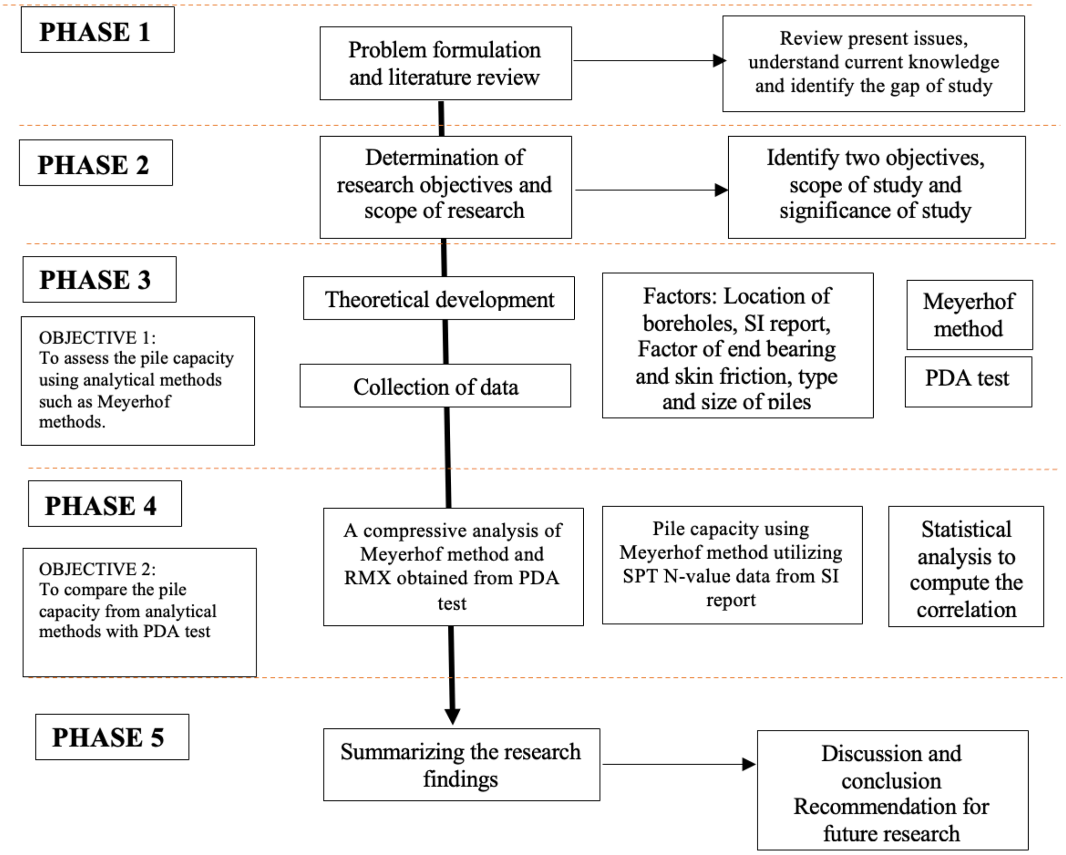

FIGURE 1. The flow chart of the study

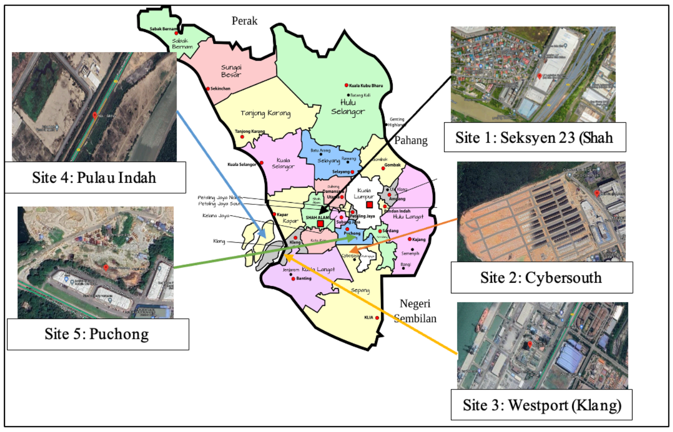

FIGURE 2. The construction sites for the data collection

## RESULTS AND ANALYSIS

The results are presented based on data collection from different sites, type of soil, size of pile and type of pile. The following are the main findings of this research.

Table 1 shows the pile characteristics. As the pile size increases, so does its capacity. Larger piles have a greater cross-sectional area and can therefore support higher loads. For example, the 250 x 250 mm pile has a minimum capacity of 500 kN, while the 450mm x 450mm pile has a minimum capacity of 1920 kN. The 400 x 400 mm piles have the greatest depth range of 42 to 48m, while the 450mm x 450mm piles have the shallowest range of 18m to 24m, despite having a higher capacity. This suggests that factors other than size, such as soil conditions and specific project requirements, influence the required pile depth. The table provides minimum and maximum actual pile capacities. This range reflects variations in soil conditions, installation methods, and testing procedures. The actual capacity of a pile is determined through field testing, and the range accounts for potential variability. Similar to the capacity ranges, the minimum and maximum actual pile depths likely reflect project-specific conditions and design considerations. The depth of a pile is determined based on the soil profile, load requirements, and desired factor of safety. The table specifies that the piles are made of reinforced concrete. RC piles are commonly used in construction due to their strength, durability, and resistance to corrosion.

TABLE 1. Pile characteristics

| Pile type and size | Minimum Actual Pile Capacity (kN) | Maximum Actual Pile Capacity (kN) | Minimum Actual Pile Depth (m) | Maximum Actual Pile Depth (m) |
|---|---|---|---|---|
| RC 250 x 250mm | 500 | 1000 | 24 | 36 |
| RC 400 x 400mm | 1700 | 2050 | 42 | 48 |
| RC 450 x 450mm | 1920 | 2750 | 18 | 24 |
| SP 400 mm dia. | 850 | 1530 | 54 | 60 |
| SP 600 mm dia. | 1750 | 2990 | 42 | 48 |
| BP 600 mm dia. | 2400 | 3534 | 12 | 24 |
| BP 900 mm dia. | 5500 | 7952 | 10 | 24 |
| BP 1200 mm dia. | 9800 | 14137 | 10 | 15 |
| BP 1800 mm dia. | 22200 | 31809 | 15 | 20 |

Figure 3 shows a Pile capacity from Meyerhof method versus RMX from PDA test for bored pile (Site 1) with an $R^2$ value of 0.9434. The slope of 1.0925 indicates a slight overestimation in the Meyerhof values compared to the RMX values. This high $R^2$ value confirms that the RMX values are reliable predictors of the Meyerhof Pile Capacity, requiring only minor adjustments for perfect alignment. The equation ($y = 1.0925x$) means that for every unit increase in the RMX Pile Capacity, the Meyerhof Pile Capacity increases by 1.0925 units. The slope, being slightly greater than 1, suggests that the Meyerhof values are generally higher than the RMX values, indicating a potential overestimation in the Meyerhof method. An $R^2$ value of 0.9434 signifies that 94.34% of the variability in the Meyerhof Pile Capacity can be explained by the RMX Pile Capacity. This strong correlation shows a solid linear relationship between the two variables, with the remaining 5.66% of the variability attributed to other factors not accounted for by the RMX values. The slight overestimation (slope > 1) implies that the Meyerhof method tends to provide higher pile capacity values compared to the RMX method. Thus, minor adjustments or calibrations may be necessary to better align the Meyerhof values with the RMX values. Overall, the strong correlation and high R² value indicate that RMX values serve as a reliable predictor of Meyerhof Pile Capacity, despite the slight overestimation.

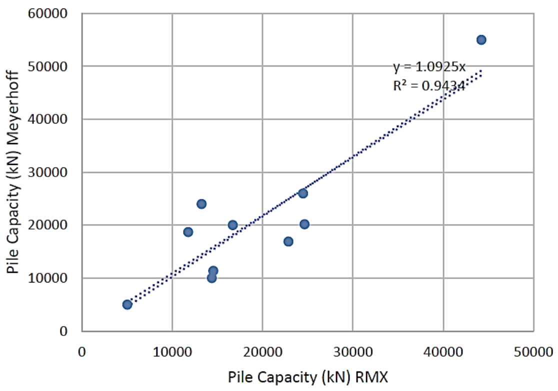

FIGURE 3. Pile capacity from Meyerhof method versus RMX from PDA test for bored pile (Site 1)

Figure 4 demonstrates a strong correlation between RMX and Measured Pile Capacities, with R² values of 0.936. The left graph has a slope of 0.799, indicating an underestimation of the measured values, while the right graph has a slope of 1.028, suggesting a slight overestimation. The right graph implies a more accurate measurement process, as its values closely align with the RMX values. The equation (y = 0.799x) indicates that for every unit increase in RMX Pile Capacity, the Measured Pile Capacity increases by 0.799 units. This slope, being less than 1, suggests that the measured values are consistently lower than the RMX values. Conversely, the equation (y = 1.028x) implies that for every unit increase in RMX Pile Capacity, the Measured Pile Capacity increases by 1.028 units. This slope, slightly greater than 1, indicates that the measured values are very close to the RMX values, with only a minor overestimation. This near one-to-one correspondence suggests that the measurement process is quite accurate, with only a minimal overestimation present. An R² value of 0.936 indicates that 93.6% of the variability in the Measured Pile Capacity can be explained by the RMX Pile Capacity. This high R² value reveals a strong linear relationship between the two variables. The remaining 6.4% of the variability is attributed to other factors not captured by the RMX values. Similarly, the left graph also reflects an R² value of 0.936, confirming that 93.6% of the variability in Measured Pile Capacity is due to RMX Pile Capacity, reinforcing the strong linear relationship. The consistent underestimation (slope < 1) might suggest the necessity for calibration or adjustment in the measurement process to better align with RMX values. The slight overestimation (slope > 1) indicates that the measured values are very close to the RMX values, with only minor adjustments needed for perfect alignment. The strong correlation, reflected in the high R², affirms that RMX values are effective predictors of Measured Pile Capacity, despite the underestimation observed.

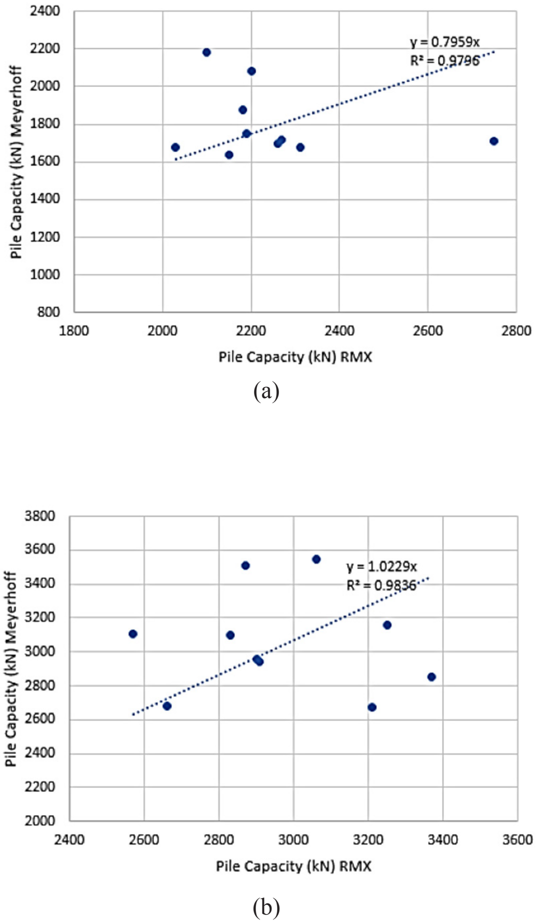

FIGURE 4. Pile capacity from Meyerhof method versus RMX from PDA test for spun pile (a) Site 2 (b) Site 5

Figure 5 demonstrates a strong correlation between RMX and Meyerhof Pile Capacities, with R² values ranging from 0.8975 to 0.9806. The first plot has a slope of 0.9421, indicating a slight underestimation. The second plot has a slope of 0.6683 and a baseline offset, suggesting a significant underestimation. The third plot has a slope of 1.086, indicating slight overestimation. Among these, the third plot appears to represent the most accurate measurement process, as its values closely align with the RMX values. The equation (y = 0.9421x) shows that for every unit increase in the RMX Pile Capacity, the Meyerhof Pile Capacity increases by 0.9421 units. This slope of slightly less than 1 implies that Meyerhof values are generally lower than RMX values, indicating a slight underestimation. The equation (y = 0.6683x + 895.5) indicates that for every unit increase in RMX Pile Capacity, the Meyerhof Pile Capacity increases by 0.6683 units, plus an additional constant of 895.5. This slope of less than 1 suggests a more significant underestimation of the Meyerhof values compared to the RMX values. The constant term (895.5) signifies a baseline offset, meaning that even when the RMX value is zero, the Meyerhof value starts at 895.5. In contrast, the equation (y = 1.086x) indicates that for every unit increase in RMX Pile Capacity, the Meyerhof Pile Capacity increases by 1.086 units. This slope of slightly more than 1 suggests that the Meyerhof values are generally higher than the RMX values, indicating a slight overestimation. An $R^2$ value of 0.9472 means that 94.72% of the variability in Meyerhof Pile Capacity can be explained by RMX Pile Capacity. This high $R^2$ value indicates a strong linear relationship between the two variables, with the remaining 5.28% of the variability due to factors not captured by the RMX values. An $R^2$ value of 0.8975 signifies that 89.75% of the variability in Meyerhof Pile Capacity can be explained by RMX Pile Capacity, which indicates a strong linear relationship, though slightly weaker than in the first plot. In this case, 10.25% of the variability is due to other factors. An $R^2$ value of 0.9806 means that 98.06% of the variability in Meyerhof Pile Capacity can be explained by RMX Pile Capacity, highlighting an extremely strong linear relationship, with only 1.91% of the variability attributed to other factors. The slight underestimation (slope < 1) may indicate the need for calibration or adjustment in the Meyerhof measurement process to more closely align with the RMX values. The strong correlation (high $R^2$ value) suggests that RMX values are a valid predictor of Meyerhof Pile Capacity, despite this slight underestimation. The significant underestimation (slope < 1) along with the baseline offset implies that the Meyerhof measurement process may require substantial calibration to better align with RMX values. The strong correlation still indicates that RMX values can predict Meyerhof Pile Capacity effectively, despite the underestimation and offset. Meanwhile, the slight overestimation (slope > 1) suggests that Meyerhof values are very close to RMX values, requiring only a minor adjustment for perfect alignment. The extremely strong correlation (very high $R^2$) further confirms that RMX values are an excellent predictor of Meyerhof Pile Capacity.

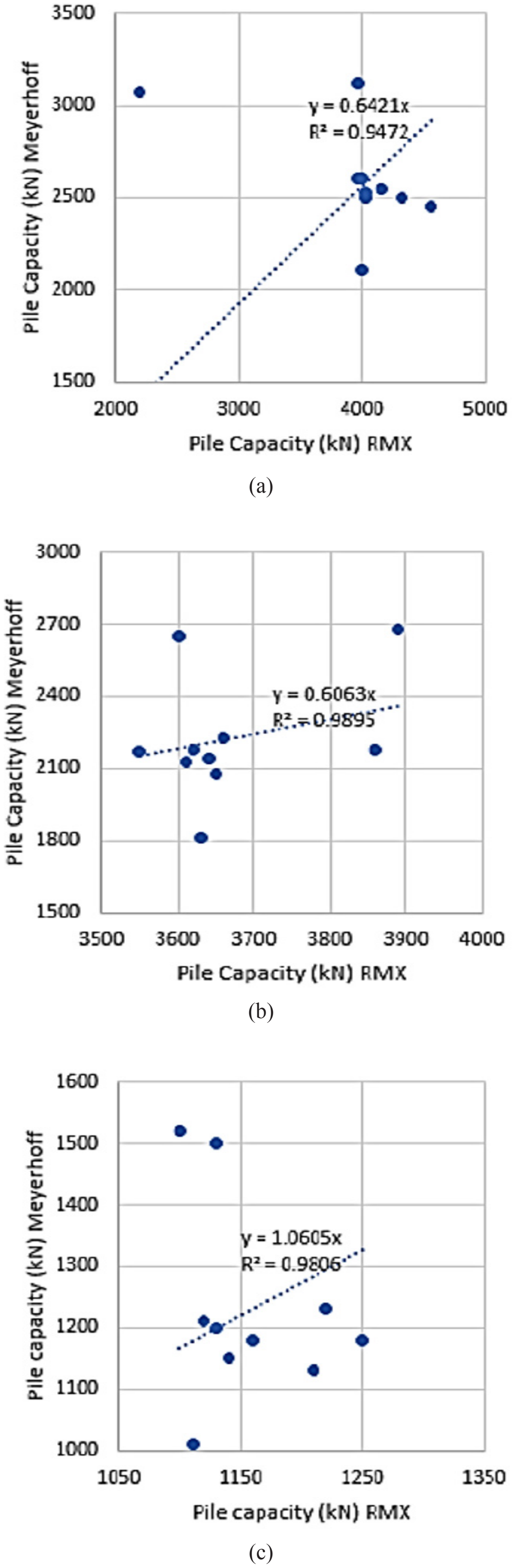

FIGURE 5. Pile capacity from Meyerhof method versus RMX from PDA test for RC pile (a) Site 3 (b) Site 4 and (c) Site 5

Figure 6 shows the Predicted versus measured pile capacity based on data collected from five sites. In the current study, the gradient of 0.7038 demonstrates a notable insight: for every unit increase in the predicted values derived from the Mayerhoff method, the measured values from the PDA test rise by approximately 0.7038 units. This reveals a moderate positive correlation between the predicted and measured values. In contrast, the previous study reported a gradient of 2.0874, suggesting that each unit increase in the expected values obtained through the Direct Method correlates with a substantial 2.0874 unit increase in the estimated values from the PDA test. This indicates a significantly stronger positive relationship than that observed in the current study. Furthermore, the $R^2$ value of 0.4008 in the current study signifies that around 40.08% of the variability in the measured values can be accounted for by the predicted values using the Meyerhoff method. This reflects a moderate fit of the regression line to the data points, yielding valuable insights. In comparison, the $R^2$ value of 0.2378 from the previous study reveals that only about 23.78% of the variability in the measured values can be explained by the predicted values from the Direct Method. This underscores a weaker fit of the regression line to the data, highlighting the critical nature of robust model fit in data analysis. Ultimately, the steeper gradient in the previous study (2.0874) compared to the current study (0.7038) signifies a stronger relationship between predicted and measured values in the right graph. Conversely, the current study's higher $R^2$ value (0.4008) indicates a superior fit of the regression line to the data points than that of the previous study (0.2378). These comparisons illuminate the distinct differences in predictive accuracy and relationship strength between the two methods analyzed, underscoring the significance of the findings. The statistical analysis was performed using Microsoft Excel. Table 2 shows the correlation of different types of piles. The off-diagonal value of 0.89 for the bored pile (BP) reveals a robust positive correlation between RMX (kN) and Meyerhof (kN). This strong relationship suggests that when the value of RMX increases, the Meyerhof value tends to rise correspondingly. Such a high correlation coefficient underscores the significant connection between these two variables, indicating that they likely influence each other in meaningful ways within the context of the study.

TABLE 2. Correlation of different types of piles

| Pile type | Value |
|---|---|
| BP | 0.89 |
| SP | -0.06 |
| RC | -0.28 |

The off-diagonal values, particularly the correlation coefficient of -0.06 for spun pile (SP), reveal a negative correlation between the variables RMX (kN) and Meyerhof (kN). This statistic shows that there is a negligible linear relationship between these two measurements. A correlation coefficient of -0.06 implies that as the RMX (kN) value exhibits an increase, the Meyerhof (kN) value tends to decrease slightly, although the effect is so minimal that it may not be statistically significant. In essence, this negative correlation reflects an inverse relationship, where variations in one variable do not substantially impact the other, thereby indicating a lack of dependence between these two datasets.

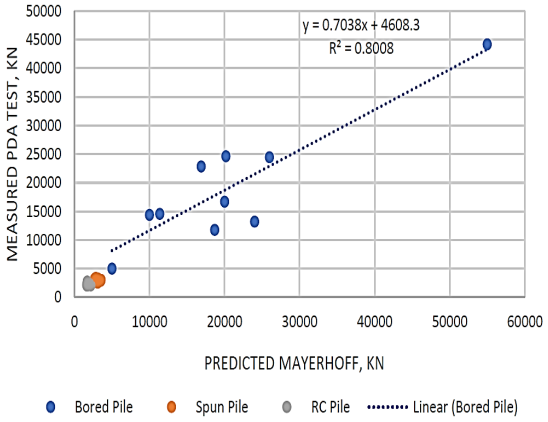

FIGURE 6. Predicted versus measured pile capacity based on data collected from five sites

The off-diagonal elements, which register as -0.28 for reinforced concrete (RC) pile, reveal a notable negative correlation between RMX (kN) and Meyerhof (kN). This suggests an inverse relationship as the RMX value increases, a corresponding decrease in the Meyerhof value is typically observed. However, the strength of this negative correlation is relatively weak, and this should reassure us about the lack of a strongly dependent relationship between the two variables. Table 3 presents a compelling comparison of the results from two studies examining various types of piles: RC, Spun Pile, and Bored Pile. The present study demonstrates a noteworthy improvement in performance, rising from 0.977 in the previous study to an impressive 0.9809 for reinforced concrete piles. This enhancement signals progress and effectiveness in the methodologies applied. The present study reveals a significant advancement in performance metrics, reflecting improved practices or innovations. The observed improvement not only suggests advancements in materials and construction techniques but also showcases effective testing methodologies that could pave the way for future enhancements in the field.

TABLE 3. Comparison of determination of $R^2$ based on previous study and current study

| Type of Pile | Previous Study (Zi Xun & Abdullah, 2023) | Current Study |
|---|---|---|
| RC | 0.977 | 0.9809 |
| Spun Pile | 0.943 | 0.9360 |
| Bored Pile | 0.951 | 0.9434 |

The present study indicates a slight decline in performance, decreasing to 0.9360 from 0.943 for spun pile. This finding emphasizes the need for further investigation into the factors contributing to this downturn. The decline in performance suggests critical areas that require further scrutiny and enhancement. The slight declines in these categories underline the necessity for targeted research and innovation to ensure performance is not only maintained but also elevated.

Similarly, the present study reveals a minor decrease in performance, from 0.951 to 0.9434 for bored piles. This decline points to potential areas for optimization and enhancement moving forward. The decrease in performance also highlights a pressing need for further evaluation to restore or surpass previous levels of effectiveness. The observed declines point to critical areas requiring further exploration and optimization to not only regain but ideally surpass previous performance benchmarks.

## CONCLUSION

The research objectives are to assess pile capacity using analytical methods such as the Meyerhof method and to compare the pile capacities obtained from analytical methods with those from the PDA test. After conducting result analysis and discussion, RC piles vary widely in terms of capacity and depth. The 250 x 250 mm piles have the lowest capacity, ranging from 500 to 1,000 kN, and moderate depths between 24 and 36 meters. The 400mm x 400mm piles provide significantly higher capacities, ranging from 1,700 to 2,050 kN, along with greater depths of 42 to 48 meters. Interestingly, although the 450mm x 450mm piles are larger, their capacity range of 1,920 to 2,750 kN overlaps with that of the 400mm x 400mm piles, yet they have shallower depths of 18 to 24 meters. This observation may indicate variations in soil conditions or differences in design methodologies.

The SP400 piles have a capacity range of 850 to 1,530 kN, which falls between the smaller and larger RC piles, but they require significantly greater depths of 54 to 60 meters. BP piles demonstrate the highest capacities, which increase with diameter. The BP600 piles have a capacity range of 2,400 to 3,534 kN, the BP900 piles range from 5,500 to 7,952 kN, the BP1200 piles have a capacity of 9800-14137 kN, and the BP1800 piles exhibit the highest capacity at 22200 to 31809 kN. Generally, BP piles necessitate shallower depths of 10 to 24 meters compared to RC and SP piles, especially for larger diameters.

There is a strong correlation ($R^2 = 0.9434$) between RMX values and Meyerhof Pile Capacities. The slope of 1.0925 indicates that Meyerhof values are slightly higher than RMX values for bored piles. For spun piles, the $R^2$ value of 0.936 demonstrates a strong connection between RMX values and Measured Pile Capacities. The data from the graph reveals a slope of 0.799, suggesting an underestimation, while a slope of 1.028 indicates a slight overestimation. In the analysis of Reinforced Concrete Piles, $R^2$ values range from 0.8975 to 0.9809, reflecting a strong relationship with RMX values. The varying slopes indicate different degrees of underestimation and slight overestimation. In summary, these analyses confirm that RMX values are reliable for predicting pile capacities, with only minor adjustments required for better alignment.

Understanding the soil behaviour of pile foundations requires a comprehensive analysis that goes beyond standard SPT-N values. It is critical to investigate additional soil properties that play a significant role in pile behaviour. This includes shear strength, which indicates the soil's ability to resist sliding forces, consolidation characteristics which describe how soil volume decreases under pressure over time; and Atterberg limits which provide insights into soil consistency at different moisture contents, particularly the plasticity index. By integrating these properties, researchers can develop a more nuanced understanding of soil-pile interactions, especially in soft ground conditions. Various soil testing methods can elucidate the relationship between these properties and pile performance.

The reliance on traditional testing like SPT and PDA tests may overlook critical insights into soil behaviour. Pile Dynamics Inc. (POI) manufactures the PDA computer, which is used to read and record the "acceleration" and "strain" transducers (Ramli et al. 2022). Therefore, exploring advanced soil investigation techniques is essential. Techniques such as CPT provide continuous soil profiles and detailed stratigraphy, allowing for a more accurate assessment of soil strength and layering. Additionally, shear wave velocity measurements offer valuable data on soil stiffness and can enhance dynamic analysis capabilities. These advancements facilitate a more detailed understanding of soil's dynamic properties and stratigraphy, crucial for effective pile foundation design.

Long-term monitoring of pile foundations in soft ground is vital to understanding their performance over time. This includes assessing settlement behaviour, which indicates how the pile behaviour changes as loads are applied, load transfer mechanisms that show how loads are distributed between soil and the pile, and potential degradation effects caused by environmental factors like moisture changes or chemical interactions. Implementing comprehensive monitoring strategies can provide critical data that informs maintenance and design adjustments over a structure's lifespan.

To enhance the performance of pile foundations in soft ground conditions, investigating the effectiveness of various ground improvement techniques is crucial. Methods such as preloading, where loads are applied to compress soil before pile installation, soil stabilization techniques that use additives to increase soil strength, and deep soil mixing, which improves soil characteristics through mechanical mixing, should be thoroughly examined.

Assessing the environmental impact of pile foundations in soft ground conditions requires a thorough examination of multiple factors. This includes understanding how soil displacement can affect the surrounding ecosystem, the implications of groundwater flow alterations, and potential adverse effects on nearby structures and utilities. Careful consideration of these factors during the design and implementation phases is essential to mitigate negative environmental consequences.

Analysing case studies of pile foundation projects, particularly in regions like the Klang Valley, is invaluable for evaluating the effectiveness of current design and construction practices. This can help identify practical challenges and highlight successful strategies used in similar soil conditions.

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## DECLARATION OF COMPETING INTEREST

None.

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