

Case Studies and Lower-bound Capacity Prediction of Precast Jacked Piles Installed in the Philippines

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ABSTRACT This research compiles multiple case studies of precast jacked pile with various lengths and slenderness ratios tested with high-strain dynamic load pile tests (HSDPT) in the Luzon region of the Philippines. This allows for the exploration of the relationship between pile slenderness ratio, HSDPT ultimate capacity, and final jacking force (P_{jack}). Evaluation of existing empirical lower-bound predictions of ultimate capacity that utilize slenderness ratio and P_{jack} was conducted, followed by establishment of a new lower-bound predictive formulas that best-fit the collected data. Four case studies are presented, with a total of 135 square precast jacked piles tested with HSDPTs. The slenderness ratios in the four case studies ranged from 5.11 to 63.8. The ratio of the ultimate capacity measured by the HSDPT to P_{jack} , also called pressure ratio, was found to be a function of the slenderness ratio. The pressure ratios generally rise above 1.0 for piles with slenderness ratios higher than 30. The actual pressure ratios and ultimate capacities measured are also compared to two existing empirical lower-bound predictions, with 93% and above of actual pressure ratios and capacities above those predicted. Two alternative lower-bound pressure ratio formulas that are a function of slenderness ratio are also proposed, particularly to deal with low-slenderness piles in the database ($L/D < 10$) that cannot be adequately modeled by existing formulas.

KEYWORDS jacked piles; high-strain dynamic load test; pile capacity; PDA tests

1 INTRODUCTION

1.1 Introduction to Pile Jacking

The use of pile jacking to install displacement piles is a relatively new pile installation technique that avoids the spoil generated by cast-in-place bored piles, and undesirable vibration and noise from pile driving with a hammer. White and Deeks (2007) documented significant reduction in noise when pile jacking is used when compared to other installation methods including hydraulic and diesel hammers, and bored piling. Peak particle velocity, which quantifies ground vibration, caused by jacked piling has also been found to be much lower than pile driven by diesel hammer or vibratory hammer (White et al., 2002). However, one limitation of jacked pile installation is the need for a relatively large working area to install the piles, as well as the need for a reaction force for the jacking machine.

Two frequently used jacking methods are (1) the press-in piling method, where previously installed piles are used to produce a reaction force for the jacking machine, and (2) the hydraulic static pile driving (HSPD) method, where dead weights are used as a reaction force. Press-in piling method was documented to have been used in Japan (White et al., 2002), while the use of HSPDs has been reported in China, Malaysia, Australia (White and Deeks, 2007), and the Philippines (Buensuceso, 2021).

Jacked piles in the Philippines are typically square, concrete, precast piles, and installed using the HSPD method (Buensuceso, 2021). HSPD method works by mounting a pile onto a jacking rig, and a hydraulic clamp holding the pile in place. The hydraulic clamp then jacks the pile downward until

it has reached the maximum length of travel, also called stroke. Jacking force applied by the HSPD can be measured from the hydraulic pressure readings. The clamp is then moved back upwards, and the process is repeated until the termination criteria to end the pile jacking have been met. The final jacking force (P_{jack}) measured during this installation process can in some cases be a reliable estimate of the pile's ultimate capacity as measured by a static load test (SLT) (Yetginer et al., 2006).

1.2 Termination Criteria for Jacked Piles

Termination criteria have been previously proposed to establish a clear relationship between measurements taken at the end of jacking and load test results. The China Academy of Building Research (2008) suggests that criteria include the final jacking force, the depth of embedment, the number of jacking cycles done at the end of installation, and the rate of settlement during the final jacking cycles.

Zhang et al. (2006) proposed the following termination criteria for two steel H-piles in a project in Hong Kong. The criteria are as follows:

- a. Piles should be founded in strong soil stratum, with SPT N-Value of at least 120, with no underlying weaker soils
- b. Piles shall be jacked to 2.5 times a design load (P_d). Under this load, the rate of pile settlement shall be less than 5 mm in 15 minutes.
- c. The piles shall be subjected to three or more jacking cycles with peak load equal to 2.5 P_d . Under this load, the rate of pile settlement shall be less than 5 mm in 15 minutes.

Figure 1 shows a database of R_{ult} (obtained from SLTs) to P_{jack} ratio vs. slenderness ratio based on 149 jacked piles in China and Hong Kong (Zhang et al., 2006). The data includes 7 SLTs from Hong Kong, conducted on steel H-piles 8 to 17 days after the jacked pile installation, and 142 SLTs from Guangdong, China, conducted on square and circular concrete piles. The square piles were 250 to 400 mm wide, while the circular piles were 400 to 500 mm in diameter. The pile lengths vary from 10 to 25 m and were founded mainly on sand, weathered soil, or clay, the soils typically found in Hong Kong.

1.3 Relationship between Ultimate Pile Capacity to Final Jacking Force and Slenderness Ratio

In the same graph, two equations were established by Zhang et al. (2006): Equation 1, a best-fit regression equation to predict pressure ratios using slenderness ratio, and Equation 2 to predict pressure ratios using slenderness ratios (L/D , or length of a pile over pile diameter or width) with a 95% confidence level that the predicted pressure ratio (α) is above the line. The probability that the pressure ratio falls below the curve represented by Equation 8 is 5%, a confidence level used to determine characteristic values for geotechnical design in Eurocode 7 (Orr, 2000).

$$\alpha = R_{ult} / P_{jack} = 1.32 - 12.48/(L/D) \quad (1)$$

$$\alpha = R_{ult} / P_{jack} = 1.13 - 12.48/(L/D) \quad (2)$$

The relationship between the slenderness ratio (L/D), the ratio of R_{ult}/P_{jack} , and predictions from Equations 1 and 2 can be seen in Figure 1.

Another set of data by Yu and Yang (2011) is shown in Figure 2. The database consists of 95 concrete jacked circular and square piles ranging in length from 5 to 60 m installed in coastal provinces in China. They also established several relationships between pressure ratio (α) and pile slenderness ratio (λ) categorized based on the soil types that the piles were founded on.

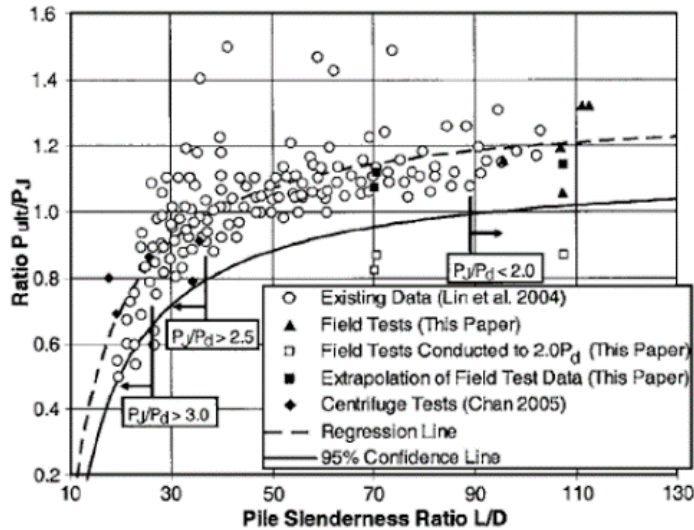


Figure 1. Pressure ratio (R_{ult}/P_{jack}) vs. slenderness ratio (L/D) from Zhang et al. (2006)

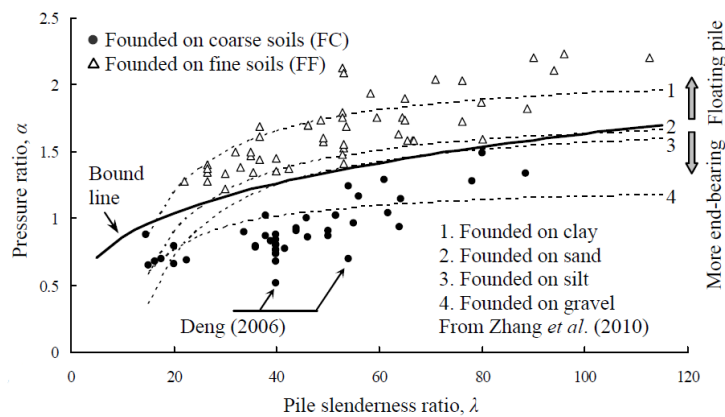


Figure 2. Relationship between pressure ratio and slenderness for concrete jacked precast piles from Yu and Yang (2011). Includes predictions from Zhang et al. (2010).

The Australian Standard (2009) AS-2159 - Piling Design and Installation also provides termination criteria for the installation of jacked piles. Section 7.3.4.1 of AS-2159 requires that the maximum jacking installation force P_{jack} be determined with Equation 3. Jacked piles are required to be subjected to repeated jacking at P_{jack} , with the number of cycles no less than 5. P_{jack} should be maintained for at least 15 seconds, and the time interval between cycles should be more than 2 minutes. Equation 4 is a derived formula for estimating the geotechnical ultimate capacity R_{ult} using P_{jack} and a coefficient of jacked pressure γ_p .

$$P_{jack} = 0.74 \gamma_p R_{ult} \tag{3}$$

$$R_{ult} = P_{jack} / (0.74 \gamma_p) \tag{4}$$

γ_p is a coefficient of jacked pressure, determined from correlations with static load test. This correlation is the ratio between the maximum jacking force and the obtained ultimate capacity from static load test, as the ultimate capacity obtained by SLT is not equal to the final jacking force. In the absence of correlations, the coefficient γ_p can be estimated using Equations 5, 6, and 7, where the coefficient γ_p increases as pile length decreases.

$$\gamma_p = 1.50 \text{ for piles greater than 15 m length} \tag{5}$$

$$\gamma_p = 1.75 \text{ for piles between 8 and 15 m length} \tag{6}$$

$$\gamma_p = 2.20 \text{ for piles with less than 8 m length} \tag{7}$$

1.4 Philippine Pile Jacking Practice and Databases

Databases of load tested jacked piles in the Philippines are limited, though increasing in availability. Buensuceso (2022) recently presented a database of 36 jacked precast square piles with a width of 40 cm installed to 36 to 45 m depth in silty soils from a project in San Simon, Pampanga, Luzon region in the Philippines. Slenderness (length of penetration vs. pile width) ratios ranged from 90 to 113.5. These piles were tested with high strain dynamic pile test (HSDPT), also known as Pile Dynamic Analyzer (PDA).

An average pressure ratio (α), or ratio of estimated ultimate capacity to final jacking force, of 3.58 was observed. Pressure ratios of up to 10 were observed, much greater than general capacity predictions for jacked piles by Zhang (2004) and predictions for jacked piles embedded in silt by Zhang et al. (2010), as seen in Figure 3.

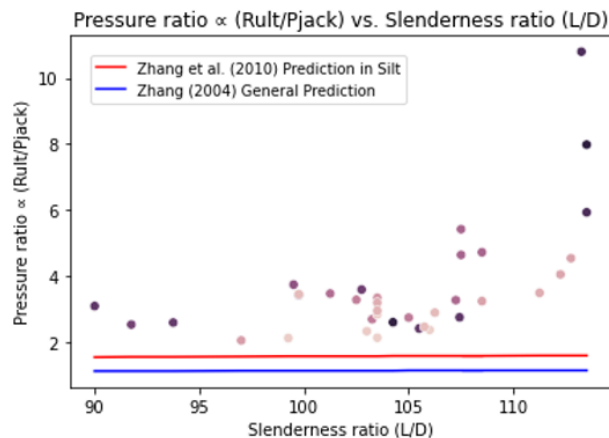


Figure 3. Predicted vs. actual pressure ratios from Buensuceso (2022). Pressure ratio predictions Zhang (2004) and Zhang et al. (2010).

The significant increase in capacity was attributed to the phenomenon of pile setup. However, the use of empirical pile setup formulas such as Skov and Denver (1988) did not significantly improve prediction accuracy, which indicated that very slender and frictional piles founded in mixed soils are not predicted particularly well by either formulas such as Equation 1 from Zhang et al. (2006) or empirical pile setup formulas.

In Philippines' practice, two termination criteria are typically used in jacked pile installation: (1) that the maximum amount of jacking force of the equipment has been used or, (2) that the entire available pile segment length has already been jacked into the ground. The maximum amount of jacking force is typically at least 2.0 times the design load or specified allowable capacity. A desired pile penetration up to a certain soil layer is also generally provided, though actual penetrations can vary greatly due to varying depths of very dense or hard materials. No specifications are typically provided regarding additional jacking cycles or settlement at the end of jacking. Jacking forces are typically calculated based on measured hydraulic pressure readings from the jacking rig. One example of a hydraulic static pile driver used in the Philippines that relies on dead weight as a reaction force can be seen in Figure 4.



Figure 4. Hydraulic static pile driving rig in the Philippines (photo from author)

Load tests are then typically done on a number or percent of piles at a project to estimate a pile's ultimate capacity R_{ult} (Likins, 2004). From the experience of the author HSDPTs are frequently used in the Philippines to verify the ultimate capacity of jacked piles, and in some cases have completely replaced static load tests. These can provide static capacity estimates, evaluate pile integrity and stresses throughout the pile, and estimate load-settlement behavior, particularly when signal matching analysis is done (Likins and Rausche, 2004). HSDPT practice is standardized in ASTM D4945 – 12, with a typical testing arrangement seen in Figure 5. HSDPTs provide a good approximation of the results from SLTs, which are considered the most reliable available predictor of long-term pile capacity and behavior (Likins et al., 1996), particularly when signal matching analysis is conducted on the PDA data.

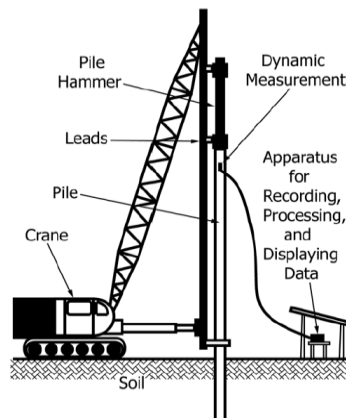


Figure 5. Arrangement for high-strain dynamic load testing from ASTM D4945 – 12

2 RESEARCH OBJECTIVES AND RESEARCH GAPS

2.1 Gap Analysis

In the experience of the author in Philippines' pile jacking practice, there is limited guidance on obtaining ultimate capacity estimates using readings taken at the end of pile jacking with jacked pile capacities only typically obtained from load test results and a geotechnical static analysis utilizing site boring logs. P_{jack} obtained during jacked pile installation can be used to estimate the expected static compressive ultimate capacity of a jacked pile, but this requires the consideration of other factors such as slenderness ratio and ground conditions (Yu and Yang, 2012), or the use of correlation coefficients to establish the relationship between P_{jack} and the ultimate capacity (AS-2159, 2009).

Significant under-predictions of compressive ultimate capacity have been previously documented in slender, frictional piles in the Philippines (Buensuceso, 2022). Over-predictions of capacity are also

possible for shorter piles, particularly if correction factors or coefficients are not used. Inaccurate capacity predictions can result in either uneconomical pile designs, where excessively long piles or numerous piles are used, or unsafe designs, where actual capacities are less than expected. Additionally, while minimum lengths of penetration required to achieve a certain capacity are typically given based on geotechnical static analysis using site boring logs, the actual penetration depth and jacking forces can greatly vary due to variations in the depth of the hard or dense soil layer, resulting in uncertain pile capacities.

2.2 Research Objectives

- a) Compile multiple databases and case studies of precast jacked piles with various slenderness ratios and different installation methods tested for their capacities by high-strain dynamic load pile tests (HSDPT) in the Philippines.
- b) Explore the relationship between final jacking force, ultimate capacity measurements from HSDPTs, and pile slenderness ratio.
- c) Establish lower-bound predictive formulas for ultimate capacity best suited for the database of HSDPT tested jacked piles in the Philippines.

2.3 Significance of the Research

The outcome of the research aims to obtain a more accurate ultimate capacity estimates estimation for jacked piles, reducing uncertainty in jacked pile capacities. Since not all piles are tested for their capacities but jacking force are recorded for every jacked pile installed. As such, potentially deficient piles with insufficient capacity can more easily and more accurately be identified during installation.

This research also aims to verify the applicability of empirical capacity prediction formulas that have been established in other countries for Philippines' subsurface conditions. This research also contributes to the growing body of research on jacked pile installation and performance in the Philippines.

3 METHODS

To achieve the objectives of the research, the overall approach selected was a quantitative approach. Pile jacking measurements including jacking forces applied and penetration lengths, as well as HSDPT results including ultimate capacity, measured settlement, and skin friction, were analyzed. Trends, relationships between measurements, and patterns were also identified.

3.1 Data Sampling

A total of 135 piles data obtained from four case studies done from June to December 2023 was used. The data was obtained from pile testing and geotechnical engineering company, BRB Solutions, Inc, in which the author has been working since 2019. The four case studies were chosen as more than 10 piles were tested for their capacity in each project. In addition, the subsurface soil conditions are also made available by relevant parties. The locations of the four case studies are shown in Figure 6. The data was anonymized to protect the privacy of parties involved in construction projects, and the propriety of confidential information. The data follows the general trend of Philippines' soil, i.e., dominated by silty sands/clays in the upper portion, underlain by siltstones/sandstones layers with varying degree of weathering.

The 135 piles data used were all square, precast piles. The penetration length of piles varies from 2.3 to 28.7 m, with slenderness ratios ranging from 5.11 to 63.8. The pile data used includes only those installed using hydraulic static pile drivers that utilize dead weights for a reaction force. Jacking forces could only be held by the static drivers for a maximum of two minutes. Piles installed with other technology, such as the press-in piler that uses reaction piles for reaction force, or static drivers capable of holding jacking forces for longer than two minutes, are omitted. All the data used in this paper is available in the Appendix.

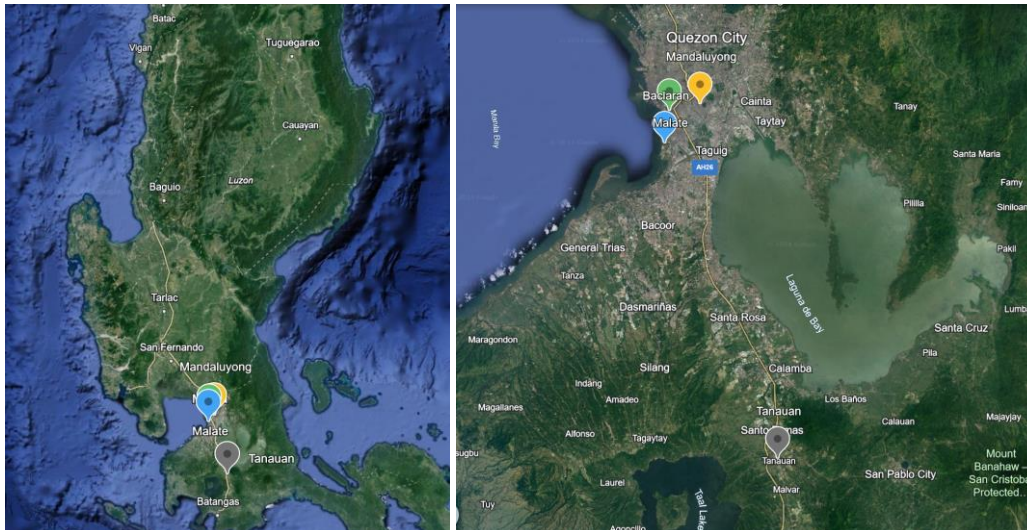


Figure 6. Location of the 4 case studies in the Philippines

3.2 Quality Assurance

Multiple measures were taken to ensure the validity and reliability of the study. HSDPT capacity estimates were done using calibrated sensors and equipment and using state-of-the-art CAPWAP signal matching software to ensure good correlations with compressive static load test results. The results of the CAPWAP analysis were the “best match analysis” with a so-called “match quality”, or quality of the signal matching analysis done, always below a recommended threshold of 5.00 (Rausche et al., 2000). The capacities obtained from HSDPT were also cross-checked against calculated pile capacities from borehole data.

It should be noted that pressure gauge readings from the static drivers were used to estimate the jacking force readings. Unlike, in compressive static load tests (SLTs), in which calibrated load cells are typically used to accurately measure loads greater than 900 kN (ASTM D-1143). Fellenius (1984) noted that hydraulic jack readings can result in over-estimates of 10 to 20% compared to readings taken with a calibrated load cell.

3.3 Analytical Approach

A relationship between P_{jack} , R_{ult} , and slenderness ratio was explored for all piles and load test results in the dataset. Actual pressure ratios, or the ratio between R_{ult} and the P_{jack} , were plotted as a function of slenderness ratio (length of penetration divided by width). R_{ult} was also plotted as a function of slenderness ratio. Actual R_{ult} and pressure ratios were then compared to predictions from Zhang et al. (2006) and AS-2159 which assumed these were functions of either slenderness ratio or pile length. For AS-2159, a predicted ultimate capacity R_{ult} was obtained using Equation 4. The coefficient γ_p were estimated based on the length of the pile (equation 5, 6 and 7), as no static load tests were conducted for correlation with the final jacking forces.

A predictive formula was considered a successful lower-bound estimate if 5% or less of the actual values fall below the predicted, a confidence level used to determine characteristic values for geotechnical design in Eurocode 7 (Orr, 2000). Limitations of the formulas for the dataset, such as the calculation of negative capacity or pressure ratio predictions for piles with very low slenderness ratio were also noted.

Alternative lower-bound formulas that better fit the collected data compared to previously proposed formulas are also presented. The “bound line” exponential function from Yu and Yang (2011) to predict pressure ratio as a function of slenderness was used as the starting point for one of the lower-bound formulas. The coefficient of the exponential function was altered by attempting multiple iterations of the coefficient in the formula until no more than 5% of the actual pressure ratios fell below the predicted ratio. A lower-bound hyperbolic formula to predict pressure ratio based on

slenderness was also proposed. The lower-bound function was selected as a hyperbolic function that passes through three points: the origin, and the two lowest pressure ratio values.

4 RESULTS

4.1 Case Study A – Sewage Treatment Plant (Mandaluyong City)

Case study A is a sewage treatment plant project in Mandaluyong City supported by jacked piles. The soil stratum begins with 6 to 9 m of residual soils or alluvial soils, followed by a hard layer of silty sands, sandy silts, or silty gravel. The sandy silts/silty sands were followed by highly weathered sandstone. Typical profiles of the soil strata and corresponding SPT N-values can be seen in Figure 7.

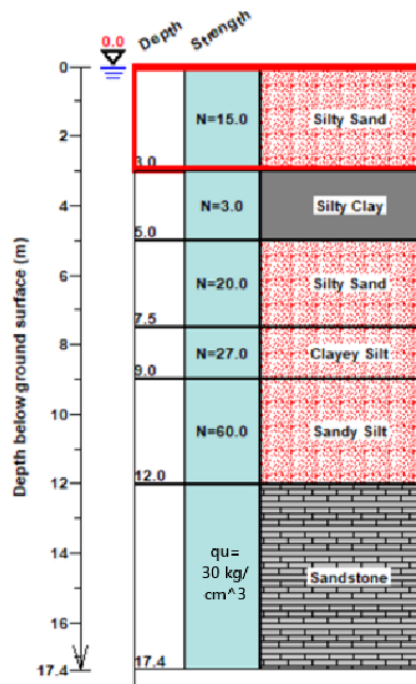


Figure 7. Typical soil profile with SPT N-value variation for Case Study A

The piles used were square piles with a width of 45 cm. The penetration lengths of 43 jacked piles investigated range from 4.9 to 12.1 m (average of 6.0 m) with slenderness ratios ranging from 10.9 to 26.9 (average of 15.5).

Final jacking forces (P_{jack}) ranged from 225.69 to 250.76 tons (2214 to 2460 kN). This project was selected to represent data where “early termination” was observed, as 15 m long pile segments were used for pile jacking, with penetrations deeper than 6 m to be expected.

All HSDPT ultimate capacities obtained were above the target capacity of 840 kN, two times the specified allowable capacity of 420 kN obtained from the calculated capacities. Pressure ratios ranging from 0.52 to 1.20 were observed (data can be seen in Appendix). These pressure ratios were all greater than 95% confidence line predictions from Zhang et al. (2006) that predicts pressure ratio from slenderness ratio (see Figure 22).

The accuracy of geotechnical ultimate capacity predictions based on the final jacking force and length from AS-2159 were also evaluated. When all 43 piles are considered, 6 of the 43 piles in the dataset had HSDPT ultimate capacities less than the predicted R_{ult} from AS-2159 (average of 1281 kN vs. a predicted capacity of 1360 kN), as seen in Figure 8. For the set of 12 piles with measured settlements greater than 2 mm, a rule of thumb for good correlations with SLT capacities, all had HSDPT capacities greater than predicted values.

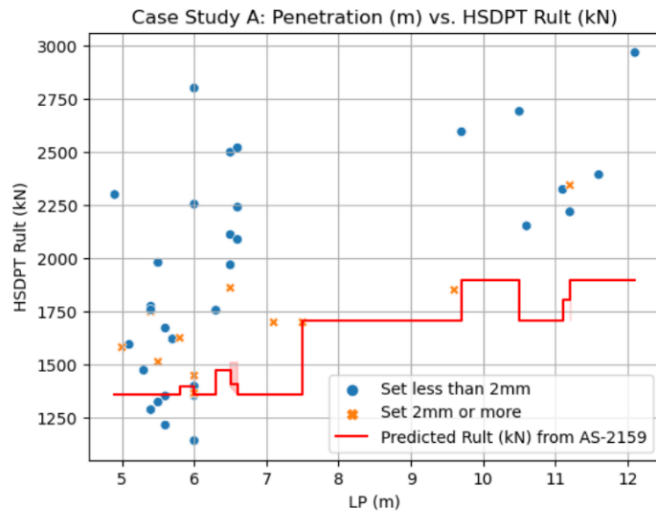


Figure 8. HSDPT capacities vs. Predicted R_{ult} from AS-2159 for Case Study A

4.2 Case Study B – Factory Building (Batangas City)

In case study B, precast jacked piles are used to support a factory building built in Batangas City. Figure 9 shows the soil profile as well as SPT N-values for the project site. The top 2 to 7 m was found to be very stiff sandy/silty clay, underlain by siltstone/sandstone.

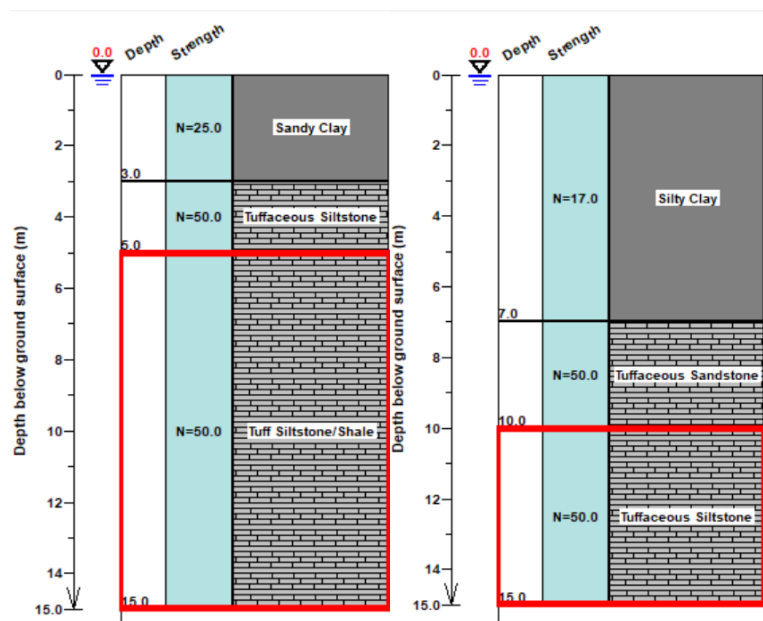


Figure 9. Typical soil profiles with SPT N-value variation for Case Study B

The 23 precast jacked piles penetration lengths vary between 2.3 to 10.3 m (average of 5.8 m) with slenderness ratios between 5.11 to 22.8 (average of 13.3). Two of the piles had a width of 30 cm, and the 21 other piles had a width of 45 cm. Pile segments ranging from 9 to 18 m were used for pile jacking. Note that pile jacking was stopped for all piles before the entire pile segment could be embedded into the ground. Final jacking forces (P_{jack}) ranging from 142.0 to 270.8 tons (average of 221.4 tons) were observed.

This case study includes jacked piles with relatively low slenderness ratios (L/D or $LP/width < 10$) not modeled well by capacity and pressure ratio prediction formulas from Zhang et al. (2006) such as Equation 1 and 2, with some predictions becoming negative.

Additionally, multiple jacking force cycles were applied and recorded by the piling contractor at the terminating depth, in contrast to other databases in the Philippines (Buensuceso, 2021, and Buensuceso, 2022) where only the force applied in the final cycle was recorded.

The reported P_{jack} in this project provided by the piling contractor was the average of either five or six jacking forces attempted at the end of installation. One benefit of applying multiple jacking cycles at the end of installation is that outlier jacking force readings can be identified. For example, if the jacked pile reaches a thin hard or dense layer, relatively high jacking forces will be measured. However, upon the application of additional jacking cycles, the hard layer may be penetrated through, and lower jacking force readings are obtained. This methodology of applying multiple trials of a final jacking force is similar to that from Lin and Wang (2004), which recommended that piles with lengths less than 14 m have at least 3 to 5 additional jacking cycles (4 to 6 total).

For this case study, eight jacked piles had consistent jacked force readings across all trials, while 15 piles had varying jacked force readings at the end of installation. Across all 23 piles, the average jacked force reading of the trials was 19% smaller than the maximum applied jacked force across all the trials. One pile of note had a maximum jacking force of 304.2 tons in the first trial, followed by 4 trial readings of 101.4 tons, resulting in an average of 142 tons, less than 50% of the initial jacking force. This trend was generally followed in the other 14 piles, with the jacking force reading in the first trial 26% higher than the average jacking force reading. Only one pile had a first trial jacking force reading that was lower than its average.

The average of the multiple jacking force trials and HSDPT ultimate capacity readings (R_{ult}) were better correlated ($R^2 = 0.3998$) compared to the jacking force readings at the first trial and the HSDPT R_{ult} ($R^2 = 0.0851$), as seen in Figure 10 and Figure 11. A wide variation in HSDPT estimates (from 1393 to 4360 kN; average of 2760 kN and standard deviation of 743 kN) could be seen for piles with a first jacking force reading of around 2960 kN. It is possible that the relatively high first jacking force reading was a case of the pile reaching a thin dense or hard layer of soil, and the collection of multiple trials and readings can be useful when relatively “early” termination is encountered or expected. Given the better correlation found, the average of the jacking force trials was used as the final jacking force P_{jack} for capacity predictions.

Pressure ratios (i.e., $R_{\text{ult}}/P_{\text{jack}}$, with P_{jack} taken as the average final jacking force), meanwhile, ranged from 0.86 to 1.82 (average of 1.21), data can be seen in the Appendix. All observed pressure ratios were above all the predicted ratios, including the 95% confidence line from Zhang et al. (2006), as seen in Figure 22.

All predicted geotechnical ultimate capacities from AS-2159 were below the measured capacities from the HSDPT, even including piles with relatively small permanent settlements during the test (i.e., less than 2 mm), as seen in Figure 12.

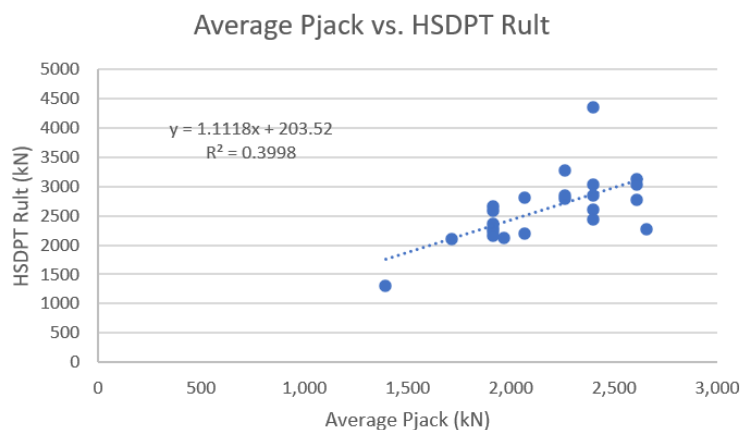


Figure 10. Average of jacking force trials vs. HSDPT ultimate capacities

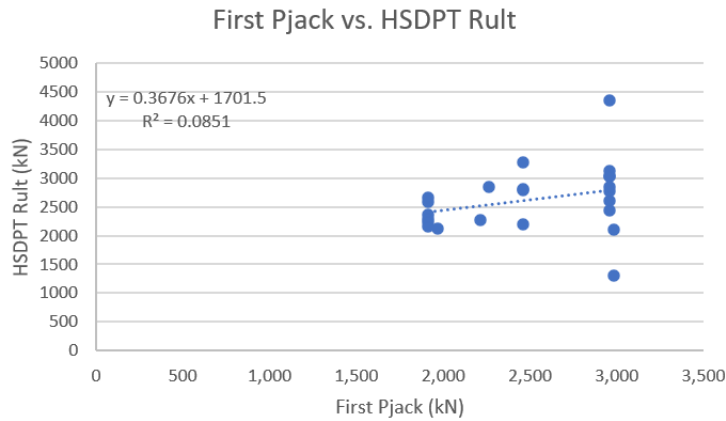


Figure 11. First trial final jacking force reading vs. HSDPT ultimate capacities

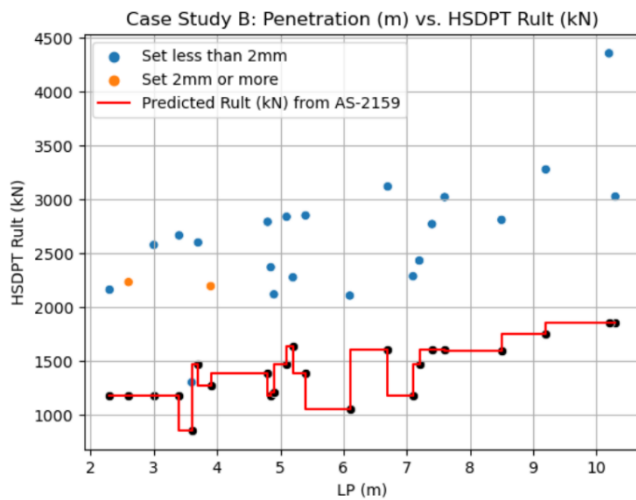


Figure 12. HSDPT capacities vs. Predicted R_{ult} from AS-2159 for Case Study B

4.3 Case Study C – High-Rise Buildings (City of Manila)

In case study C, the jacked piles are used to support multiple high-rise buildings in the City of Manila. Figure 13 shows the soil profile and SPT N-values for the site. The soil consists of medium-dense silty sand in the upper 5 m, followed by medium silty clay to 7.5 m depth. The third layer (7.5 m to 17.5 m depth) consists of dense silty sand, underlain by highly weathered Guadalupe Tuff Formation (GTF).

Forty-one (41) square precast jacked piles with width of 45 cm were tested with HSDPT. The penetration lengths vary from 16.1 to 28.7 m (average of 23.4 m), with slenderness ratios ranging from 35.8 to 63.8 (average of 51.9). Total pile lengths of 30 m, consisting of two segments spliced together with an epoxy-dowel splice, were used for pile jacking at the project.

The piles were likely to be founded on highly weathered Guadalupe Tuff Formation (GTF). 39 of 41 of the piles were installed with a P_{jack} of 326 tons (3198 kN), the maximum capacity of the jacking machine. The other two piles were installed with a P_{jack} of 132.5 and 150.5 tons (1300 and 1476 kN). This is less than the recommended final jacking force of at least 2.0 times the working load (1400 kN) from references such as Lin and Wang (2004).

This case study covers piles with relatively longer and more slender piles compared to the previous two case studies (average LP/width of 51.9 vs. 15.5 and 13.3). Of particular interest were two jacked piles with relatively low P_{jack} readings compared to other piles and a specified allowable capacity, and the increase in capacity observed between the end of installation and the conducted HSDPT.

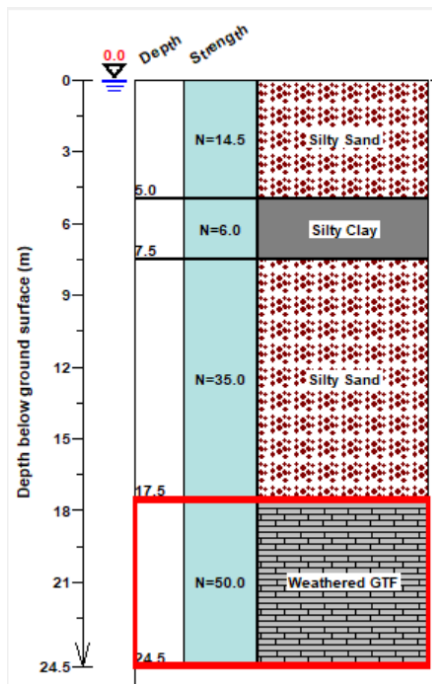


Figure 13. Typical soil profile with SPT N-value variation for Case Study C

The capacity obtained by HSDPT for all the piles meets the required ultimate capacity of 2800 kN (factor of safety = 2.0), including the two piles with low jacking forces. This indicated that a significant amount of pile setup (i.e., capacity increase) occurred, particularly for the two piles with penetration of 25.7 and 26.0 m, and relatively low P_{jack} . All actual pressure ratios remained above the lower-bound prediction from Zhang et al. (2006) as seen in Figure 14, while all HSDPT estimated ultimate capacities also remained above those predicted by AS-2159 as seen in Figure 15. This is despite all piles having HSDPT sets of roughly 0 mm, providing likely underestimates of the SLT ultimate capacity.

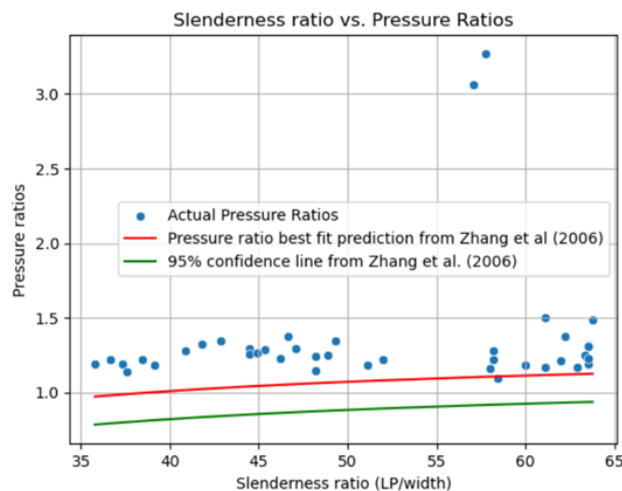


Figure 14. Slenderness vs. pressure ratios including predicted and lower-bound pressure ratios from Zhang et al. (2006) for Case Study C

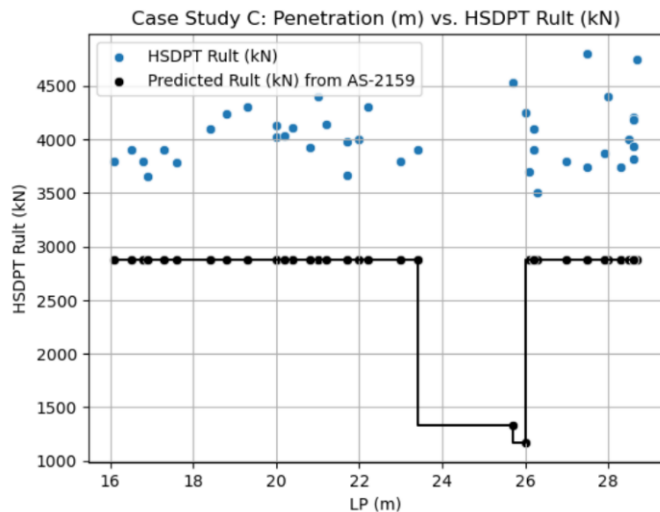


Figure 15. HSDPT capacities vs. Predicted R_{ult} from AS-2159 for Case Study C

4.4 Case Study D – High-Rise Buildings (City of Manila)

In Case Study D, jacked piles were used to support high-rise buildings located in Coastal Metro Manila. Boreholes taken at the project indicated the upper 12 m to be medium dense to dense silty sands, with a layer of weathered sandstone and siltstone beneath. Comparisons could be made in this case study between the capacities and HSDPT results among the side piles, center piles, and driven piles. A typical profile of the soil strata and corresponding SPT N-values can be seen in Figure 16.

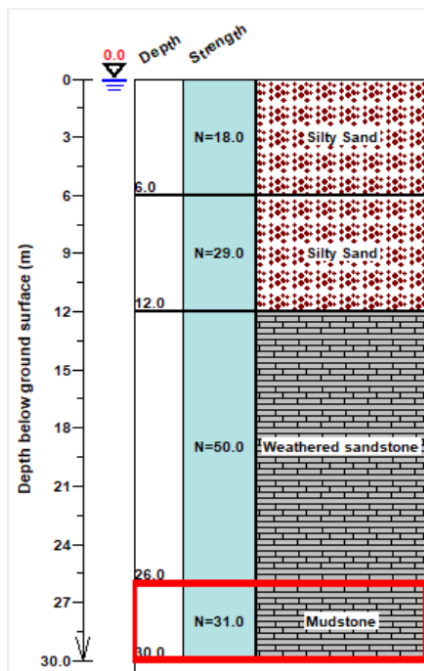


Figure 16. Typical soil profile with SPT N-value variation for Case Study D

35 square precast piles were included in the database with a width of 45 cm, with 28 jacked piles and 7 driven piles installed with a pile-driving hammer. Of the 28 jacked piles, 9 piles were installed using the side piling mechanism of the static driver, with a P_{jack} of 250.8 tons. The pile segment length used for side piles was 9 m. Side piles had an average penetration of 8.6 m. The other 19 piles were installed using the center piling mechanism with a P_{jack} of 376 to 378 tons. Pile segment lengths used for center piles varied from 7 to 18 m). Center piles had an average penetration of 8.2 m. Overall, jacked pile penetration after installation ranged from 7.0 to 10.0 m (average of 8.4 m).

The 7 precast driven piles that were also installed at the project have pile segment lengths of either 9 or 18 m. The piles were driven to penetration lengths ranging from 8 to 9.7 m (average of 8.7 m), with end-of-drive (EOD) blow counts of 10 blows per 300 mm for one pile, while the other 6 piles have EOD blow counts ranging from 12 blows per 8 mm to 12 blows per 21 mm. Overall, slenderness ratios from 13.3 to 21.1 (average of 18.0) were observed for the 35 piles.

HSDPTs were done on the 35 precast piles as proof tests up to at least 2.0 times an allowable capacity of 1200 kN (i.e., to a target of 2400 kN). Side jacked piles had the smallest average mobilized ultimate capacities (R_{ult}), with values ranging from 2026 to 2783 kN (average of 2350 kN). Center jacked piles had R_{ult} values ranging from 2499 to 3400 kN (average of 2898 kN), while driven piles had R_{ult} values from 2806 to 3988 kN (average of 3322 kN).

All 28 jacked pile capacities measured by the HSDPT remained above the predicted capacities by Zhang et al. (2006) as seen in Figure 17. However, 4 of the jacked piles (all center piles with lengths from 8.0 to 8.3 m) were found to have HSDPT capacities below the predicted capacity from AS-2159, as seen in Figures 18 and 19.

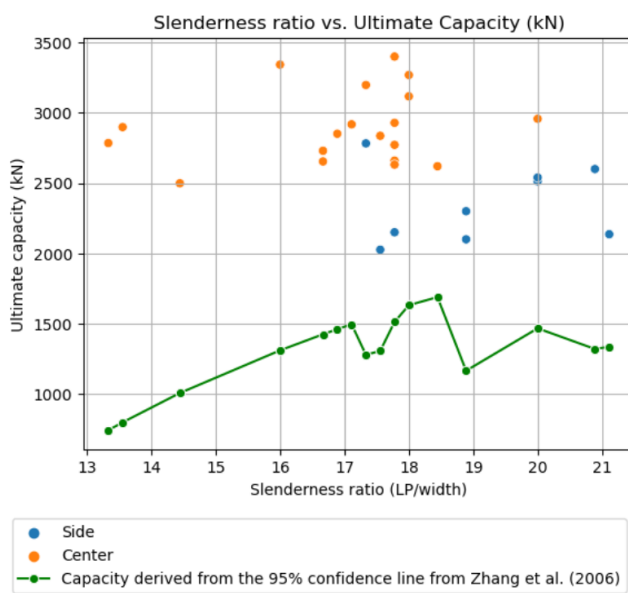


Figure 17. HSDPT capacities vs. predicted capacity from Zhang et al. (2006) for Case Study D

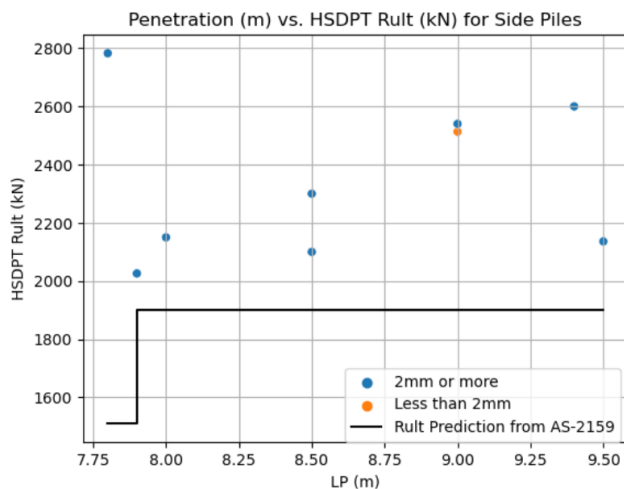


Figure 18. HSDPT capacities vs. predicted R_{ult} from AS-2159 for Case Study D for side piles

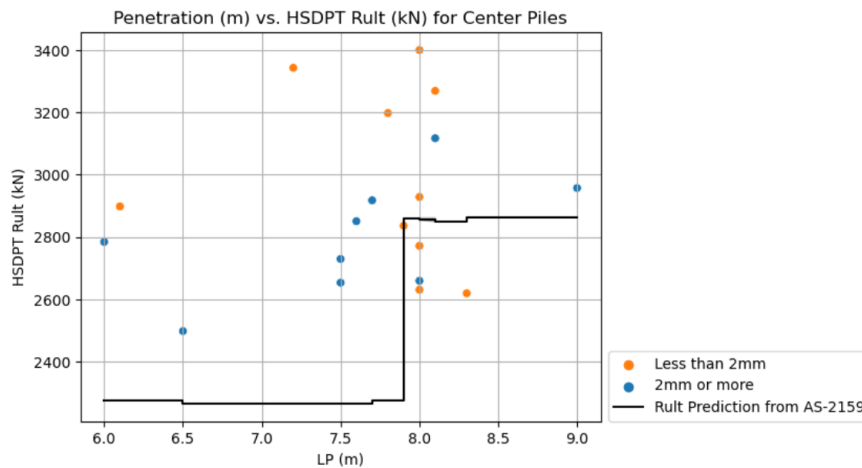


Figure 19. HSDPT capacities vs. predicted R_{ult} from AS-2159 for Case Study D for center piles

4.5 Summary

In summary, 125 of the 135 (93%) jacked piles in the case studies had actual capacities above a predicted geotechnical ultimate capacity from AS-2159, as seen in Figure 20. Moreover, 9 of the 10 piles with capacities below predicted from AS-2159 had HSDPT sets below 2 mm and thus the HSDPT capacity obtained would be lower than that obtained from SLT ultimate capacity. Higher capacities are likely to be expected if sets above 2 mm were mobilized for piles evaluated, though the increase in capacity is not known. Considering only the data of 126 piles with HSDPT sets above 2 mm, 125 of the 126 jacked piles (99%) now have actual capacities above a predicted R_{ult} . This suggests that the R_{ult} prediction can safely be used, with only 1% chance of failure or overestimation.

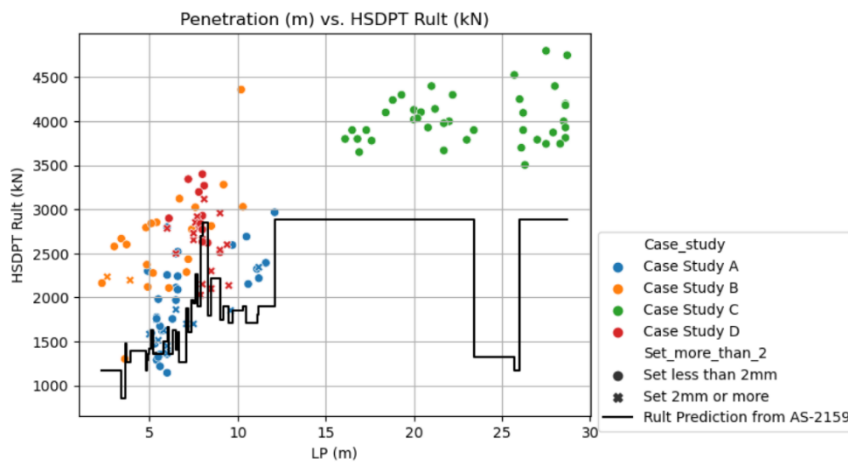


Figure 20. HSDPT Capacities vs. R_{ult} prediction from AS-2159

The accuracy of the predictions can also be visualized by comparing the theoretical and actual coefficient of jacked pressures (γ_p) or the ratio of the final jacking force to 0.74 times the ultimate geotechnical capacity, with 125 of the 135 of the jacked piles with theoretical γ_p above the actual γ_p , as seen in Figure 21. Note that there were three possible values of $\gamma_{p,theo}$ for piles in this dataset: 2.20 for piles with penetration lengths (LP) less than 8 m, 1.75 for piles with LP between 8 and 15 m, and 1.5 for piles with LP greater than 15 m. $\gamma_{p,actual}$ can be obtained from Equation 8, with the ultimate capacity estimate R_{ult} obtained from HSDPTs rather from a static load test.

$$\gamma_{p,actual} = \frac{P_{jack}}{0.74R_{ult}} \tag{8}$$

Four of the piles with theoretical γ_p below the actual γ_p are from Case Study D, with penetration lengths (LP) between 8.0 and 8.3 m, near the boundary of 8 m of AS-2159. The HSDPT capacities of these four piles were found to be 3 to 9% smaller than the AS-2159 prediction (average of 7%), though this may have been a function of insufficient settlements during the HSDPT, with 3 of the 4 piles having sets below 2 mm. Six of the piles, meanwhile, are from Case Study A, with penetration lengths between 5.0 and 6.0 m. Similarly, all 6 of these piles had settlements less than 2 mm during the HSDPT. Actual γ_p was consistently smaller than theoretical γ_p in Case Study C and Case Study B.

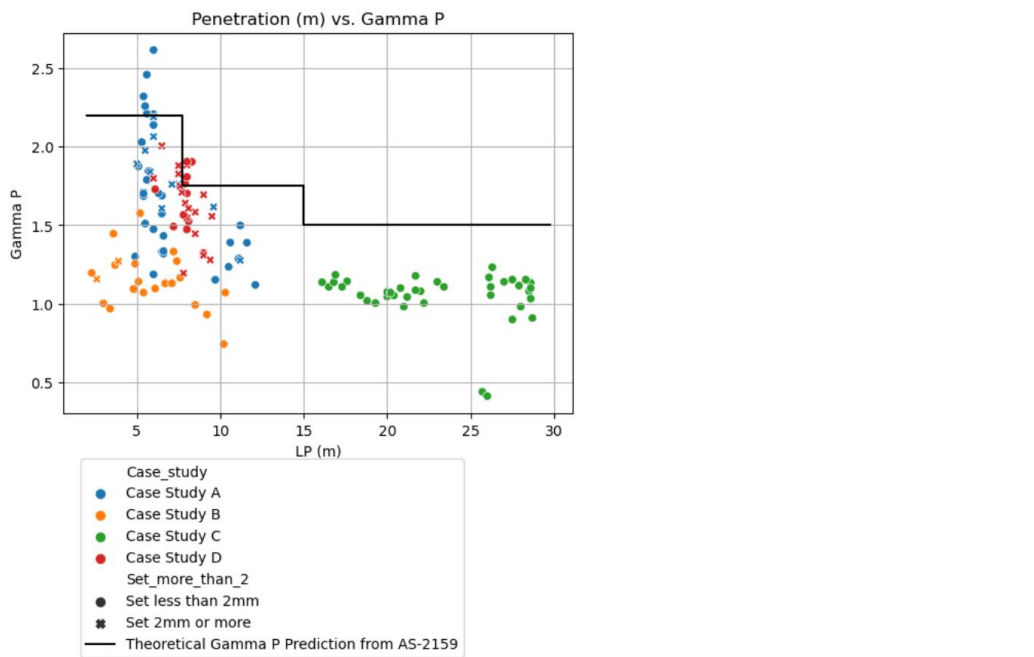


Figure 21. Penetration vs. Coefficient of Jacked Pressures γ_p from AS-2159

All 135 jacked piles also had actual pressure ratios above the 95% confidence line from Zhang et al. (2006) as seen in Figure 22, even when including piles with relatively small HSDPT sets. These findings complement the objective of Zhang et al. (2006) for the 95% confidence line to serve as a geotechnical characteristic value.

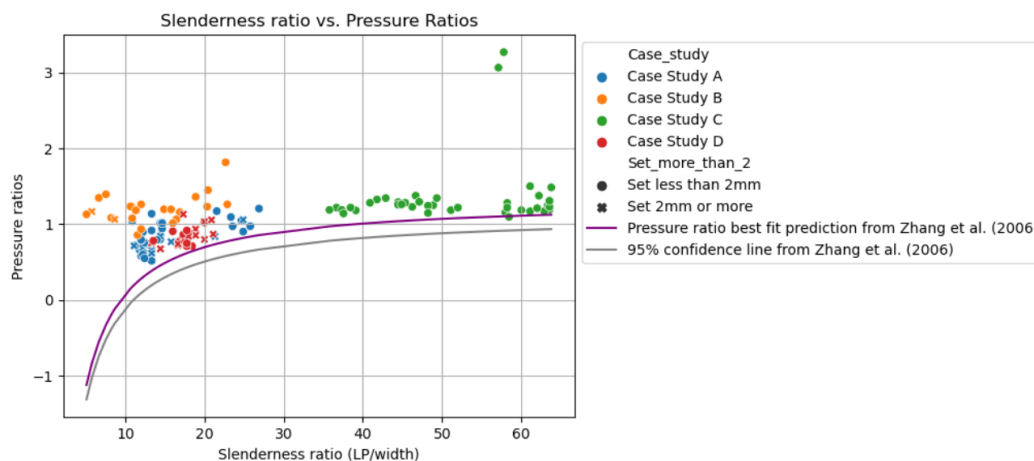


Figure 22. Slenderness ratio vs. pressure ratio for all 135 jacked piles

5 DISCUSSION

Figure 23 shows a graph of pressure ratio (α) against the slenderness ratio from the pile data presented in this paper. The graph also shows the relationship proposed by existing literature. The data by the author is different than existing literature, in which pressure ratio is greater than 1.0 for $L/D > 30$, in contrast to the threshold of about $L/D > 50$ observed by Zhang et al. (2006). Pressure ratios increase to more than 1.0 for more slender piles because of the greater proportion of skin resistance for longer piles. This is because long-term skin friction is likely to be significantly greater than the friction at the end of jacking. Cases of pressure ratios below 1.0 were observed only for slenderness ratio < 30 . Zhang et al. (2006) suspected that the toe resistance mobilized for less slender piles during a load test was less than the resistance mobilized during pile jacking, resulting in pressure ratio < 1 . Less slender piles with pressure ratios close to higher than 1.0 were observed in the current database (mostly in Case Study B). This may be attributed to difference in toe resistances during the high-strain dynamic load test and during installation, accompanied by some shaft resistance increase.

An alternative lower-bound prediction with a 5% probability that the actual pressure ratios (α) are below predicted ratios is presented in Equation 9, with 130 of the 135 (96.3%) actual pressure ratios below the lower-bound function. This alternative prediction is an exponential function similar to the bound line proposed by Yu and Yang (2011), which has the benefit of being able to give more reasonable pressure ratio predictions for low slenderness piles ($L/D < 10$). The prediction can be graphically seen in Figure 24.

$$\alpha = 0.298 (L/D)^{0.28} \quad (9)$$

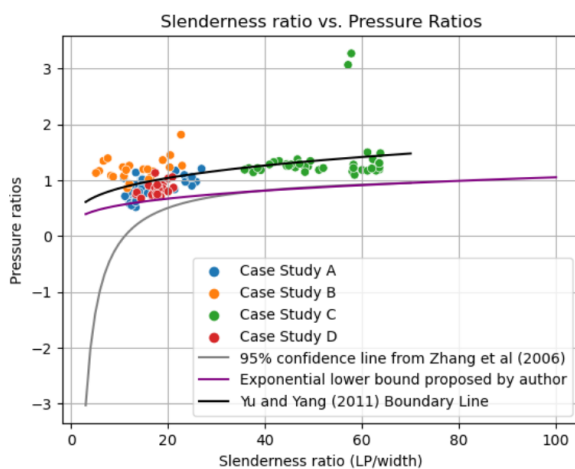


Figure 23. Pressure ratio vs. slenderness ratio including a proposed lower-bound exponential function

Alternatively, best-fit (g_1), lower-bound (g_2), and upper-bound (g_3) hyperbolic functions are presented in Figure 24. The equations for g_1 , g_2 and g_3 are given in equation 10-12. Like with the previously proposed exponential function in Equation 9 no negative pressure values are predicted for any of these functions, unlike the hyperbolic functions presented by Zhang et al. (2006) and Zhang et. al. (2010) for less slender ($L/D < 10$) piles. The lower-bound line was designed to have 100% of actual pressure ratios above the line. Meanwhile, the best-fit line was designed to have 50% of pressure ratios above and 50% below, and the upper-bound to have almost all pressure ratios below, excluding three points considered outliers. The root mean square error (RMSE) of the best-fit prediction line g_1 is 0.323.

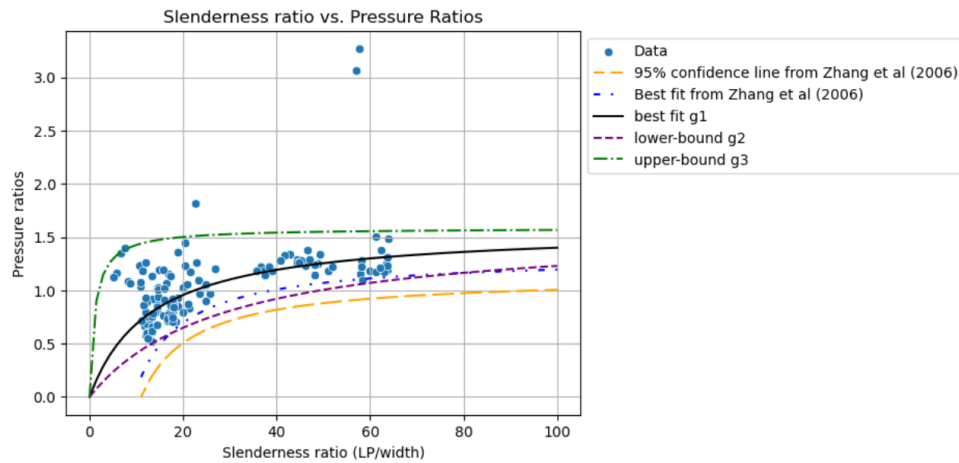


Figure 24. Slenderness ratio vs. pressure ratio including new best-fit, lower-bound, and upper-bound functions

$$g_1 = \alpha = \frac{x}{8.288 + 0.631x} \quad (10)$$

$$g_2 = \alpha = \frac{x}{18.188 + 0.631x} \quad (11)$$

$$g_3 = \alpha = \frac{x}{0.7 + 0.631x} \quad (12)$$

6 CONCLUSIONS

This research compiled a database of 135 precast jacked piles with varying lengths and slenderness ratios tested with high-strain dynamic load pile tests (HSDPT). The pressure ratio was found to be a function of the slenderness ratio, with pressure ratios generally increasing above 1.0 for slenderness ratios above 30. Actual pressure ratios and ultimate capacities measured were compared to predictions from AS-2159 and Zhang et al. (2006), with all pressure ratios above the 95% confidence line from Zhang et al. (2006) and 93% of piles with capacities above the predicted geotechnical ultimate capacity by AS-2159. Two alternative lower-bound pressure ratio formulas that are a function of slenderness ratios are also proposed, particularly to deal with low-slenderness piles in the database ($L/D < 10$). Nevertheless, the uncertainty regarding discrepancies between the force applied by the hydraulic jack and the actual force being applied to the pile should be noted. There is also a slight increased uncertainty associated with using HSDPT results without site-specific correlations with SLTs. As such, it is not recommended to obtain ultimate pile capacity solely from final jacking force (P_{jack}) and slenderness ratio. A number of load verification tests (either SLT, HSDPT, or a combination of HSDPT and SLTs) and geotechnical static analysis should also be conducted to complement the pile capacity estimated from P_{jack} and slenderness ratio.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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APPENDIX

PDA No.	Case study	Width (mm)	Days to restrrike	P _{JACK} (kN)	LP (m)	HSDPT measured set per blow (mm)	R _{ULT} (kN)	Slenderness ratio	Pressure ratio
1	A	450	19	2,460	6.5	0.50	2112	14.44	0.86
2	A	450	18	2,460	6.5	1.10	2499	14.44	1.02
3	A	450	18	2,460	6.5	1.00	1970	14.44	0.80
4	A	450	16	2,460	6.6	0.50	2520	14.67	1.02
5	A	450	15	2,460	6.0	1.00	2800	13.33	1.14
6	A	450	9	2,214	4.9	0.80	2300	10.89	1.04
7	A	450	10	2,460	6.0	0.80	2255	13.33	0.92
8	A	450	10	2,460	10.5	0.10	2691	23.33	1.09
9	A	450	9	2,214	9.7	0.60	2595	21.56	1.17
10	A	450	14	2,214	6.0	1.10	1356	13.33	0.61
11	A	450	11	2,214	5.3	1.00	1475	11.78	0.67
12	A	450	14	2,214	5.4	1.90	1290	12.00	0.58
13	A	450	20	2,214	5.1	1.80	1596	11.33	0.72
14	A	450	20	2,214	5.7	1.10	1622	12.67	0.73
15	A	450	6	2,214	5.4	1.80	1776	12.00	0.80
16	A	450	6	2,214	5.5	3.60	1515	12.22	0.68
17	A	450	20	2,214	5.6	1.70	1354	12.44	0.61
18	A	450	13	2,214	6.6	0.80	2089	14.67	0.94
19	A	450	13	2,214	6.0	2.10	1367	13.33	0.62
20	A	450	12	2,214	6.5	2.00	1862	14.44	0.84
21	A	450	12	2,214	6.6	1.90	2241	14.67	1.01
22	A	450	12	2,214	6.3	1.10	1757	14.00	0.79
23	A	450	10	2,214	5.5	0.80	1326	12.22	0.60
24	A	450	13	2,214	6.0	1.20	1145	13.33	0.52
25	A	450	14	2,214	5.6	1.50	1218	12.44	0.55
26	A	450	12	2,460	11.6	0.90	2393	25.78	0.97
27	A	450	12	2,460	11.2	0.40	2219	24.89	0.90
28	A	450	11	2,214	10.6	1.30	2153	23.56	0.97
29	A	450	7	2,214	9.6	2.40	1852	21.33	0.84
30	A	450	5	2,214	5.8	2.80	1627	12.89	0.73
31	A	450	100	2,214	5.5	1.00	1981	12.22	0.89
32	A	450	103	2,214	6.0	1.60	1400	13.33	0.63
33	A	450	104	2,214	5.6	1.00	1673	12.44	0.76
34	A	450	6	2,214	11.1	1.00	2324	24.67	1.05
35	A	450	11	2,460	12.1	0.00	2967	26.89	1.21
36	A	450	6	2,214	11.2	3.00	2344	24.89	1.06
37	A	450	6	2,214	7.5	6.00	1700	16.67	0.77
38	A	450	6	2,214	7.1	8.00	1700	15.78	0.77
39	A	450	6	2,214	6.0	10.00	1450	13.33	0.65
40	A	450	8	2,214	6.0	6.00	1367	13.33	0.62
41	A	450	8	2,214	5.4	7.00	1750	12.00	0.79
42	A	450	8	2,214	5.4	1.00	1759	12.00	0.79
43	A	450	8	2,214	5.0	6.00	1583	11.11	0.71
44	B	450	6	2,610	6.7	0.00	3122	14.89	1.20
45	B	450	5	2,610	7.6	1.00	3024	16.89	1.16
46	B	450	5	2,610	7.4	1.00	2773	16.44	1.06
47	B	450	15	1,914	4.85	0.25	2372	10.78	1.24
48	B	450	14	1,968	4.9	0.00	2120	10.89	1.08
49	B	450	22	2,657	5.2	0.50	2278	11.56	0.86
50	B	450	26	1,914	7.1	1.00	2288	15.78	1.20
51	B	450	14	1,914	3.0	0.40	2579	6.67	1.35
52	B	450	20	2,401	10.3	0.00	3029	22.89	1.26
53	B	450	27	2,263	4.8	0.50	2794	10.67	1.23
54	B	450	48	1,914	3.4	0.70	2668	7.56	1.39
55	B	450	48	1,914	2.6	2.80	2234	5.78	1.17
56	B	450	44	1,914	2.3	0.00	2163	5.11	1.13
57	B	450	18	2,262	5.4	0.90	2853	12.00	1.26
58	B	300	129	1,711	6.1	0.60	2108	20.33	1.23
59	B	450	120	2,401	5.1	0.00	2841	11.33	1.18
60	B	450	122	2,401	3.7	1.00	2602	8.22	1.08
61	B	450	120	2,401	10.2	0.00	4360	22.67	1.82
62	B	450	5	2,401	7.2	0.10	2434	16.00	1.01
63	B	450	122	2,263	9.2	0.00	3281	20.44	1.45
64	B	300	130	1,393	3.6	0.60	1302	12.00	0.93
65	B	450	14	2,066	3.9	2.70	2196	8.67	1.06
66	B	450	4	2,066	8.5	0.80	2812	18.89	1.36
67	C	450	8	3,198	27.5	0.00	4800	61.11	1.50
68	C	450	8	3,198	28.0	0.00	4400	62.22	1.38

PDA No.	Case study	Width (mm)	Days to restrike	P _{JACK} (kN)	LP (m)	HSDPT measured set per blow (mm)	R _{ULT} (kN)	Slenderness ratio	Pressure ratio
69	C	450	8	3,198	22.0	0.00	4000	48.89	1.25
70	C	450	8	3,198	21.0	0.00	4400	46.67	1.38
71	C	450	8	3,198	27.0	0.00	3791	60.00	1.19
72	C	450	8	3,198	19.3	0.00	4300	42.89	1.34
73	C	450	8	3,198	18.8	0.00	4241	41.78	1.33
74	C	450	8	3,198	20.0	0.00	4130	44.44	1.29
75	C	450	7	3,198	28.6	0.00	3813	63.56	1.19
76	C	450	8	3,198	26.1	0.00	3700	58.00	1.16
77	C	450	8	3,198	16.5	0.00	3900	36.67	1.22
78	C	450	8	3,198	17.6	0.00	3780	39.11	1.18
79	C	450	7	3,198	20.8	0.00	3929	46.22	1.23
80	C	450	7	3,198	20.4	0.00	4104	45.33	1.28
81	C	450	8	3,198	20.0	0.00	4020	44.44	1.26
82	C	450	7	3,198	27.5	0.00	3744	61.11	1.17
83	C	450	7	3,198	28.7	0.00	4750	63.78	1.49
84	C	450	8	3,198	28.3	0.00	3745	62.89	1.17
85	C	450	8	3,198	28.6	0.00	4200	63.56	1.31
86	C	450	8	3,198	23.0	0.00	3790	51.11	1.19
87	C	450	7	3,198	16.8	0.00	3800	37.33	1.19
88	C	450	8	3,198	22.2	0.00	4300	49.33	1.34
89	C	450	9	3,198	26.2	0.00	4096	58.22	1.28
90	C	450	9	3,198	21.7	0.00	3978	48.22	1.24
91	C	450	7	3,198	16.1	0.00	3800	35.78	1.19
92	C	450	9	3,198	28.5	0.00	4000	63.33	1.25
93	C	450	10	3,198	28.6	0.00	4181	63.56	1.31
94	C	450	10	3,198	28.6	0.00	3930	63.56	1.23
95	C	450	10	3,198	28.6	0.00	4182	63.56	1.31
96	C	450	11	3,198	23.4	0.00	3900	52.00	1.22
97	C	450	24	1,476	25.7	0.00	4527	57.11	3.07
98	C	450	8	1,300	26.0	0.00	4251	57.78	3.27
99	C	450	11	3,198	26.3	0.00	3505	58.44	1.10
100	C	450	10	3,198	26.2	0.00	3900	58.22	1.22
101	C	450	10	3,198	21.2	0.00	4141	47.11	1.29
102	C	450	10	3,198	27.9	0.00	3873	62.00	1.21
103	C	450	9	3,198	16.9	0.00	3650	37.56	1.14
104	C	450	8	3,198	20.2	0.00	4034	44.89	1.26
105	C	450	7	3,198	18.4	0.00	4100	40.89	1.28
106	C	450	8	3,198	17.3	0.00	3900	38.44	1.22
107	C	450	12	3,198	21.7	0.00	3669	48.22	1.15
108	D	450	7	2,460	8.5	6.70	2300	18.89	0.93
109	D	450	8	2,460	9.0	0.10	2513	20.00	1.02
110	D	450	7	2,460	9.0	3.00	2540	20.00	1.03
111	D	450	8	2,460	9.5	7.50	2136	21.11	0.87
112	D	450	7	2,460	8.5	6.00	2100	18.89	0.85
113	D	450	7	2,460	7.9	5.20	2026	17.56	0.82
114	D	450	7	2,460	9.4	2.80	2600	20.89	1.06
115	D	450	10	3,690	8.3	1.60	2620	18.44	0.71
116	D	450	10	3,690	8.0	0.70	2929	17.78	0.79
117	D	450	9	3,690	7.7	2.20	2918	17.11	0.79
118	D	450	7	2,460	7.8	3.20	2783	17.33	1.13
119	D	450	10	3,690	7.6	2.40	2851	16.89	0.77
120	D	450	11	3,690	7.5	3.00	2654	16.67	0.72
121	D	450	11	3,690	7.2	1.00	3343	16.00	0.91
122	D	450	10	3,690	8.1	0.70	3269	18.00	0.89
123	D	450	11	2,460	8.0	2.60	2150	17.78	0.87
124	D	450	11	3,690	7.5	2.70	2730	16.67	0.74
125	D	450	22	3,706	7.8	0.82	3198	17.33	0.86
126	D	450	23	3,706	7.9	0.00	2836	17.56	0.77
127	D	450	22	3,706	8.0	3.00	2660	17.78	0.72
128	D	450	21	3,706	8.1	3.38	3117	18.00	0.84
129	D	450	22	3,706	8.0	0.00	3400	17.78	0.92
130	D	450	16	3,706	9.0	3.33	2958	20.00	0.80
131	D	450	22	3,706	8.0	1.00	2631	17.78	0.71
132	D	450	22	3,706	8.0	1.80	2772	17.78	0.75
133	D	450	328	3,706	6.0	2.70	2785	13.33	0.75
134	D	450	197	3,706	6.1	0.00	2898	13.56	0.78
135	D	450	193	3,706	6.5	4.60	2499	14.44	0.67