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Predicting the Ultimate Capacity of Frictional Jacked Concrete Piles Installed in Mixed Silty Sands in the Philippines

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Abstract *– Jacked piles have increasingly been used to support structural loads, though methods for ultimate axial capacity prediction and installation termination criteria remain relatively undeveloped compared to driven and bored piles. These methods were also primarily trained on databases from China and Hong Kong which have different soil conditions and pile jacking technology and methodology. This paper studies the utility of final jacking force (Pjack) readings as an estimate of the actual ultimate capacity of jacked frictional precast piles installed in 36 to 45 m of silty soils in the San Simon, Pampanga, Luzon region in the Philippines. The accuracy of existing capacity prediction methods are assessed vs. the well-established method of using capacity estimates from high-strain dynamic load tests (PDA tests). The ratios of PDA estimated capacities to final jacking forces during installation were an average of 3.58, much higher than empirically predicted ratios ranging from 1.12 to 1.59. This increase was attributed to the phenomenon of pile setup, though empirical pile setup formulas also significantly under-predicted the increase. This indicates existing pile jacking installation criteria and pile setup models may not be applicable for this pile and soil configuration.*

Keywords: jacked piles; load test; PDA tests; pile foundations; pile setup;

I. INTRODUCTION

1.1 Background of the Study and Related Literature

1.1.1 Jacked Pile Installation

The installation of precast displacement piles with pile jacking is a relatively new technique that grew in popularity because it can avoid undesirable noise and vibration generated by traditionally driven piles, and spoil or excess soil generated during the installation of cast-in-place bored piles.

The jacked pile installation method allows for the measurement of a static capacity during the installation, which in some cases can be a reliable estimate of the pile's ultimate capacity as measured by a static load test (SLT) [1]. The reliability depends on multiple factors such as the pile's length of penetration, the bearing layer, and the number of jacking load cycles applied at the end of installation.

Two common jacking methods are the press-in method, which uses previously installed piles to produce a reaction force for the jacking machine [2], and the hydraulic static pile driving (HSPD) method, which utilizes counterweights to produce the reaction force [3]. Press-in piling is more commonly seen and used in Japan and the United Kingdom, while HSPD piles are more widespread in Mainland China, Hong Kong, and the Philippines, where they have colloquially been termed “pushed piles”.

Pile jacking was originally used to install sheet piles for excavation support [4], though jacked piles have increasingly been used as a substitute to driven piles to support structural loads. However, guidelines for the use of jacked piles are more scarcely given, which might be because of their relatively limited history of use [5].

1.1.2 Jacked Pile Termination Criteria and Ultimate Capacity Estimates

Researchers in Hong Kong and China have recently proposed and used empirical termination criteria involving jacked piles that aim to indicate that the piles’ capacity and serviceability requirements will be met. Typical termination criteria specify: (1) a final jacking force (Pjack), or the jacking force being applied immediately before the end of the installation, which should be held a certain amount of time, (2) a number of required re-jacking cycles, or the number of times the final jacking force is applied before the end of installation, and (3) the duration of the jacking cycles.

The Chinese pile design code gives general guidelines that a minimal final jacking force (Pjack) be determined by establishing the minimum Pjack needed to obtain a required ultimate capacity. This can be obtained by installing trial piles, measuring the final jacking force, and subjecting the piles to load tests. The Chinese pile design code also requires that 2 to 5 re-jacking cycles be done, with fewer cycles for shorter piles, and that the Pjack be applied multiple times and maintained for 5-10 seconds per cycle. [6]

Pjack is particularly useful when proven to reliably predict a pile’s static ultimate capacity (Pult or Rult) obtained from static load tests (SLT) because of the similarities in the physical base of jacking penetration and the SLT. This is because the actual capacity of all piles installed at a project can be reliably estimated at the time of installation, rather than only a percentage or number of piles subjected to load tests a number of days after installation.

A required Pjack relative to a certain design load (Pd) is often specified for certain projects. Ratios of at least 2.5 was recommended by Zhang et al. [4], while ratios of least 2.0 was suggested by Lin and Wang [7].

In Philippine practice, only two termination criteria are typically used in jacked pile installation practice: (1) how deeply embedded the pile should be into a hard layer, and (2) that the maximum amount of jacking force has been used. The maximum amount of jacking force is typically at least 2.0 times the design load or specified allowable capacity, or the maximum amount of counterweight available at the project. No specifications are typically provided regarding additional jacking cycles or measuring settlements at the end of jacking.

Load tests are typically done to estimate a pile’s ultimate capacity (Pult or Rult), particularly to assess time-dependent changes. Static load tests or high-strain dynamic pile load tests are two of the most commonly-used load tests for this purpose.

High-strain dynamic pile load tests are the dominant type of load test used in the Philippines for jacked piles, and in some cases have completely replaced static load tests. The Pile Driving Analyzer (PDA) test of Pile Dynamics is the standard HSDPT used in the Philippines. These are able to provide static capacity estimates, evaluate pile integrity and stresses throughout the pile, and estimate load-settlement behavior.

PDA tests provide a good approximation of the results from SLTs, which are considered the most reliable predictor of long-term pile capacity and behavior [8]. PDA tests, however, are typically more affordable to conduct and less time-consuming than SLTs and can be done on a greater number of piles at a project [9]. This allows possibly problematic piles or highly variable ground conditions to be evaluated. To obtain the best results from PDA tests, signal matching analysis (SMA) must be performed on pile top force and velocity measurements taken of an axial impact force from a drop hammer applied on the pile.

Certain limitations of PDA tests have been found, such as an incomplete assessment of time-dependent soil changes, and the incomplete mobilization of ultimate capacity relative to what can be obtained in a SLT.

To evaluate time-dependent capacity changes, PDA tests should be done a certain amount of time after the pile has been installed, as the results of a PDA tests highly depend on the time that the test was conducted. This would allow pile setup to be quantified, or to evaluate the rarer phenomenon of soil relaxation, which results in a loss of capacity over time.

A minimum net pile top settlement of at least 2 mm per blow during the dynamic test is recommended to ensure a reasonable estimate of the pile’s ultimate capacity from a SLT. Lower net settlements may result in lower-bound estimates of the pile’s capacity [10]. However, higher settlements are not always possible due to reasons such as cracks and damage occurring at the pile head because of the impact blow and hammer limitations.

1.1.3 Jacked Pile Databases

Various researchers in China and Hong Kong have presented databases of the relationship between Pult and Pjack. This ratio of Pult to Pjack is also known as the pressure ratio or $\propto$.

Zhang et al. [4] compiled a database of 149 jacked piles in China and Hong Kong with axial ultimate capacities estimated by SLTs. Two equations were presented: (1) a best-fit regression equation to predict pressure ratios using slenderness ratio, and (2) an equation to predict pressure ratios using slenderness ratios (L/D, or length of a pile over diameter or width) with a 95% confidence level that the predicted pressure ratio is above the line.

$$\propto = P_{ult}/P_{jack} = 1.32 - 12.48/(L/D) \tag{1}$$

$$\propto = P_{ult}/P_{jack} = 1.13 - 12.48/(L/D) \tag{2}$$

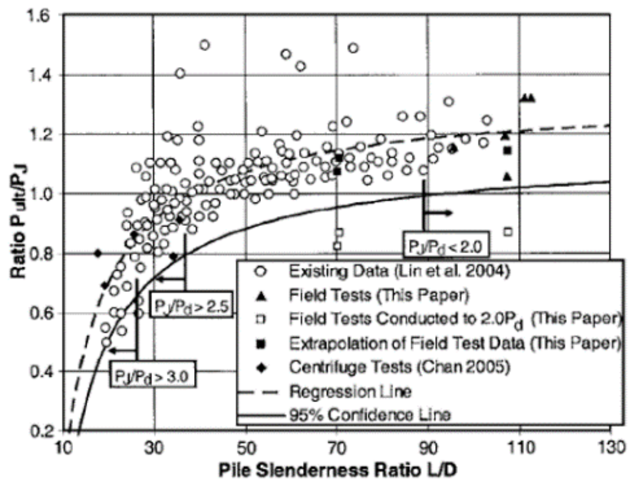

Figure 1. Slenderness ratio (L/D) vs. pressure ratio (Pult/ Pjack) from Zhang et al. [4]. Includes data from Lin and Wang [7] and Chan [11].

In Figure 1, the estimated ultimate capacity (Pult) is determined by a compressive static load test conducted a certain time after the installation of the pile, while Pjack is the final jacking force at the end of termination. Pd is the design load of the pile. For a given slenderness ratio, or pile length divided by diameter, there is a predicted ratio between Pult and Pjack. At least 95% of predicted ratios between Pult and Pjack were bless than the actual measured ultimate capacity and the Pjack.

Other researchers from China such as Lin and Wang [7], Zhang [12], and Zhang et al. [13] also found correlations between the slenderness ratio (L/D) and pressure ratio (∝). The relationships are represented by a hyperbolic function seen in Equation 3. Parameter A represents the maximum pressure ratio for long piles, while the parameter B reflects the curvature of the function.

$$\propto = A - B/(\mathrm{L/D}) \qquad (3)$$

The parameter values of A and B have been found to depend on local soil conditions, and particularly on the surrounding and end-bearing soils. Table 1 presents values of A and B for jacked precast concrete square and circular piles in various regions in China.

Initial correlations from Lin and Wang [7], with 101 piles in the database, and Zhang [12], with 26 piles, provided generalized parameters for precast concrete jacked piles installed in a variety of soils and rocks in the Pearl River Delta and Shunde regions of China. Subsequent research by Zhang et al. [13] with a database of nearly 2000 piles provided different parameters for varying soil conditions. Note that Zhang et al. [13] cautioned that many of the piles included in their database were not loaded to failure in the SLTs. As such, ultimate capacities were likely underestimated.

Table 1. Parameters for pressure ratio predictions for precast concrete jacked piles

#	Reference	Region	Pile geometry	Lengths	Surrounding soils	End-bearing soils	A	B
1	Lin and Wang [7]	Pearl River Delta, China	Square and circular	Mostly 10 to 25 m	Fill, sludge, clay, sand	Varied soils and rocks	1.45	14.00
2	Zhang [12]	Shunde, China	Not provided	Not provided	Not provided	Not provided	1.25	12.00
3	Zhang et al. [13]	Zheijang, China	Circular	Mostly 10 to 40 m	Clay	Clay	2.12	18.62
					Clay	Silt	1.78	21.26
					Clay	Sand	1.82	18.53
					Clay	Gravel	1.26	9.85
					Clay	Rock	1.20	5.32
					General; soil condition not considered		1.56	10.95

Yu et al. [5] presented a database of 95 concrete jacked circular and square piles ranging in length from 5 to 60 m installed in coastal provinces in China. The relationship between pressure ratio (ultimate capacity of pile from static load test vs. final jacking force) and pile slenderness ratio was presented under two categories of soil conditions: 1) piles surrounded and founded in fine-grained soils and 2) piles surrounded by fine-grained soils and founded on coarse-grained soils. These relationships can be seen in Figure 2.

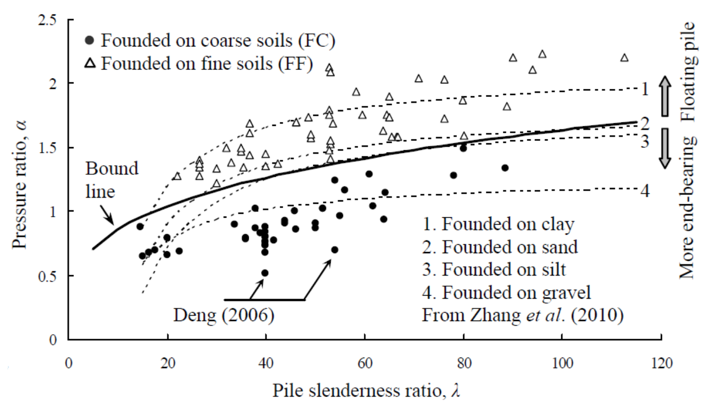

Figure 2. Relationship between pressure ratio and slenderness ratio for concrete jacked precast piles founded in fine-grained and coarse-grained soils from Yu et al. [5]. Includes data from Zhang et al. [13].

From Yu et al. [5], higher pressure ratios ∝ were observed for piles founded on fine-grained soils (FF) and lower ratios were observed for those founded on coarse-grained soils (FC). A bound line segregating the two categories can expressed by the exponential function in

Equation 4.

$$\propto = 0.45(\mathrm{L/D})^{0.28} \tag{4}$$

Databases outside of China are more limited, though increasing in availability. Buensuceso [14] presented a database of jacked piles installed in the coastal area of the Metro Manila region of the Philippines that were subjected to high-strain dynamic load tests.

The jacked square concrete piles were installed in an area with soil subsurface conditions generally consisting of four strata: a) a 2 m thick, medium dense silty sand layer with an average Standard Penetration Test (SPT) N-value of 20 blows/foot, b) an 8 m thick very soft clay layer with N-value=2 bl/ft, c) a 5 m thick stiff clay layer with N-value=12 bl/ft, and d) a weathered sandstone layer until about 40 m. 254 piles were tested with high-strain dynamic load tests (PDA tests) and had a width of 450 mm and lengths ranging from 10 to 21 m. The piles were jacked to depths ranging from 10.3 to 21.9 m, with an average of 15.1 m.

Buensuceso [14] found that 97.5% of the observed pressure ratios were above a 95%-confidence line from Zhang et al. [4] from Equation 1, as seen in Figure 3. This was for the 40 piles in the database with PDA test results that correlate well with SLT capacity estimates (i.e., with permanent pile sets above 2 mm during PDA testing). However, these PDA-tested jacked piles could not be reliably predicted by Equation 5 from Zhang et al. [13] for jacked piles with surrounding soil of clay and founded in rock, despite similar subsurface conditions. The pressure ratios obtained were generally less than predicted.

This could be because of a number of factors including (1) differing surrounding soil conditions, (2) differing end-bearing rock behavior and composition, (3) the use of different jacking rigs with different jacking times in China and the Philippines, or (4) the differing load test used to verify the capacities (SLT vs. PDA).

$$\propto = 1.20 - 5.32/(\mathrm{L/D}) \tag{5}$$

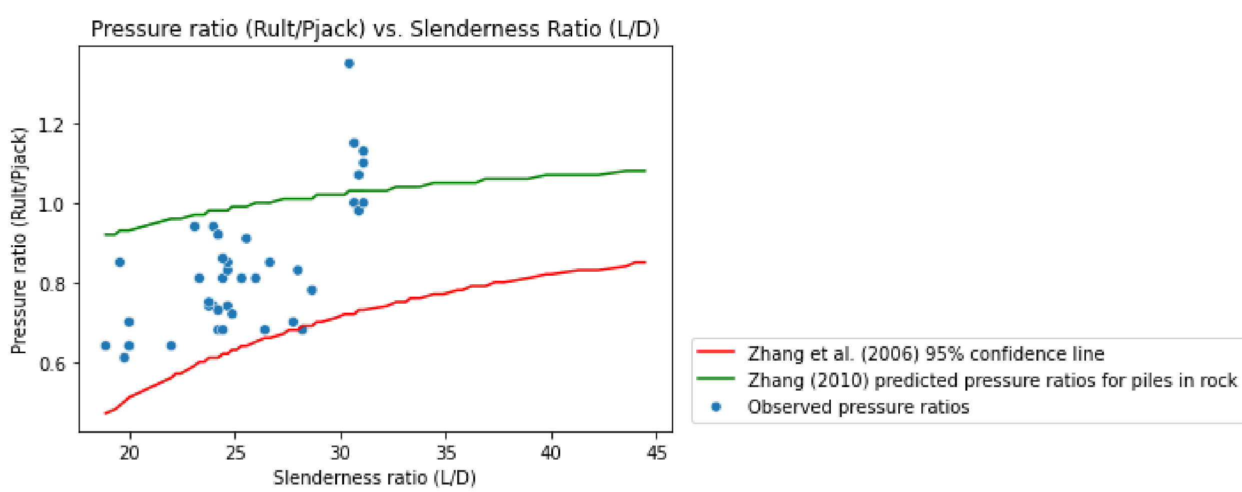

Figure 3. Observed vs predicted pressure ratios from Buensuceso [14]

1.1.4 Pile Re-Jacking

A post-installation procedure called re-pressing or re-jacking can also be done on jacked piles. This utilizes the same jacking rig to re-jack an already installed pile several times after specified intervals to investigate the time-related behavior of pile capacity. In particular, re-jacking tests can quantify the pile setup effect or the increase in skin friction over time. The test assumes that the peak jacking force applied in each re-jacking cycle is the pile's ultimate capacity at the time.

While SLTs or PDA tests can be conducted to estimate a pile's ultimate capacity, these may require alternative setups or additional equipment. Re-jacking tests allow for the use of the same jacking setup used for the initial installation. The re-jacking results of three 25 to 26 m jacked piles installed in Zhuhai, China were presented by Yu et al. [5]. These were open-ended prestressed concrete pipe jacked piles with an outer diameter of 400 mm and a wall thickness of 65 mm and surrounded by silty soils and founded on clayey soils. These would be classified as jacked piles founded into fine-grained soils (FF), as previously defined.

Interval re-jacking tests were performed over four days after installation. Pressure ratios for the three piles reached at least 3.0 during the last re-jacking test more than 90 hours after installation. The rate of increase of the pressure ratio was noted to be particularly significant after the first 10 hours, as seen in Figure 4.

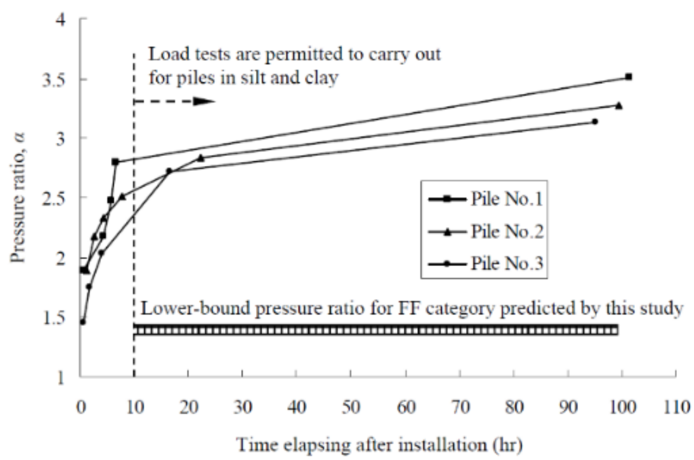

Figure 4. Time-related increase in pressure ratio ∝ from re-jacking tests from Yu et al. [5]

1.1.5 Pile Setup

Increases in capacity over time after installation of displacement piles have typically been attributed to the phenomenon of pile setup. Setup primarily occurs because of the dissipation of excess porewater pressures generated during pile installation. It has been documented in fine-grained soils around the world and has been attributed to increase capacities up to 12 times an initial capacity [15].

Pile setup typically occurs in three phases: Phase 1, non-linear rate of excess porewater pressure dissipation; Phase 2, linear rate of excess porewater pressure dissipation; and Phase 3, aging. Note that there is often overlap between successive phases (i.e., aging occurs before complete dissipation of excess porewater pressure). Additionally, different soil types at different elevations can be at different phases of setup at a given time.

The duration of Phase 1 is a function of soil and pile properties. Typically, the less permeable the soil and pile, and the greater the displaced soil volume, the longer the duration of the first phase. For clean sands, the logarithmic rate of dissipation may become linear immediately after installation. For cohesive soils, the logarithmic rate may stay nonlinear for several days.

Phase 2 involves a linear dissipation of excess pore water pressure and linear capacity increases with regard to time in the logarithmic scale. Similar to Phase 1, the duration of Phase 2 is related to the pile and soil properties. The less permeable the soil and pile, and the greater the displaced soil volume, the longer the duration of Phase 2. For clean sands, the phase may complete almost immediately or continue for several hours. For fine-grained granular soil or mixed soils, the phase may last for several hours up to several weeks. Finally, for cohesive soils, the phase can continue for several weeks up to even years [16]. Phase 3, or aging, occurs after the dissipation of excess pore water pressures has been completed, though the rate of increase is very slow and very small as to be of no practical consequence.

To measure and quantify pile setup, at least two measurements are required: a pile's capacity at the end of installation, or as soon as possible afterward, and a capacity a certain time after installation. These increases in capacity can typically be quantified by either a SLT or a high-strain dynamic load tests (typically PDA tests). Empirical formulas have also been proposed for quantifying pile setup; these are outlined in Table 2.

A commonly used empirical formula to predict setup is from Skov and Denver [17] which models setup as linear with respect to the log of time, starting from an empirical initial time value to. Svinkin [18] and Svinkin and Skov [19], meanwhile, modeled the increase in capacity from the end-of-driving (EOD) or end of installation of the piles.

Table 2. Empirical pile setup formulas

Author	Equation	Remarks
Skov and Denver [17]	Qt/Qo=1+A[log(t/to)]	to=0.5 for sand, 1 for clay A=0.2 for sand, 0.6 for clay
Svinkin [18]	Qt=1.4QEOD * t0.1	Upper bound
	Qt=1.025 QEOD * t0.1	Lower bound
Svinkin and Skov [19]	Ru(t)/REOD – 1 = B [log10(t) + 1]	B is similar to A from Skov and Denver (1988) [17]

1.2 Problem Statement and Objectives

This research paper studies the accuracy and reliability of capacity estimation methods for very slender, frictional jacked piles installed in the Philippines. This research specifically assesses the reliability of research from China and Hong Kong that utilize final jacking force and slenderness ratio to predict ultimate capacity, and of empirical pile setup formulas. This research also establishes a database of ultimate capacity estimates from high-strain dynamic load tests (PDA tests) used for load verification.

1.3 Significance of the Study

This paper studies the utility of final jacking force (Pjack) readings as an estimate of the actual ultimate capacity of jacked frictional precast piles installed in mixed soils in the Philippines. The accuracies of existing capacity prediction methods are assessed vs. the well-established method of using capacity estimates from high-strain dynamic load tests.

Safety factors (for allowable stress design, ASD) or resistance factors (for load and resistance factor design, LRFD) are typically assigned to ultimate capacity predictions to lower the risk of foundation failure and compensate for uncertainties in the prediction method [20]. Smaller errors of existing capacity prediction methods could indicate higher loads (i.e., lower safety factors) could be safely assigned to piles when these methods are properly used.

There is also a limited sample of very slender, frictional jacked piles in the Hong Kong and Chinese jacked pile databases used to train capacity prediction methods. This study would assess the reliability of these formulas on an “out of sample” dataset.

1.4 Scope and Limitations

The piles included in the pile database are relatively limited in configuration and quantity; this study does not intend to generalize a variety of pile and soil types in the Philippines. As such, the implications of this study should be used with caution in projects with different subsurface conditions and pile configurations.

Previous research also used static axial load tests (SLTs) to verify the ultimate capacities of piles. This research uses capacity estimates from high-strain dynamic load tests (PDA tests) done as “proof tests” with minimal pile top settlements. This indicates that the capacity estimates in this research are likely under-estimates of the ultimate capacity.

II. SITE CONDITIONS AND DATASET

2.1 Site Conditions

A case study of jacked precast concrete piles installed in the San Simon, Pampanga, Luzon region of the Philippines is presented in this section. The location is presented in Figure 5. The soil subsurface conditions generally consist of alluvial materials from the ground level down to around 61.5 to 70.5 m depths. These consist of silty sand, poorly graded sand, sandy to clayey silt, and sandy to silty clay. These are classified as “founded on silt” for comparison with correlations found by Zhang et al. [13].

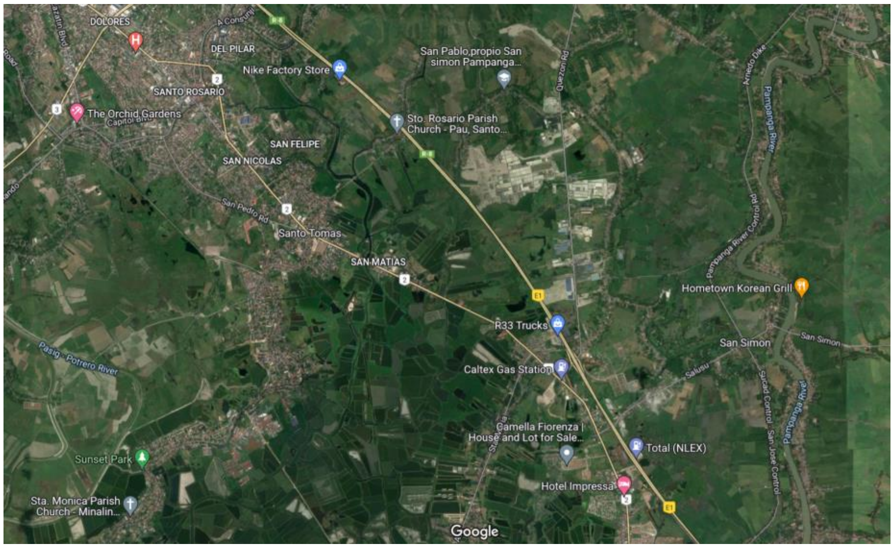

Figure 5. Location where piles were installed.

Lower average SPT N-Values (average of 11 blows per ft) were typically observed in the upper 38.0 m. This consisted of varied layers of silty sand, poorly graded sand, sandy to clayey silt, and sandy to silty clay.

Higher N-Values were seen below 38.0 m depth (average greater than 50 bl/ft). The soil investigation noted that the higher SPT N-Value layer also reached as far as 60.0 m below the ground level. Lower zones with higher SPT N-values (exceeding 40 bl/ft) were observed to mostly be silty sand.

Deep pile foundations were used to transmit the loads to a more competent stratum. Square, jacked, precast piles, in particular, were chosen due to the ease of installation and minimal construction noise and vibration. A YZY800 Starke hydraulic static pile driver was used to install the piles. It is noted that this driver can only hold loads for up to 2 minutes at a time, in contrast to the jacking rigs in past research in China that could hold loads for around 15 minutes.

No specifications regarding termination criteria, particularly a minimum required final jacking force, were provided in the geotechnical investigation and report. The piles were installed either until the maximum counterweight for the static pile driver had been used, or the entire pile length was embedded in the ground.

Test piles were initially subjected to high-strain dynamic load tests (PDA tests) to verify actual pile capacities. These were conducted as “proof tests” tested to capacities up to at least 2 times design loads of either 900, 1150, or 1200 kN. Ultimate capacity estimates (Rult) were obtained from the signal matching analysis software CAPWAP. Finally, all PDA tests were conducted as “restrike tests” after at least 11 days to evaluate time-dependent capacity changes.

The dynamic tests were performed using a Pile Driving Analyzer (PDA) Model 8G manufactured by Pile Dynamics, Inc. (PDI), USA, with test methodology in accordance with ASTM D4945 specifications. The PDA 8G machine used for the tests was calibrated within 2 years of the tests, and a calibration check was done before each test was conducted, as required by ASTM D4945 [21]. Two calibrated strain transducers and two calibrated accelerometers were placed on opposite sides of the piles to obtain force and velocity measurements to be used for the signal matching analysis.

2.2 Pile and Test Database

36 concrete square precast piles were subjected to PDA tests. These had a width of 350 to 400 mm and pile lengths ranging from 45 to 47 m. The piles were installed to depths ranging from 36.9 to 47.0 m (penetration lengths or LP), with an average of 43 m. Slenderness ratios, defined in this study as the length of penetration of the pile over the width of the piles, ranged from 90 to 113.5. The piles were jacked up to final jacking forces during pile installation (Pjack) ranging from 380.1 to 1368.5 kN with an average of 1081.2 kN. Histograms of final jacking forces, penetration lengths, and slenderness ratios are presented in Figures 6 and 7.

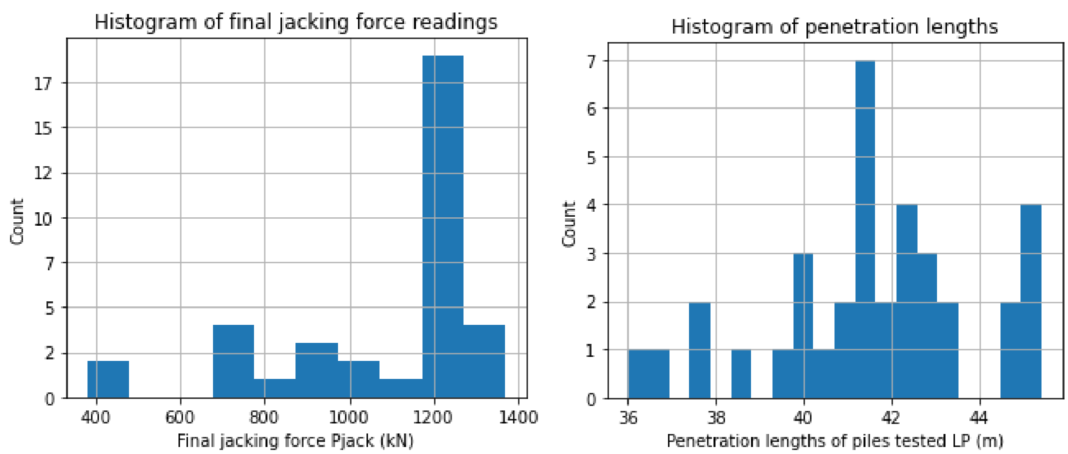

Figure 6. Histograms of final jacking force readings (Pjack) and penetration lengths (LP)

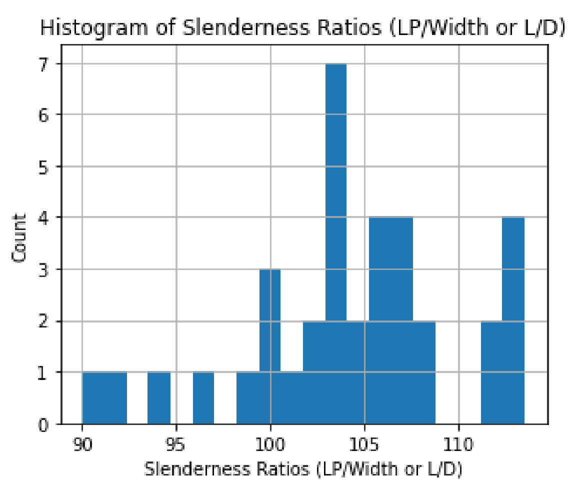

Figure 7. Histogram of slenderness ratios (LP/D)

Pressure ratios, defined in this study as the ratio of CAPWAP measured ultimate capacity (Rult) and Pjack, range from 0.33 to 1.14 with an average of 0.92 were observed. These ratios are significantly lower than the recommended ratios of at least 2.5 by Zhang et al. [4] and at least 2.0 by Lin and Wang [7]. A histogram of measured pressure ratios are presented in Figure 8. Note that no termination criteria was specified during pile installation for this project.

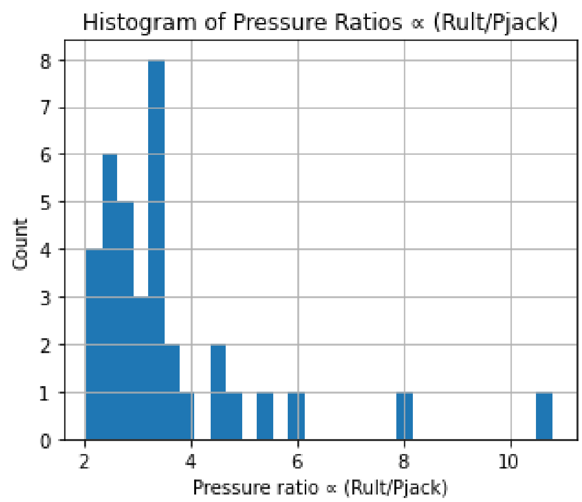

Figure 8. Histogram of pressure ratios

PDA tests were conducted as restrike tests at least 11 days after installation to evaluate time-dependent capacity changes and to verify that required loads could be supported. The number of days to the restrike test ranged from 11 to 136 days, with an average of 63.8 days. A histogram of the days to PDA restrike test is presented in Figure 9.

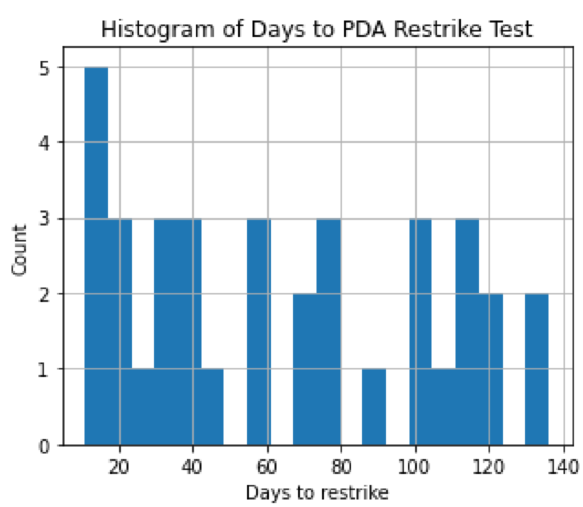

Figure 9. Histogram of days to the PDA restrike test

For the PDA tests conducted, either a 7-ton KJ hammer or an 8-ton hydraulic hammer were raised to maximum drop heights ranging from 0.3 to 0.7 m, with an average of 0.4 m. Testing was stopped when field capacity measurements indicated the measured ultimate capacity (Rult) would be greater than 2 times a specified design load.

The impact blows applied resulted in a permanent pile settlement of 0 mm per blow for 34 of the 36 tests. The other two tests resulted in pile sets of 0.5- and 2-mm per blow. Note that sets below 2 mm per blow generally result in lower-bound estimates of ultimate capacity. Note that none of the piles included in the dataset were classified as defective.

2.3 Measured vs. predicted ultimate capacities

Using estimates obtained from signal matching analysis software CAPWAP, the measured capacities all exceeded the provided target capacities, despite relatively small observed final jacking forces (average of 1081.2 kN). Rult ranged from 2496 to 4552 kN (average of 3506 kN). A CAPWAP estimated load-settlement curve for one of the jacked piles tested can be seen in Figure 8. This test shows a mobilized capacity of 2496 kN, skin resistance of 2134 kN, and end bearing of 362 kN. An estimated pile top set of 17.3 mm and an estimated pile toe set of 5 mm were predicted at the mobilized capacity in Figure 10.

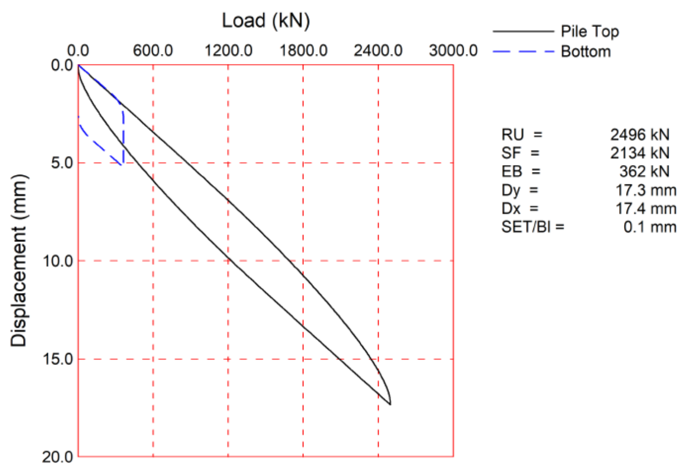

Figure 10. CAPWAP estimated load-settlement curve

PDA testing with signal matching analysis also allows for estimates of the shaft and toe resistance. Shaft resistance ratio (ratio of skin resistance to ultimate capacity, or Rskin/Rult) was on average 86.1% (77.0 to 92.8%) of the ultimate capacity, indicating that the bulk of the capacity increases came from increases in skin friction. The relationship between the shaft resistance ratio, and pressure ratio, can be seen in Figure 11. The days between installation and the restrike test are quantified by the shade of the points in Figure 11 (i.e., darker shades indicate a larger number of days).

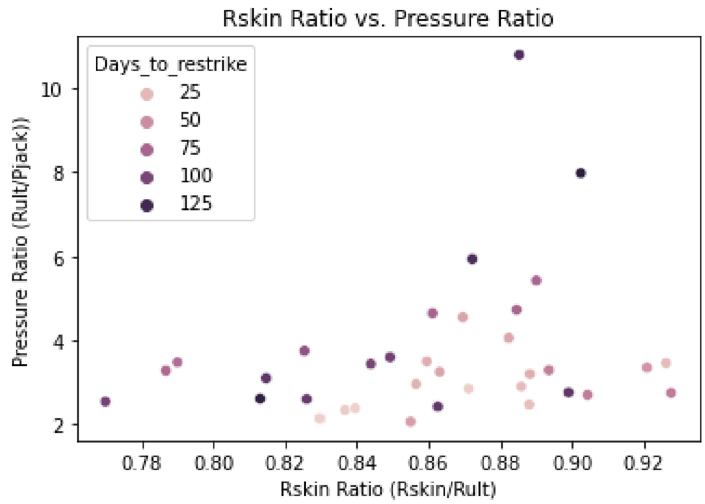

Figure 11. Shaft resistance ratio vs. pressure ratio

The relationships between Rult and LP/D, Pjack and LP/D, and Pressure Ratios and Days to Restrike, are presented in Figures 12, 13, and 14. A relatively weak positive correlation (R2=0.1984) was seen between measured pressure ratios and days to restrike.

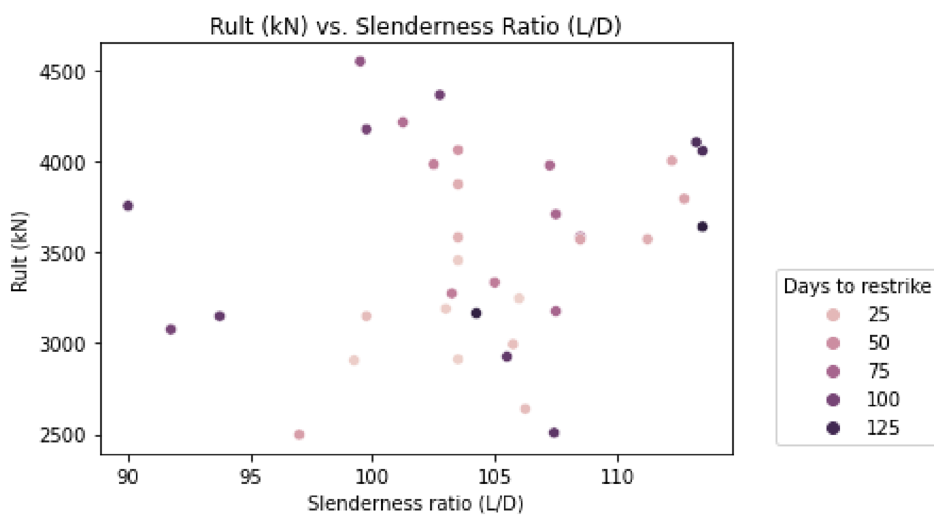

Figure 12. CAPWAP estimated ultimate capacities (Rult) vs. slenderness ratio

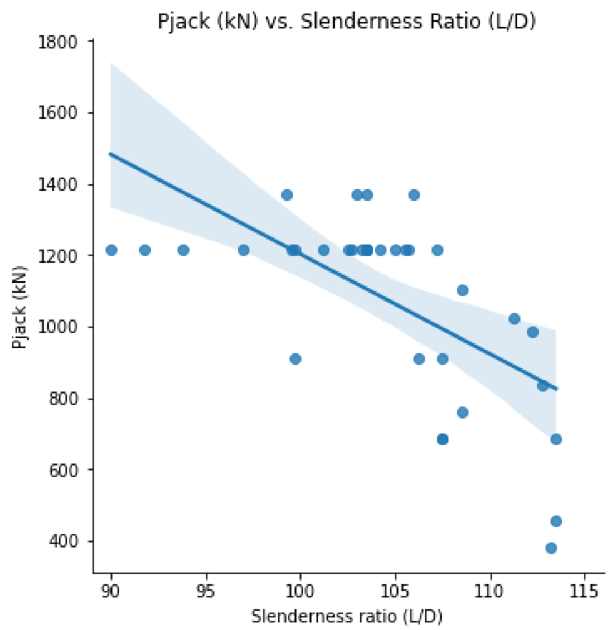

Figure 13. Final jacking force (Pjack) vs. slenderness ratio

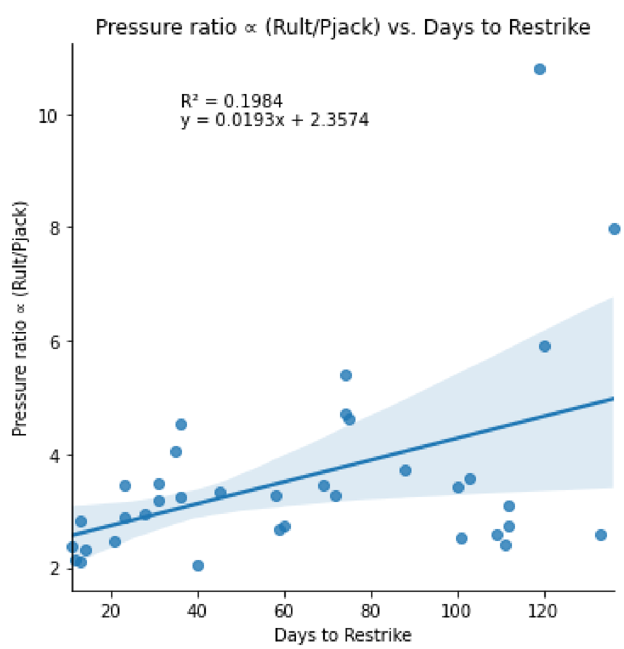

Figure 14. Pressure ratios vs. days to PDA restrike test

An average pressure ratio of 3.58 was observed, with values ranging from 2.05 to 10.80, as seen in Figure 15. These are significantly larger than predicted pressure values from Zhang [4] of 1.12 to 1.14 for jacked piles and from Zhang et al. [13] for jacked piles in silt of 1.58 to 1.59. This is despite all 36 piles not being PDA tested to an actual ultimate capacity, as indicated by the relatively small pile settlements (not more than 2 mm).

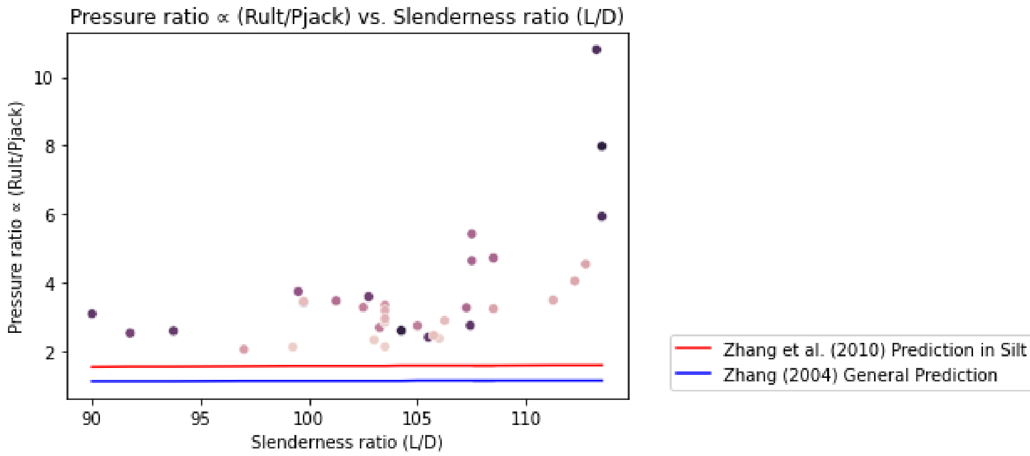

Figure 15. Predicted vs. actual pressure ratios.

There was an average of 63.8 days between the installation of the jacked piles and the PDA tests. Given the mixed fine and coarse-grained soils seen at the project, it is likely that Phase 2 of pile setup (a logarithmically linear increase of capacity and decrease of excess pore water pressure) had completed, as this would at most take several weeks. In contrast, while the databases in Table 1 did not present the number of days between installation and testing, Yu et al. [5] tested up to 100 hours (4.2 days) after installation.

The significant increase in measured capacity is likely attributable to pile setup, particularly since the measured PDA capacities were predominantly skin friction (77 to 92.8% with an average of 86.1%) and the significant amount of time that had passed between installation and PDA test (average of 63.8 days). The average penetration length of piles at the project was 41.59 m vs. lengths in prior research that did not exceed 40 m. These findings indicate that final jacking forces may not be a reliable indicator for very slender piles (LP/D > 90) with large, expected pile setup.

It is noted that while the observed pressure ratios are significantly larger than those predicted by previous researchers' empirical formulas, increases in capacity of and above this magnitude attributed to pile setup have previously been observed [15].

The predictive ability of empirical pile setup formulas to estimate pile capacity is assessed in this section. The root mean square error (RMSE) was used to quantify the error of these predictions, which can be seen in Table 3. The RMSEs for capacity prediction formulas using slenderness ratios from Zhang [4] and Zhang et al. [13] are also presented in Table 3 for comparison.

Table 3. RMSE of capacity predictions using setup and pressure ratio formulas

Author	Formula	RMSE
Upper bound capacity prediction from Svinkin setup formula [18]	Qt=1.4QEOD * t0.1	1477
Capacity prediction from Svinkin and Skov setup formula [19]	Ru(t)/REOD - 1 = B [log10(t) + 1]	1474
General jacked pile capacity prediction from Zhang pressure ratio formula [4]	Rult = Pjack * (1.25 - 12/(L/D))	2365
Capacity jacked pile capacity from Zhang et al. pressure ratio formula for piles founded in silt [13]	Rult = Pjack * (1.78 - 21.26 / (L/D))	1934

Large RMSEs were observed using pile setup formulas predicting ultimate capacity from Svinkin and Skov [19] and the upper bound of capacities from Svinkin [18]. As seen in Figures 16 and 17, the empirical pile setup formulas visibly underpredicted the actual pressure ratios (Rult/Pjack). The largest underpredictions occurred in the piles with slenderness ratios greater than 110. These piles also generally had the lowest final Pjack of the piles in the database (average of 728 kN).

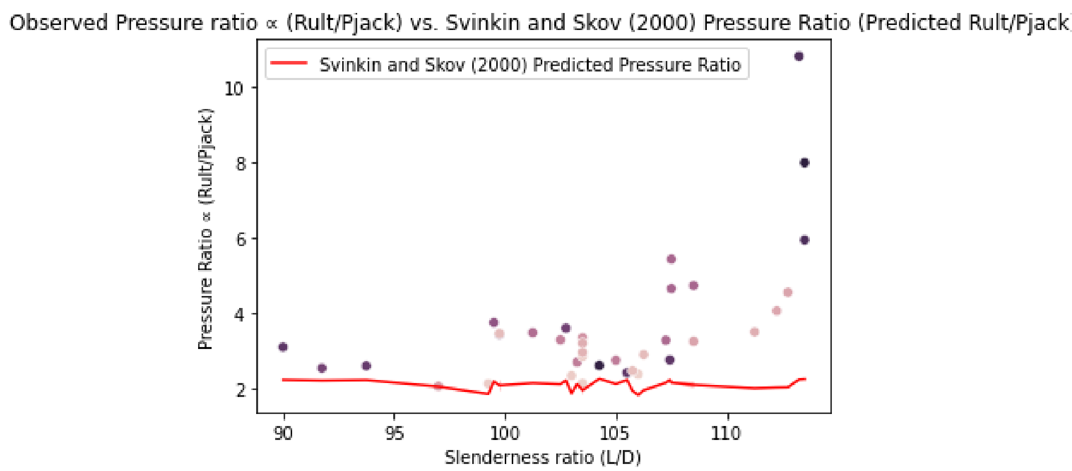

Figure 16. Observed vs. predicted pressure ratios after setup from Svinkin and Skov [19]

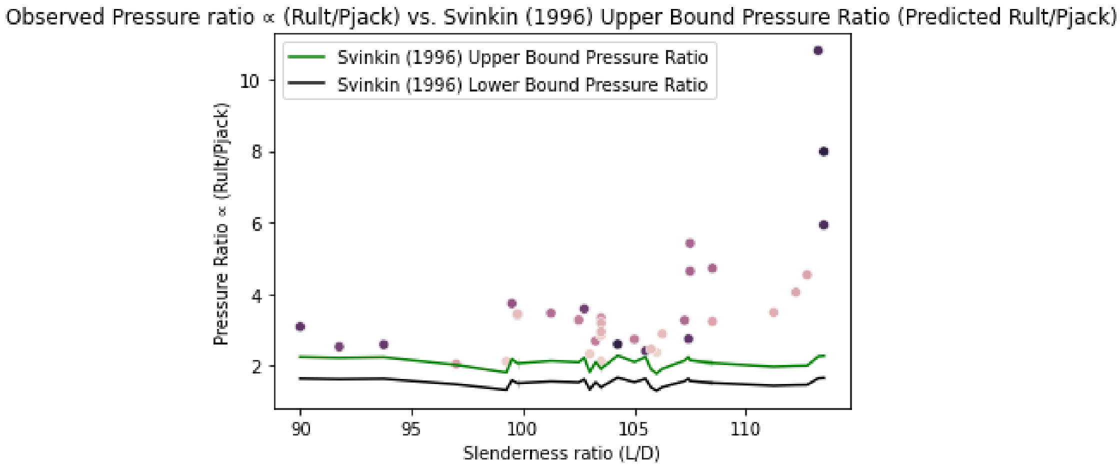

Figure 17. Observed pressure ratios vs. the upper and lower bound pressure ratios after setup from Svinkin [18]

Note that setup formulas such as the one from Skov and Denver [17] could not be used because no time had passed between the end-of-installation and the capacity measurement. Additionally, an empirical setup formula could not be produced as only two ultimate capacity measurements were made.

The low observed pressure ratios were likely caused by a combination of relatively low final jacking forces and relatively high PDA measured capacities. The average ratio of final jacking force to allowable capacity was only 0.9211, when this would typically be at least 2.0 and in some cases 2.5. Ratios as low as 0.33 could be seen, as seen in Figure 18.

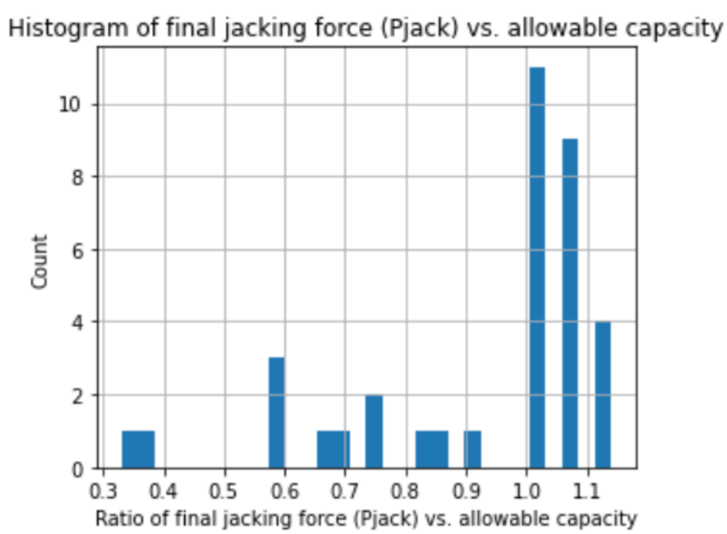

Figure 18. Histogram of final jacking force (Pjack) vs. allowable capacity

Despite the low observed final jacking forces, the ratios of the measured capacities during the PDA restrike test (Rult) and a specified allowable capacity all exceeded 2.0, as seen in Figure 19. Ratios as high as 3.96 were observed, despite limiting the pile top settlement during PDA testing to avoid damaging the piles. This indicates that the actual ultimate compressive capacities of the piles may be larger than initially designed, despite the low observed final jacking forces. As previously discussed, this was likely caused by a large degree of pile setup.

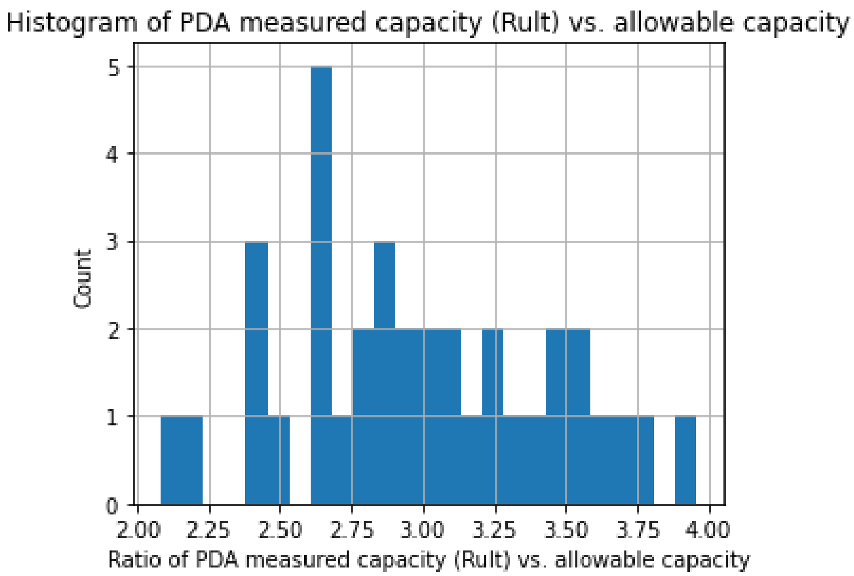

Figure 19. Histogram of PDA measured capacity (Rult) vs. allowable capacity

III. CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

This paper established a database of very slender (L/D > 90), frictional jacked concrete piles installed in mixed fine- and coarse-grained soil in Pampanga, Philippines, and the significant increase in pile capacity observed between the end of installation and during a PDA test conducted at least 11 days after the installation. The observed pressure ratios ranged from 2.05 to 10.80 with an average of 3.58, much higher than those predicted by previously established empirical formulas for jacked piles from China.

The significant increase in measured capacity was attributed to pile setup, particularly since the measured PDA capacities were predominantly skin friction (77 to 92.8% with an average of 86.1%) and the significant amount of time that had passed between installation and PDA test (average of 63.8 days). These findings indicate that final jacking forces may not be a reliable indicator for very slender piles (L/D > 90) with large, expected pile setup.

However, empirical pile setup formulas still significantly underpredicted the measured ultimate capacities, despite the PDA tests providing significant underestimates of the actual ultimate capacity as indicated by low measured test settlements. This is likely attributable to the relatively low final jacking forces observed during installation, and the higher-than-expected PDA measured capacities.

The large prediction errors are suspected to be caused by the lack of similarly slender and frictional jacked piles in databases used by Chinese researchers, and the uncertainty in (1) the amount of pile setup that will occur between the end of installation and the test, and (2) accurately identifying soil conditions in these databases.

3.2 Recommendations

These results indicate that very slender and frictional piles (L/D > 90) founded in mixed soils are not modeled particularly well by either existing pile jacking termination criteria or empirical pile setup formulas. This may be because of a lack of similar piles and subsurface conditions in the databases used to train these empirical formulas and criteria, particularly in the Philippine setting.

As such, termination criteria for similar subsurface conditions and pile configurations should account for the significant pile setup that can occur. Empirical pressure ratio formulas could be updated to include the number of days between the end of installation and the conducted test to account for time-based capacity changes. A minimum number of days before performing the load tests could also be included when establishing empirical criteria to allow the majority of the setup to occur.

Additionally, interval re-jacking tests may also be considered a certain time after the initial termination of jacking, which would allow Phase 1 of pile setup (i.e., non-linear dissipation of excess pore water pressure) to complete. Jacking force readings obtained are more likely to be reliable indications of the piles' ultimate capacity.

Multiple interval re-jacking tests combined with PDA tests at later dates could also allow for the development of empirical pile setup formulas at these projects, particularly given the observed inaccuracy of existing pile setup formulas predicting capacities in this paper. This can be done during the "test piling" phase of projects, where initial capacity estimates from soil investigations and static analysis are verified.

III. CONCLUSIONS AND RECOMMENDATIONS

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