Empirical methods for predicting precast jacked pile capacity – Case studies in the Philippines

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ABSTRACT

This paper details case studies of precast jacked piles tested with high-strain dynamic load pile tests in the Philippines, to allow for the exploration of the relationship between pile slenderness ratio (L/D), high-strain dynamic load test capacity, and final jacking force (P_{jack}), the evaluation of empirical lower-bound predictions of ultimate capacity that utilize slenderness ratio and P_{jack}, and the establishment of lower-bound formulas more suitable for the collected data. A total of 135 jacked, square, precast piles tested with high-strain dynamic load tests with slenderness ratios from 5 to 64 are included in the database. The ratio of an ultimate capacity measured in the high-strain dynamic load test to P_{jack}, also called pressure ratio, was found to be a function of the slenderness ratio, with pressure ratios generally rising above 1.0 for piles with slenderness ratios above 30. Actual pressure ratios and ultimate capacities measured were compared to two previously established empirical lower-bound predictions, with 93% and above of actual pressure ratios and capacities above those predicted. Two new lower-bound pressure ratio formulas that are a function of slenderness are also proposed, particularly to deal with low-slenderness piles seen in the database (L/D < 10).

Key words: *Termination criteria; jacked piles; high-strain dynamic pile load tests; PDA tests*

1. Background of the research

1.1 Pile Jacking

The use of pile jacking to install displacement piles that support structural loads is a relatively novel technique that avoids the spoil generated by cast-in-place bored piles, and the undesirable vibration and noise from pile driving with a hammer. Jacked piles installed in the Philippines are typically square, concrete, precast piles, and installed using a hydraulic static pile driver (Buensuceso, 2021). The final jacking force (P_{jack}) measured during the pile jacking process can in some cases be a reliable estimate of the pile's ultimate capacity as measured by a static load test (Yetginer et al., 2006).

Empirical termination criteria have been proposed to establish a relationship between measurements taken at the end of jacking and load test results. The China Academy of Building Research (2008) suggests 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) presented a database of 149 jacked piles in China and Hong Kong with axial ultimate capacities estimated by compressive static load tests. The piles ranged in length from 10 to 25 m, and were founded on mainly sand, weathered soil, and clay. Pressure ratio (α) is defined as the ratio of the ultimate capacity of the pile (P_{ult}) to the final jacking force (P_{jack}). Predicting pressure ratios during pile jacking is critical, as it can allow for the prediction of ultimate compressive capacity using only pile installation data.

Two equations were presented by Zhang et al. (2006) regarding pressure ratio: Equation 1, a best-fit equation for pressure ratios using slenderness ratio (L/D, or length of a pile over pile diameter or width), and Equation 2, which predicts pressure ratios using slenderness ratios 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 2 is 5%, a confidence level used to determine characteristic values for geotechnical design in Eurocode 7 (Orr, 2000).

$$\alpha = \frac{P_{ult}}{P_{jack}} = 1.32 - 12.48\left(\frac{L}{D}\right) \qquad (1)$$

$$\alpha = \frac{P_{ult}}{P_{jack}} = 1.13 - 12.48\left(\frac{L}{D}\right) \qquad (2)$$

The relationship between slenderness ratio (L/D), the pressure ratio P_{ult}/P_{jack}, and predictions from Equations 1 and 2 can be seen in Figure 1. Zhang et al. (2006) remarked that pressure ratios rose above 1.0 for longer piles (with L/D greater than 50) as the pile capacity was mostly shaft resistance, and the long-term shaft resistance was significantly larger than the resistance at the end of jacking due to pile setup effects (i.e., skin friction increase over time due to dissipation of excess porewater pressure).

Pressure ratios were frequently less than 1.0 for shorter piles with L/D < 30, as these are more dependent on toe resistance, and toe displacement at failure as defined by commonly used methods in establishing ultimate capacity from static load test results such as the Davisson's criterion was suspected to be insufficient to mobilize the same amount of toe resistance activated at the end of jacking. (Zhang et al., 2006).

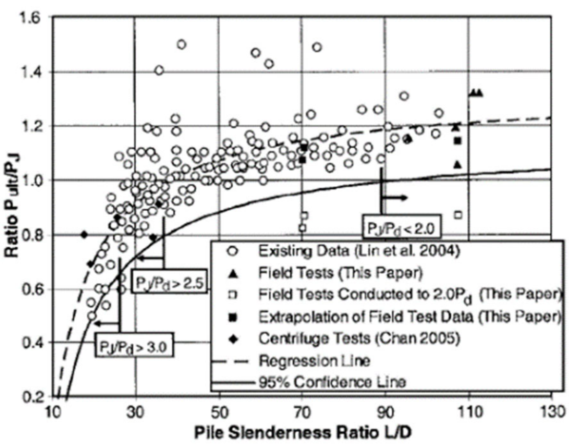

Fig 1. Slenderness ratio (L/D) vs. pressure ratio (P_{ult}/P_{jack}) from Zhang et al. (2006).

Yu and Yang (2011) 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. Relationships between pressure ratio (α) and pile slenderness ratio (λ) were presented for varied soils and can be seen in Figure 2, with pressure ratio again generally increasing with slenderness ratio.

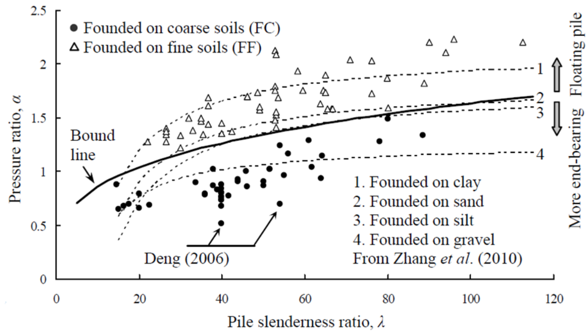

Fig 2. Relationship between pressure ratio and slenderness for concrete jacked precast piles from Yu and Yang (2011). Includes data from Zhang et al. (2010).

The Australian Standard (AS-2159) Piling Design and Installation (2009) 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_{max}) be determined with Equation 3. Jacked piles must be subjected to repeated jacking at P_{max}, with the number of cycles no less than 5. P_{max} must be maintained for not less than 15 seconds, and the time interval between cycles should not be less than 2 minutes. Equation 4 is a derived formula for estimating a geotechnical ultimate capacity (R_{ug}) using P_{max} and a coefficient of jacked pressure γ_p.

$$P_{max} = 0.74\,\gamma_p R_{ug} \qquad (3)$$

$$R_{ug} = \frac{P_{max}}{0.74\,\gamma_p} \qquad (4)$$

γ_p is a coefficient of jacked pressure, determined from static load test correlations. This correlation is the ratio between the maximum jacking force and a proven ultimate capacity from a static load test, as the jacking installation procedure is not considered equivalent to a static load test. Without any available correlations, the coefficient γ_p can be taken from Equations 5, 6, and 7, where the coefficient γ_p increases as pile length decreases.

γ_p =1.5 for piles greater than 15 m length (5)
γ_p =1.75 for piles between 8 and 15 m length (6)
γ_p =2.2 for piles with less than 8 m length (7)

In Philippine practice, two termination criteria are typically used: (1) that the maximum amount of jacking force has been used or, (2) that the entire available pile length has been jacked into the ground. The maximum amount of jacking force available is typically at least 2.0 to 2.5 times a 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 3.

Fig 3. Hydraulic static pile driving rig in the Philippines (photo from author)

High-strain dynamic pile load tests are frequently used in the Philippines for jacked pile load verification, and in some cases have completely replaced static load tests. Also called PDA tests, these tests involve applying an axial impact force on a pile using a drop weight or hammer, resulting in a relatively large strain at the pile top. Resulting force and velocity measurements at the pile top are measured and subjected to signal matching analysis. The results can then be used to estimate static compressive capacity, evaluate pile integrity and stresses throughout the pile, and estimate load-settlement behavior (Likins and Rausche, 2004).

Initially used as a quality assurance tool for preformed, driven piles, high-strain dynamic load tests have increasingly been used to assess the ultimate bearing capacity of other types of piles, including jacked piles and bored piles (Likins and Rausche, 2008). High-strain dynamic load testing methodology is standardized in ASTM D4945, with a typical testing arrangement seen in Figure 4. These come with the benefits of generally requiring less equipment, costing less, and taking less time to complete compared to static load tests, though dynamic load tests are generally regarded as being slightly less accurate.

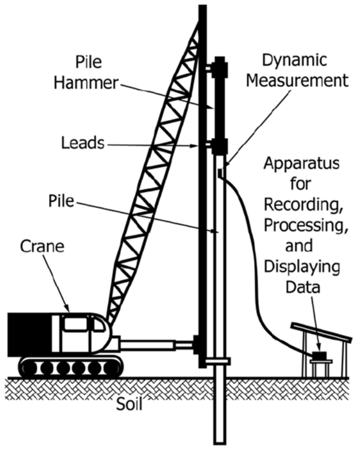

Fig 4. Arrangement for high-strain dynamic load testing from ASTM D4945-12

Nevertheless, high-strain dynamic load tests still provide a good approximation of the results from static load tests, which are considered the most reliable available predictor of long-term pile capacity and behavior (Likins et al., 1996). Extensive correlations have been done between high-strain dynamic load tests and static load tests, though there remains slightly increased risk and uncertainty associated with high-strain dynamic load tests compared to static load tests (Likins, 2004). This is reflected in the higher safety factor of 2.25 suggested by AASHTO (1992) for high-strain dynamic load test capacities vs. the safety factor of 2.00 for static load test capacities. One suggested method for reducing high-strain dynamic load test uncertainty is to conduct site-specific correlations between static load test and high-strain dynamic load tests (Rausche, 2019), or to test a larger percentage of piles with high-strain dynamic load tests vs. static load tests for a similar safety factor, as recommended by the PDCA code (2001).

1.2 Significance of the research

In the experience of the author in Philippine pile jacking practice, there is limited guidance on obtaining ultimate capacity estimates using readings taken at the end of jacking. Jacked pile capacities are typically only obtained from load test results and a geotechnical static analysis utilizing site boring logs. P_{jack} can be used to estimate an expected static compressive ultimate capacity, but the use of this requires the consideration of other factors such as slenderness ratio and ground conditions (Yu and Yang, 2011), or the use of correlation coefficients to establish the relationship between P_{jack} and an ultimate capacity (AS-2159, 2009).

While empirical capacity prediction formulas utilizing P_{jack}, slenderness, and other coefficients have been established in other settings, this research can assess whether these would remain applicable for jacked piles installed in a variety of subsurface conditions in the Philippines. More accurate ultimate capacity estimates would reduce uncertainty in jacked pile installation, since not all piles in a project are tested with load tests. However, jacking forces 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. Piles incorrectly identified to have insufficient capacity can also be minimized.

Finally, while minimum penetration depths needed to achieve a certain capacity are typically given when a geotechnical static analysis using site boring logs is done, actual penetrations and final jacking forces can greatly vary due to variations in the depth of a very hard or dense soil layer, resulting in uncertain pile capacities.

1.3 Objectives of the research

1. Compile case studies of precast jacked piles with a range of slenderness ratios tested with high-strain dynamic load pile tests in the Philippines.
2. Explore the relationship between final jacking force, high-strain dynamic load tests capacities, and pile slenderness ratio.
3. Establish lower-bound predictive formulas for ultimate capacity best suited for the dataset.

2. Pile and Test Database

2.1 Piling Method

The jacked piles in this database were installed using hydraulic static pile drivers that utilize dead weights for a reaction force. Jacking forces could only be held per jacking cycle for a maximum of two minutes. The maximum stroke of the drivers ranged from 1.6 to 1.8 m. The maximum piling speed reported by the piling contractors for the static drivers was around 9 to 10 metres per minute, and the minimum piling speed was around 2 metres per minute. Final jacking forces (P_{jack}) applied ranged from 132.5 to 378 tons.

Piles installed with other technology used to install jacked piles such as the press-in piler that uses reaction piles for reaction force are not included in this database.

Additionally, pressure gauge readings from the static drivers were used to estimate the jacking force readings. In compressive static load tests, calibrated load cells are typically used to accurately measure loads greater than 900 kN (ASTM D-1143); load cells were not used during pile jacking for the piles in this database. 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.

2.2 Case Studies

135 precast jacked square piles with slenderness ratios from 5.11 to 63.8 and lengths of penetration from 2.3 to 28.7 m tested with high-strain dynamic pile load tests were compiled into four case studies in this research.

Beginning with Case Study A, the project is a sewage treatment plant in Mandaluyong City, Philippines, supported by jacked piles. 43 precast jacked piles were installed into 6 to 9 m of residual soils or alluvial soils, followed by a hard layer of silty sands, sandy silts, or silty gravel. Penetrations ranging from 4.9 to 12.1 m (average of 6.0 m) and slenderness ratios from 10.9 to 26.9 (average of 15.5) were observed. Final jacking forces (P_{jack}) ranged from 225.7 to 250.8 tons (2214 to 2460 kN).

All high-strain dynamic load test ultimate capacities were above a target capacity of 840 kN, two times a specified allowable capacity of 420 kN obtained from a geotechnical static analysis. Pressure ratios ranging from 0.52 to 1.20 were observed. These were all greater than 95% confidence line predictions from Zhang et al. (2006) that relied on slenderness ratio seen in Figure 1.

The accuracy of geotechnical ultimate capacity predictions based on the final jacking force and length from AS-2159 were also evaluated. Since no correlations were done between a static load test and the final jacking force, coefficient γ_p was taken from Equations 5, 6, and 7 depending on the lengths of the piles, and used to compute a predicted geotechnical ultimate capacity (R_{ug}). 6 of the 43 piles in the dataset had high-strain dynamic load test capacities less than a predicted R_{ug} from AS-2159 (average of 1281 kN vs. a predicted of 1360 kN). For the group of 12 piles with measured sets greater than 2 mm, a rule of thumb for good correlations with static load test capacities, all had high-strain dynamic load test capacities greater than the predicted R_{ug}.

In Case Study B, precast jacked piles are to support a proposed factory building to be built in Batangas, Philippines. 23 precast jacked piles surrounded by residual soils and bearing onto a weathered volcanic tuff layer were included, with penetration lengths from 2.3 to 10.3 m (average of 5.8 m) and slenderness ratios from 5.11 to 13.3. Final jacking forces (P_{jack}) ranging from 142.0 to 270.8 tons (average of 221.4) were observed.

Pressure ratios ranged from 0.86 to 1.82 (average of 1.21), all above those predicted from Zhang et al. (2006). All predicted geotechnical ultimate capacities from AS-2159 were also below the measured capacities from the high-strain dynamic load test, even including two of the 23 piles with relatively small permanent settlements during the test (i.e., less than 2 mm).

In Case Study C, a proposed development consisting of multiple high-rise buildings in Manila, Philippines is to be supported by precast jacked pile foundations. 41 precast jacked piles are included, with penetration lengths varying from 16.1 to 28.7 m (average of 23.4 m) and slenderness ratios from 35.8 to 63.8 (average of 51.9), with the piles bearing on varying depths of the highly weathered Guadalupe Tuff Formation.

39 of 41 of the piles were installed with a P_{jack} of 326 tons (3198 kN). 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 (or allowable capacity) from references such as Lin and Wang (2004), that is, two times a provided allowable capacity of 1400 kN (i.e., to a target of 2800 kN).

High-strain dynamic load test capacities were all above a target capacity of 2800 kN, even for the two piles with relatively low P_{jack}. This indicates that a significant amount of pile setup (i.e., capacity increase) occurred, particularly for the two piles with relatively low P_{jack}. All actual pressure ratios were above the 95% confidence line from Zhang et al. (2006), while all high-strain dynamic load test capacities also remained above those predicted by AS-2159. This is despite all piles having measured sets of roughly 0 mm during the high-strain dynamic load test, indicating these were likely underestimates of an ultimate capacity from a static load test.

In Case Study D, a proposed high-rise development located in Coastal Metro Manila is to be supported by precast piles. 35 precast piles were included in the database, with 28 of these jacked piles and 7 of these driven piles installed with a pile driving hammer. Boreholes taken at the project indicated the upper 12 m to be medium dense to dense silty sands, with a layer of highly weathered sandstone and siltstone underneath.

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 other 19 piles were installed using the center piling mechanism, with a P_{jack} of 376 to 378 tons. Jacked pile penetration ranged from 7.0 to 10.0 m (average of 8.4 m). Side piles had an average penetration of 8.6 m, and center piles an average penetration of 8.2 m. 7 precast driven piles were also installed at the project. The piles were driven to penetrations ranging from 8 to 9.7 m (average of 8.7 m). Overall, slenderness ratios from 13.3 to 21.1 (average of 18.0) were observed for the 35 precast piles.

High-strain dynamic load tests 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 high-strain dynamic load test remained above predicted capacities from Zhang et al. (2006). However, 4 of the jacked piles (all center piles with lengths from 8 to 8.3 m) were found to have high-strain dynamic load test capacities below the predicted capacity from AS-2159.

2.3 Results and Discussion

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. However, 9 of these piles had high-strain dynamic load test sets below 2 mm and likely under-estimates of static load test ultimate capacity. Higher capacities are likely if sets above 2 mm were mobilized for piles evaluated, though the magnitude of this increase is unknown. The accuracy of the predictions can also be visualized by comparing 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 5. Note that piles in each case study (i.e., Case Study A, B, C, and D) are distinguished from one another by color.

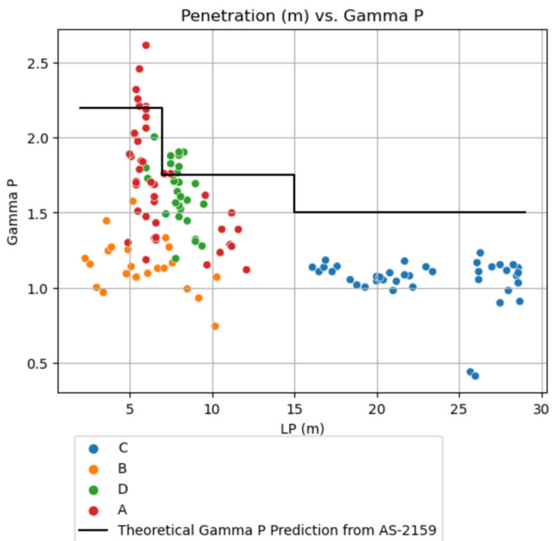

Fig 5. Penetration vs. Coefficient of Jacked Pressures from AS-2159

All 135 jacked piles also had actual pressure ratios above the 95% confidence line from Zhang et al. (2006) as seen in Figure 6, even when piles with relatively small high-strain dynamic load test sets are included.

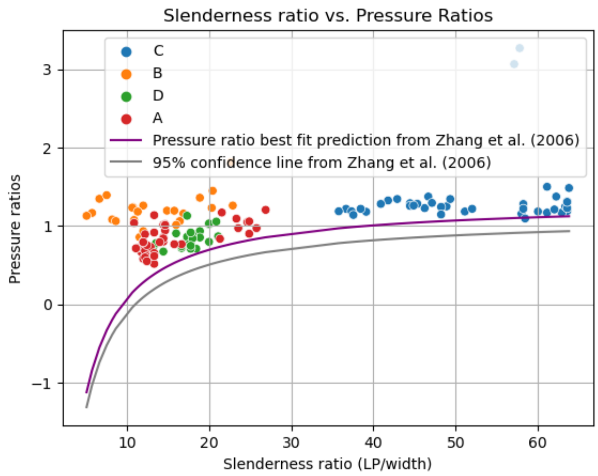

Fig 6. Slenderness ratio vs. pressure ratio

These findings complement the objective of Zhang et al. (2006) for the 95% confidence line to serve as a geotechnical characteristic value, with the probability that the actual pressure ratios are below predicted ratios at 5%.

Pressure ratios can also be seen to be a function of slenderness ratio, with pressure ratios becoming 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 likely rose above 1.0 for more slender piles because of the greater reliance these longer piles had on skin resistance, and with long-term skin friction likely significantly greater than the friction at the end of jacking.

Cases of pressure ratios below 1.0 were observed for L/D < 30, and as previously discussed, Zhang et al. (2006) suspected that the toe resistance mobilized for these lower slenderness piles during a load test was less than the resistance mobilized during pile jacking. Lower slenderness piles with pressure ratios closer to or even above 1.0 observed in the database (mostly in Case Study B) may have had similar 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 are below predicted ratios is presented in Equation 5, with 130 of the 135 (96.3%) actual pressure ratios below the function. The prediction can be graphically seen in Figure 7. This alternative prediction is an exponential function similar to the bound line proposed by Yu and Yang (2011), which allows for reasonable pressure ratio predictions for very low slenderness piles (L/D < 10), with pressure ratios still generally converging to 1.0 at higher slenderness ratios. As seen in Figure 6, negative pressure ratios, implying negative ultimate capacities, are predicted by Zhang et al. (2006) for piles with L/D < 10.

$$\alpha = 0.298\,(L/D)^{0.28} \tag{5}$$

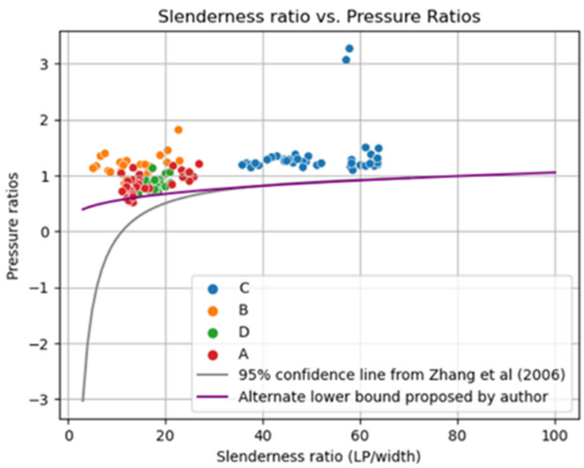

Fig 7. Slenderness ratio vs. pressure ratio including a proposed lower-bound exponential function

Best-fit (g_1), lower-bound (g_2), and upper-bound (g_3) hyperbolic functions are also presented in Figure 8 and represented in Equations 6, 7 and 8. Like with the previously proposed function in Equation 5, no negative pressure values are predicted for lower slenderness (<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.

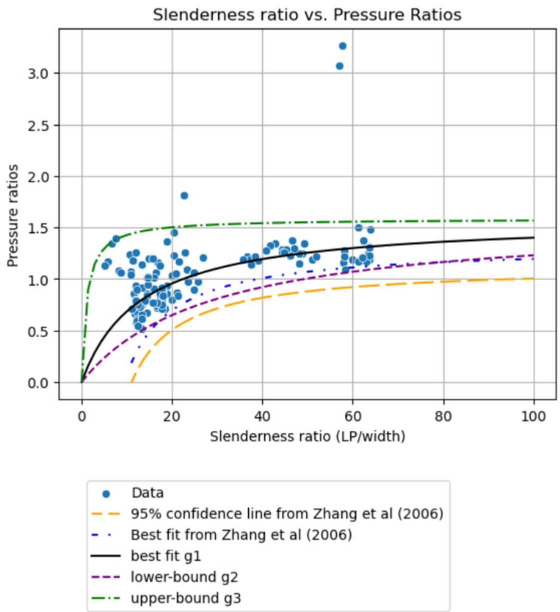

Fig 8. Slenderness ratio vs. pressure ratio including hyperbolic best-fit, lower-bound, and upper bound functions

$$\boldsymbol{g_1 = \alpha = \frac{x}{8.288 + m_1 x}} \tag{6}$$

$$\boldsymbol{g_2 = \alpha = \frac{x}{18.188 + m_1 x}} \tag{7}$$

$$\boldsymbol{g_3 = \alpha = \frac{x}{0.7 + m_1 x}} \tag{8}$$

Where $m_1 = 0.631$

3. Concluding Remarks

This research compiled a database of 135 precast jacked piles slenderness ratios from 5 to 64 tested with high-strain dynamic load pile tests. 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 measured ultimate capacities 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 a predicted geotechnical ultimate capacity from AS-2159. Two alternative lower-bound pressure ratio formulas that are a function of slenderness are proposed, particularly to deal with low slenderness piles (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 due to friction losses should be noted. There is also the slightly increased risk associated with using high-strain dynamic load test results without site-specific correlations with static load tests. As such, it is not recommended that the final jacking force (P_{jack}) measured, and slenderness ratio, be used as the sole means of establishing allowable design loads or capacities. A number of load verification tests (either static load test, high-strain dynamic load test, or a combination of high-strain dynamic load test and static load tests) and geotechnical static analysis should also be conducted to complement jacked pile capacity estimates from P_{jack} and slenderness.

4. Further work

Future work that can be conducted includes conducting additional load tests on jacked piles in different locations, pile types (say, timber or steel pipe piles), pile jacking equipment, and subsurface conditions in the Philippines, and comparing the results with the findings in this paper. The reliability of capacity and pressure ratio predictive methods established with high-strain dynamic load tests can also be compared to those established using static load tests, given the slightly higher uncertainty associated with dynamic load tests vs. static load tests.

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