FIELD TRIALS AND LOAD TESTS OF THE PAILE SYSTEM OF EXPANDED BASE PILES

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ABSTRACT

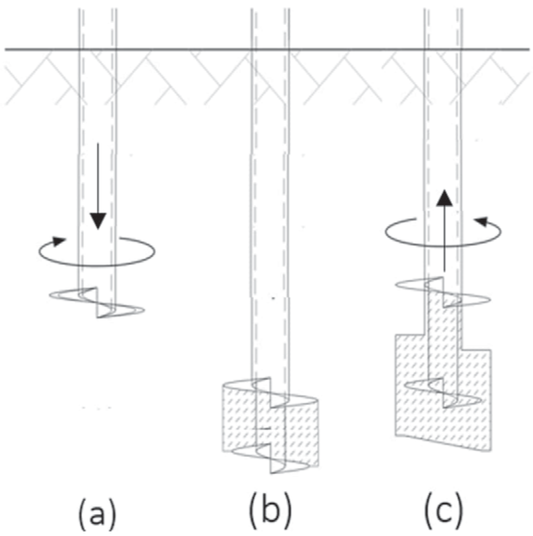
This study presents the results of static load tests on expanded base piles, installed using the novel PAILE method. This method facilitates the installation of a range of foundation and ground improvement piles with enlarged bases and, therefore, at a significantly reduced material consumption compared with current methods. The results of the static load tests in loose to medium-dense sands demonstrate that the performance of piles installed in loose to medium dense sands using the PAILE method can be predicted using direct CPT methods. This allows the determination of pile capacity and load/settlement factors corresponding to drilled displacement and precast driven piles, respectively.

Additionally, the PAILE method allows the resistance of each expanded base pile to be measured during installation. As a result, the risk related to insufficient geotechnical capacity is minimised and the resistance is recorded for every single substructure. Advanced analytics can be performed on the multi-sensor installation data using Artificial Intelligence, hence the "AI" in the PAILE name.

By utilising proven, existing technology in a novel way, expanded base piles can be installed using smaller machinery, with higher productivity and less material than with traditional piling equipment.

1 INTRODUCTION

PAILE is a technique that allows the formation of concrete piles with enlarged and prestressed bases, in a single, continuous process. The motivation behind development and the principles of the technique have been described by Zakrzewski and Buttling (2022).



(a) The auger is screwed into the ground with the helices closed together, advancing like a corkscrew.

(b) Upon reaching design depth, the two helices are forced apart to form an enlarged base by displacing soil, and concrete is simultaneouly pumped in.

(c) Concrete is continued to be pumped in, as the auger is screwed out of the ground and pile shaft is formed.

Figure 1: Phases of PAILE foundation installation

The main components of the PAILE tooling, which enables the formation of the expanded base pile, are an external tube with one or more helical plates, an internal tube with a single helical plate at the bottom, and a mechanism that provides the thrust necessary to extend the tubes telescopically, thus displacing and prestressing the soil and form an enlarged base.

The construction sequence is conceptually shown in Figure 1. In the first phase of the construction sequence, as shown in Figure 1(a), the PAILE auger is screwed into the ground at pitch (i.e. like a corkscrew) with the helix closed.

Once the design depth is reached, the unique construction of the auger allows the creation of an enlarged base by pushing the lower part of the helix down against the reaction of the upper part, as illustrated in Figure 1(b). The diameter and height of the base are defined by the size of the helices and the telescopic movement of the parts, respectively. During the base forming phase, the bottom helix displaces and compacts soil underneath the pile base, which is equivalent to preloading the base of a pile to improve subsequent load/settlement performance, subject to the limit set by the available upward pressure.

While the base is being formed (Figure 1(b)), and while the auger is recovered from the ground (Figure 1(c)), concrete is pumped in such that there is no void. Once the hole is filled and the auger removed from the ground, reinforcement can be installed in a similar way to CFA piles.

The pile installation process can be further studied at http://paile.solutions. The technology described in this paper is patented and patent-pending.

2 FIELD LOAD TESTS

Following intensive small-scale tests and trials, the PAILE system was demonstrated in several locations in South-East Queensland.

The main objectives of the field trials were to:

- demonstrate that the process of installation of piles with enlarged bases called the PAILE method, can be successfully implemented at true scale and using conventional piling equipment;
- verify the performance of PAILEs under compression and tension loads in sandy soils; and
- provide the relationship between final static load tests and the Real-Time base resistance measurements recorded during installation

2.1 GROUND CONDITIONS

The site chosen for the first full scale trials was located in Hope Island, QLD, Australia. Prior to the works, three (3) Cone Penetration Tests (CPTu) were performed to assess the ground conditions (refer to Figure 2).

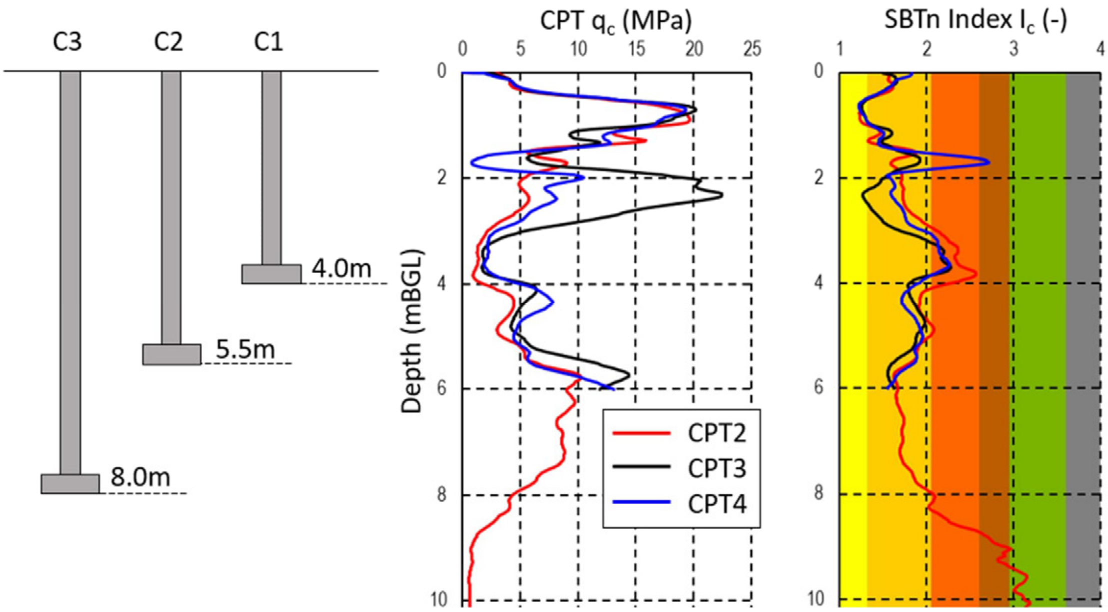


Figure 2: Test piles (left) vs plots of CPT cone resistance q_c in MPa (centre) and SBTn index Ic (right).

The following soil profile was inferred from the CPTs:

- Dredged Sand Fill, approximately 1.5m thick layer of medium dense to dense sand, underlain by
- Medium Dense Sands, extending to approximately 8.5m depth, with a layer of Loose Sand/Silt mixture at between 3.5m to 4m depth, underlain by
- Firm to Stiff Clay extending to the CPT termination depth at 20m.

2.2 DETAILS OF TEST PILES

The diameter of the PAILE tool displacement body was 270mm and the diameter of the helical plates was 650mm. The tool size translates to the resulting pile geometry base/shaft 650/270 with the diameter ratio D / d_s = 2.4.

The PAILE tool was fitted to a conventional 40t piling rig (refer to Figure 9 below) with a 165kNm torque capacity rotary head.

Out of 100+ installed piles across several trial sites and demonstration campaigns, three (3) were selected to discuss in this paper as the most representative for depths between 2m and 8m.

Figure 3: PAILE tool fitted to piling rig Comacchio CH450 with helical plates closed (left) and open (right).

2.1.1 Pile C1

Pile C1 was installed at 4m depth (refer to Figure 2) and instrumented with two vibrating wire strain gauges. One gauge was mounted approximately 1m above the base of the pile and the other at about 1m below the top of the pile.

A static compression load test was carried out 43 days after installation, following a procedure from AS2159:2009.

Results of the test are presented in Figure 4 below, where the black line denotes load vs settlement at pile head, while the blue dotted line denotes load vs settlement at pile base.

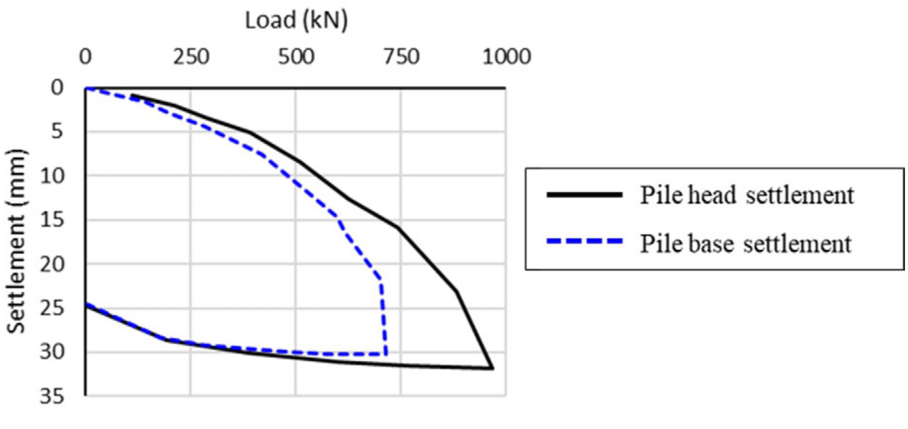


Figure 4: Results of static load test on pile C1.

Figure 5 presents a comparison of CPT cone resistance (red line) and soil yield stresses inferred from gathered data, where the dotted line denotes average q_c over distance +/-1.5 D from the pile base, x denotes soil yield stress measured during base formation and + denotes pile base yield stress from static test.

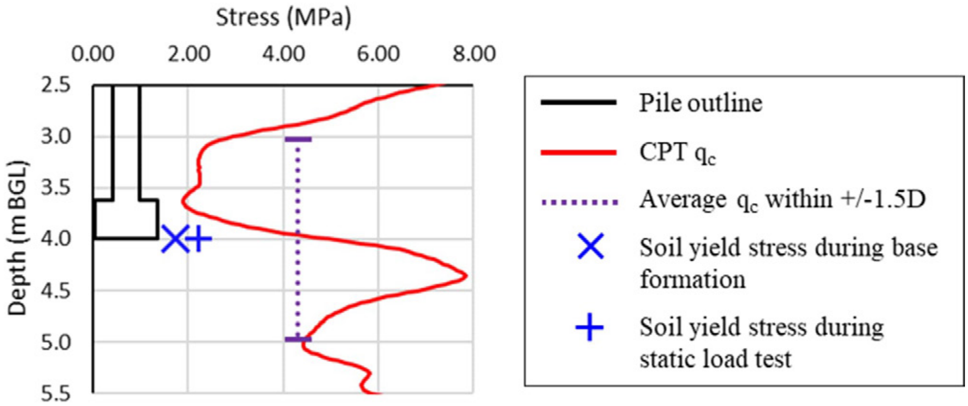


Figure 5: Comparison of stresses within pile C1 base zone of influence.

The following conclusions and observations have been drawn from the analysis of the construction records and static test data:

- The ratio of maximum base bearing stress measured during the test to the average CPT q_c is equal to q_b / q_{cavg} = 0.52. This value compares well with a base bearing factor typically recommended for the design of drilled displacement piles α_b = 0.50 (refer e.g. to Bustamante & Gianeselli (1982) or NF P94-262 (2012)).
- The maximum load at the pile base measured during the test was 713kN. Extrapolation of the base load vs settlement curve using the method proposed by Chin (1970, 1972), resulted in an inferred ultimate base resistance of 741kN. This load corresponded to a base yield pressure of 2234kPa.
- During the formation of the enlarged base, a total load of 451kN was measured. It was observed that, during the process, the upper helix moved upward, which was consistent with the location of the base with respect to the CPT q_c profile (refer to Figure 5). The soil yield stress during base formation was thus 1740kPa, marked by the x, while that measured in the test was 2234 kPa, marked by the +.
- The above observation shows that the soil resistance measured during the construction of the pile base provides a reasonably good indication of the pile base's ultimate resistance while being on the conservative side because it is limited by the available upwards stress.
- 95% of the base resistance was mobilised at a settlement corresponding to 3.3% of the base diameter. Typically, full mobilisation of pile base resistance in sandy soils occurs at settlements of 10% to 20% of base diameter. This observation confirms that the process of forming the pile base leads to stiffer load settlement behaviour and, as such, allows the base resistance to be better utilized at working load conditions.

2.1.2 Pile C2

Pile C2 was installed to a depth of 5.5m below the ground surface and a compression static load test was carried out 44 days later.

Figure 6 below presents the load/deflection curve as measured during the test, where solid black lines and dashed red lines denote load vs pile head settlement measured and predicted using LCPC2012 as per NF P94-262 (2012), respectively.

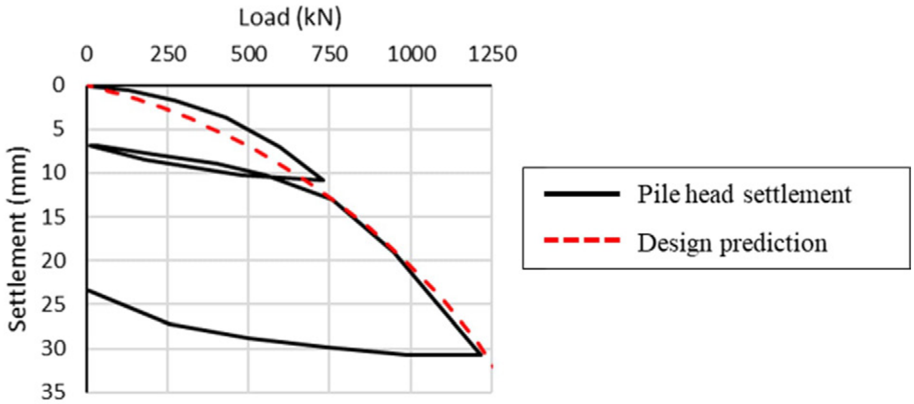


Figure 6: Results of static load test on pile C2.

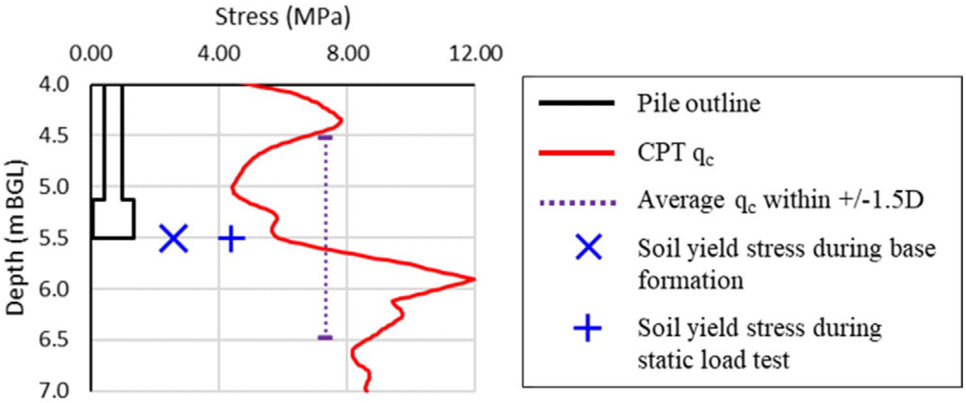


Figure 7: Comparison of yield stresses within pile C2 base zone of influence.

Figure 7 presents a comparison of soil yield stresses, where x denotes pressure measured during base formation, + denotes pile base yield pressure inferred from static test and the purple dotted line denotes average CPT q_c over depth +/-1.5 D from pile base. The following conclusions and observations have been drawn from the analysis of the construction records and static test data:

- The pile base ultimate resistance was predicted to be 3664kPa and 4226kPa, using LCPC1982 and LCPC2012 methods, respectively.
- Extrapolation of the pile total resistance using the method proposed by Chin (1970, 1972), resulted in an inferred ultimate pile resistance of 1941kN, which was 8% higher than predicted 1802kN using LCPC2012 method.
- The predicted load/deflection line (red dotted line) was calculated assuming pile base load transfer law as for precast driven piles, which offer the highest pile base stiffness. While the PAILE method uses a screwing process to penetrate the ground, the measured load settlement curve fits well with the prediction. It is suggested that this is probably due to the compaction of the soil under the pile during the base-forming stage.
- During the formation of the enlarged base, a total load of 703kN was measured. It was observed that, during the process, the upper helix again moved upward which was consistent with the location of the base with respect to the CPT q_c profile (refer to Figure 7). The soil yield stress during base formation was thus 2574kPa, marked with an **x**, while the base pressure inferred from the test was 4362 kPa, marked with a +.
- The observed load/settlement behaviour was slightly stiffer than predicted up to ~730 kN load, which corresponds well with the maximum force measured during the base formation process of 703 kN. This confirms that the process of forming the base leads to a stiffer load/settlement behaviour of the completed pile.
- The ratio of maximum base bearing stress inferred from the test to the average CPT q_c is equal to q_b / q_{cavg} = 0.60. This value is higher than the base bearing factor typically recommended for the design of

drilled displacement piles $\alpha_b = 0.50$, which is again consistent with the base having been preloaded during construction.

2.1.3 Pile C3

Pile C3 was drilled to a depth of 8m, and a static tension load test was carried out 45 days after installation.

During the base formation process, the bottom helical plate moved downward, thus increasing the pile depth to 8.4m.

Figure 8 below presents the load/deflection curve measured during the test.

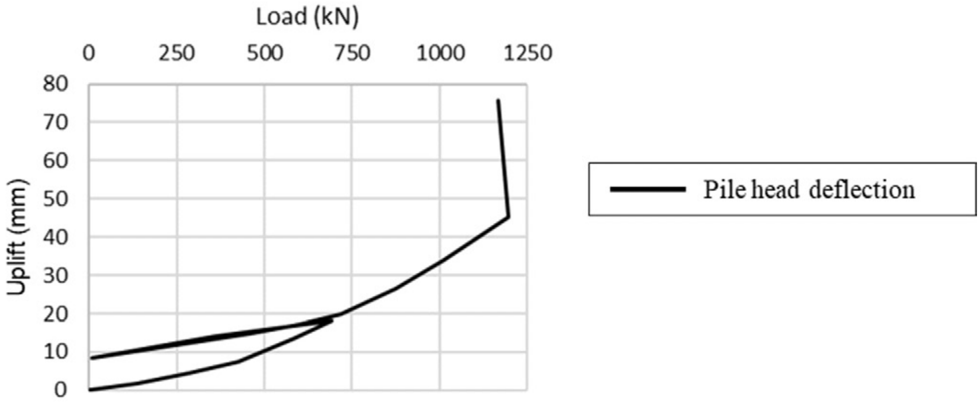


Figure 8: Results of static load test on pile C3.

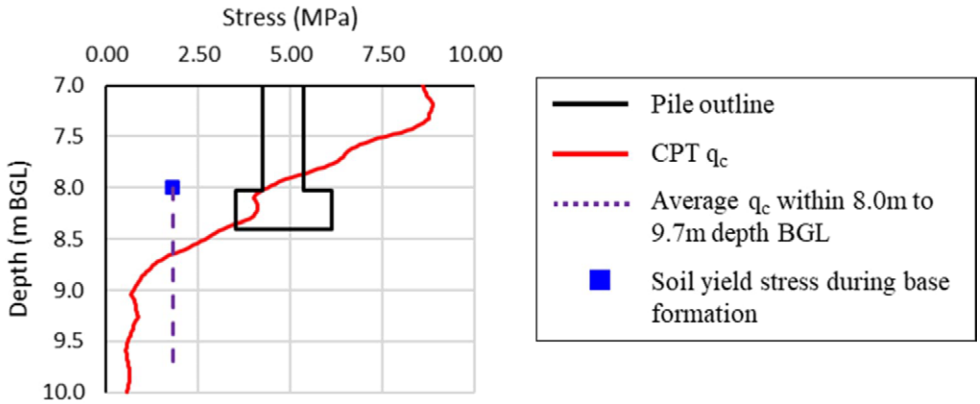


Figure 9: Comparison of yield stresses within pile C3 base zone of influence.

Figure 9 presents a comparison of CPT cone resistance (red line) and soil yield stresses inferred from gathered data, where the blue square denotes soil yield stress measured during base formation, the red line denotes CPT q_c and the purple dashed line denotes average CPT q_c within 2.66 D below the helical plate location at the start of the base formation process.:

The following conclusions and observations have been drawn from the analysis of the construction records and static test data:

- The total ultimate uplift resistance of the pile predicted using the nearest CPT data (located 10m away) was 1394kN.
- The maximum applied load during the test was approximately 1350kN after which geotechnical failure occurred.
- The maximum sustained load after the failure was 1195kN. Every attempt to increase the load above 1250kN resulted in the creeping of the pile.
- During the formation of the enlarged base, a total load of 600kN was measured. It was observed that, during the process, the bottom helix moved downward which was again consistent with the location of the base with respect to the CPT q_c profile (refer to Figure 9). The soil yield stress during base formation

was 1809kPa (relevant to the helix bottom surface), which corresponds to the average CPT q_c between depths of 8.0m and 9.7m (refer dashed purple line in Figure 9).

2.3 GEOMETRY VERIFICATION

Upon completion of static load tests, some of the piles of different testing campaigns have been excavated and recovered from the ground for inspection. Photos of piles fully recovered from the ground are shown in Figures 10 & 11.

Figure 10: PAILE formed in fill

Figure 11: PAILE formed in loose to medium dense sand

The following observations have been made during inspection of the piles:

- The piles were confirmed to have achieved the target geometry, i.e. shaft and base diameters corresponding to the PAILE tool displacement body and helical plates diameter, respectively. This clearly shows that it is possible to form an enlarged base using the PAILE method in a controlled manner. The resultant base dimensions are driven by the diameter and stroke of the helical plates and are therefore controllable.
- The pile shafts were solid and without any signs of contamination with soil, consistent with injecting concrete as the helix was expanded.

3 CONCLUSIONS

The method enables the installation of foundation piles with enlarged bases, of a range of capacities, at significantly reduced concrete volumes when compared with currently available piling techniques. Additionally, the mobilised base resistance of each pile installed via PAILE is measured and effectively verified during installation. Since the base capacity of a PAILE is typically 85% to 95% of the total capacity, the risk related to insufficient geotechnical capacity is significantly reduced. These quasi-static resistance measurements could be further aggregated across a project footprint and analysed to deliver a comprehensive site risk profile and enable further optimization/verification of the project design.

The full-scale field trials discussed in this paper confirmed that:

- The installation of a full-scale foundation pile with an enlarged and prestressed base using the PAILE method is practical and effective.
- The geometry of the installed piles has been confirmed to be in line with the design assumptions.
- Soil resistance measured during the construction of the pile base provides a reasonably good indication of the pile base ultimate resistance while being on the conservative side.
- The capacities measured during static tests have been shown to be slightly (~5%) higher than anticipated from the design.
- Data from the static tests indicate that the load settlement curves of the piles are stiffer up to the value of the load used to form the base. This confirms that the PAILE method of base formation leads to stiffer pile response and hence can offer better utilisation of pile resistance under working conditions.
- The ground disturbance above the base does not negatively impact the performance of compression piles.
- A base bearing factor of between α_b = 0.50 and 0.60 is considered suitable for the design of PAILE foundations in similar ground conditions.

In summary, some of the advantages offered by the PAILE technology include:

- High load/settlement stiffness due to preloading of the pile base
- Simple and continuous installation process in one pass
- Minimised ground heave due to high capacity-to-pile volume ratio
- No induced ground vibrations during pile installation
- Use of cost-effective building material (reinforced concrete)
- Requires comparatively small and manoeuvrable piling equipment

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CRediT authorship contribution statement

P. Adam Zakrzewski: Writing - original draft. **Stephen Buttling:** Writing – review & editing.

5 REFERENCES

AS 2159:2009 Australian Standard, A. S. 2159-2009 Piling-Design and Installation.

Bittar, E., Lehane, B. M., Blake, A., Richards, D., White, D., Mahdavi, S., & Cerfontaine, B. (2023). CPT-based design method for helical piles in sand. *Canadian Geotechnical Journal*, *61*(1), 102-117.

Bustamante, M, and L Gianeselli. (1982). Pile Bearing Capacity Prediction by Means of Static Penetrometer CPT. *Proceedings of the 2nd European Symposium on Penetration Testing*, 493–500.

Chin, F. K (1970). Estimation of the ultimate load of piles from tests not carried to failure. *Proceedings of the 2nd Southeast Asian Conference on Soil Engineering*, Singapore.

Chin, F. K (1972). The inverse slope as a prediction of ultimate bearing capacity of piles. *Proceedings of the 2nd Southeast Asian Conference on Soil Engineering*, 83-91.

NF P94-262 (2012). Justification of geotechnical work – National application standards for the implementation of Eurocode 7 – Deep foundations, AFNOR, Paris.

Zakrzewski, P. A. and Buttling, S. (2022). A novel ground Improvement and deep foundation system using PAILEs. Estimation of the ultimate load of piles from tests not carried to failure. DFI-PFSF Piling & Ground Improvement Conference, Sydney.