Pile Load Displacement Prediction by Using Non-linear Load Transfer Curves

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ABSTRACT: Instrumented pile load tests help geotechnical engineers to gain a better understanding of pile-soil behavior under a given load. There are several types of tests available, including static load tests (SLT) using kentledge as a reaction system, bi-directional static load tests (BDSLT), rapid load tests (RLT), and high-strain dynamic load tests (HSDPT). The selection of the appropriate test method depends on the pile type, geological formation, the test's purpose, and the availability of equipment and resources. Non-linear load transfer curves obtained from instrumented static load tests can be used to predict pile load displacement for working test pile and ensure that it falls within the allowable displacement criteria. For BDSLT on working test piles, it is crucial to ensure the correct placement of the sacrificial jacks in the pile. Thus, predictions by using load transfer analysis (T-Z mehod) can lower the possibility of early failure prior to reaching the required test load. This study compares the predicted and actual results of both SLT and BDSLT, revealing that the computed load displacement aligns with the actual field test results. Pile optimization by using the load transfer method is also presented in this paper. The simulation result shows that further optimization can be applied to the pile length with the pile settlement remains within the local specification pile settlement acceptance criteria.

KEYWORDS: Pile load test, Non-linear load transfer curve, Pile displacement prediction, and Sustainable construction.

1. INTRODUCTION

In general, the design of deep foundations relies on determining their capacity with an appropriate factor of safety. One commonly used approach is capacity-based design, which involves utilizing empirical correlations with Standard Penetration Test (SPT-N) data developed by Meyerhof in 1976. This method, combined with extensive local experiences, has proven successful in ensuring that piles settle well below the maximum allowable settlement. However, when pile load displacement analysis is not conducted, the design tends to be overly conservative, leading to unnecessary resource wastage.

Pile testing is frequently performed to evaluate the geotechnical capacity of a pile and verify its integrity. The conventional top-down static load test (SLT) is the most popular testing method, involving the use of concrete blocks or steel plates as a reaction system. One advantage of this method is that it provides direct measurements of pile head settlement. However, it is relatively expensive, not environmentally friendly, and raises safety concerns, especially when setting up the reaction system on soft soil, near residential areas, or along busy highways. Besides, this method may not be able to mobilize the pile socketed in granitic rock. Additionally, the reaction system itself can affect the load test results due to residual stresses acting on the pile during its setup and testing (Fakharian et al., 2014; Zhang et al., 2014).

Another commonly used static load test is the bi-directional static load test (BDSLT) or known as Osterberg Cell method (Osterberg, 1995; Schmertmann et al., 1997). This method involves using sacrificial jacks embedded in the pile to exert force in both upward and downward directions, simulating upper shaft friction against lower shaft resistance (lower shaft friction and end bearing), and vice versa. Compared to the conventional static load test, it is much safer and requires less space. Challenge lies with this method is the proper placement of sacrificial jacks. Without a thorough understanding of the ground conditions, premature failure due to incorrect jack placement often occurs, leading practitioners to lose confidence in using the BDSLT as an alternative to the conventional top-down static load test.

In this study, the focus is on presenting pile load displacement curves that are constructed based on load transfer (T-Z) method (Coyle and Reese, 1966; Poulos, 1989; Fellenius, 2023) by using site-specific load transfer curves (t-z and q-z curves) (Zhang et al., 2012; Setiawan and Rahardjo, 2019; Rachmayanti and Rahardjo, 2020) obtained from instrumented ultimate pile load tests. The simulation results are then compared to the actual measured pile load test results. Additionally, the study includes the simulation of both upward and downward displacements in BDSLT using the T-Z method. Furthermore, this paper discusses the construction of the equivalent top load (ETL) curve, which is achieved through the modified method proposed by Prof. Schmertmann (Seo et al., 2016) and compared to the load transfer approach.

2. PILE LOAD TEST

2.1 Pile information and instrumentation

This study focuses on three project sites characterized by different soil formations. Table 1 provides the test pile details for each site. All the piles described herein are bored cast in-situ piles with diameters range from 0.6m to 1.8m, constructed in wet by using polymer as stabilizing fluid. The construction process begins with the insertion of a temporary steel casing into the ground, which is done using an excavator-mounted hydraulic vibratory hammer. When dealing with piles in soil, a bored piling machine equipped with a drilling bucket and cleaning bucket is employed to remove the soil during the drilling process and clean the sediment from the pile base. In cases where the piles are socketed in sedimentary rock with low Rock Quality Designation (RQD), a bullet teeth core barrel is used for coring work. However, when encountering strong granite during the drilling process, a core barrel fitted with roller bits has proven to be the most efficient tool for coring the granite rock to the required depth. Cleaning the pile socketed in rock prior to the concreting process involves an additional step known as the air lifting method.

At Site A, there is one ultimate test pile and one working test pile, both socketed in moderately weathered granite with an average Rock Quality Designation (RQD) of 50%. Site B consists of one ultimate test pile and one working test piles founded in dense silty sand with Standard Penetration Test (SPT-N) values exceeding 100. For Site C, both ultimate and working test piles are tested by using BDSLT method. These piles are socketed in weak, highly weathered mudstone with an average RQD of 25%.

All ultimate test piles are instrumented with vibrating wire strain gauges at predetermined locations to assess the load distribution along the pile. In the case of the SLT method, three telltale rod extensometers are installed in the pile, with one fixed near to the pile toe to measure total pile compression and subsequently to be used to calculate the pile toe displacement.

Table 1 Test pile information

Site	Test Pile	Size	Pile Length	Test Method
A(RFS)	Ultimate	0.8 m	27.00 m	BDSLT
	Working	0.6 m	23.50m	SLT
B(Hill)	Ultimate	0.8 m	23.61 m	BDSLT
	Working	1.2 m	25.95 m	SLT
C (HC)	Ultimate	1.8 m	13.59 m	BDSLT
	Working	1.5 m	20.15 m	BDSLT

In BDSLT testing, a minimum of two telltale rod extensometers are installed on top of the top bearing plate to directly measure upper section pile compression. Two additional sets of telltale rods are fixed at the top of the bottom bearing plate and near the pile toe to measure bottom plate and pile toe displacement, respectively.

The top of the pile is measured directly using a digital survey level, as the use of the reference beam method is not recommended due to the potential of higher errors (Sinnreich and Simpson, 2009). The instrumentation schematic drawings and soil profiles for the ultimate test piles are presented in Figures 1, 2, and 3.

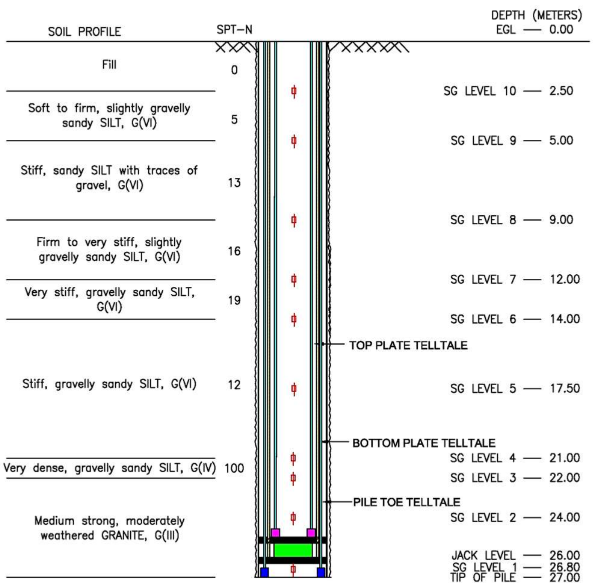

Figure 1 Site A ultimate load test schematic drawing

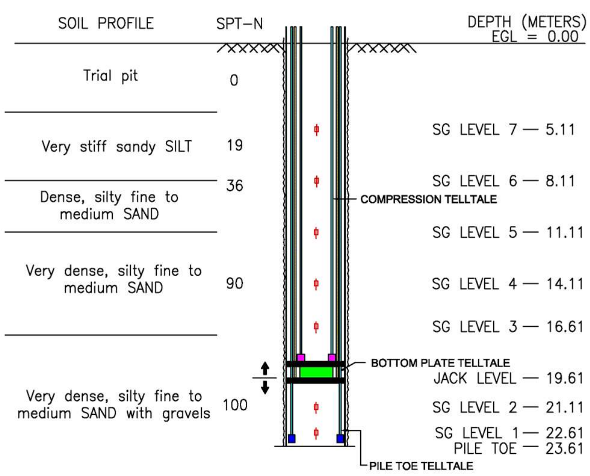

Figure 2 Site B ultimate load test schematic drawing

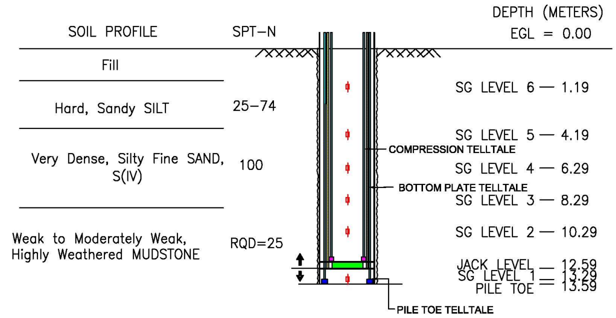

Figure 3 Site C ultimate load test schematic drawing

2.2 Initial pile design and ultimate load test result

The modified Meyerhof approach based on SPT-N is widely used by most of the consultants in Singapore and Malaysia. This method relates the SPT-N values obtained from the standard penetration test to shaft friction (f_s) and end bearing resistance (q_b) as shown in Eq. (1) and Eq. (2) below.

$$f_s = K_s \, N \tag{1}$$

where N is the SPT-N value and K_s is the coefficient factor of shaft friction

$$q_b = K_b \, N \tag{2}$$

where N is the SPT-N value and K_b is the coefficient factor of end bearing.

However, this method does not take into consideration of the displacement required to achieve the target capacity. Initial design soil parameters for the shaft friction and end bearing resistance of the ultimate test pile are presented in Table 2.

Table 2 Initial design soil parameters

Site	Soil Description	f_s (kPa)	q_b (kPa)
A	Soil	K_s =2.5	-
	Granite G(III)	400	9,000
B	Soil N<100	K_s =2.5	
	Soil N>100	K_s =2.5	6,000
C	Soil N<100	K_s =2.0	
	Mudstone	350	6,000

Ultimate test pile load displacement curves are presented in Figure 4, Figure 5 and Figure 6. The load transfer curves established from three ultimate load tests are presented in Figure 7 to Figure 12. For Site A, the test pile is not fully mobilized especially on the shaft friction. The achieved end bearing capacity is 10,820 kPa with approximately 1.5 mm toe displacement. Maximum shaft friction achieved in granite is approximately 600kPa with segment displacement of 4.1 mm. To mobilize the rock friction, it is often required to have a displacement of 15-20mm (Ayithi and Ryan, 2019). Hence, the 600kPa achieved is still far from the ultimate capacity. As the shaft friction capacity is not proven during the ultimate load test, the adopted parameter for granite is capped at 600kPa. For end bearing, the adopted parameter is also capped at 10,000kPa as based on the local specification, the pile base is required to be grouted if the adopted parameter for end bearing is larger than 10,000kPa. Site B ultimate load test results shows upper shaft friction is close to ultimate value with maximum shaft friction is 3 to 3.3N for soil with SPT-N equal or more than 100. The end bearing displacement is tested beyond 10% of the pile diameter. For Site C, upper friction is approaching ultimate values and the pile end bearing is mobilized adequately for load transfer analysis.

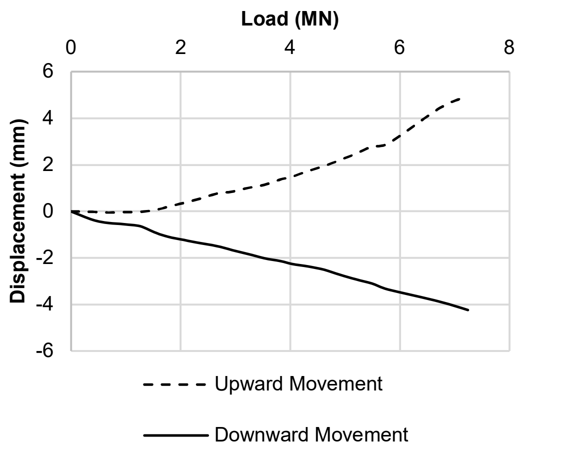

Figure 4 Site A Ultimate test pile load displacement curve

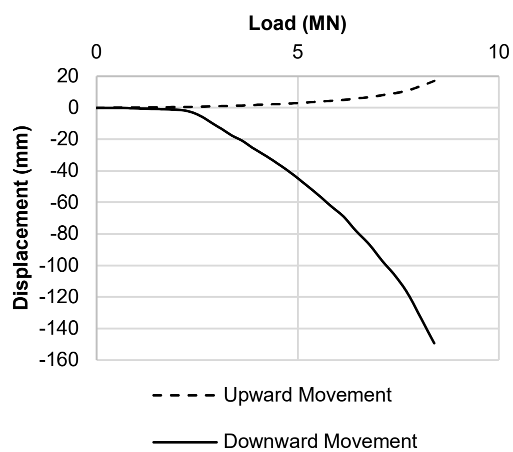

Figure 5 Site B Ultimate test pile load displacement curve

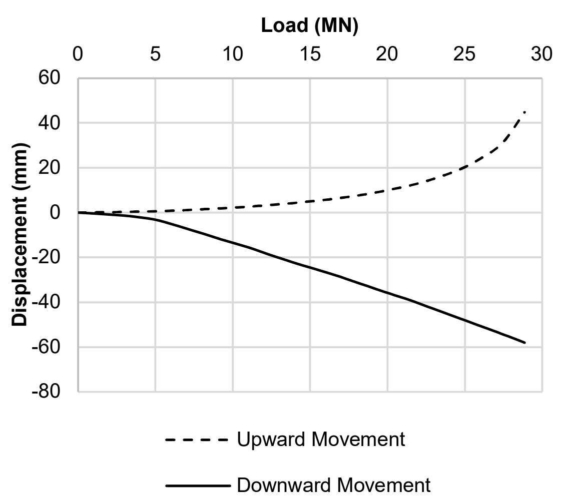

Figure 6 Site C Ultimate test pile load displacement curve

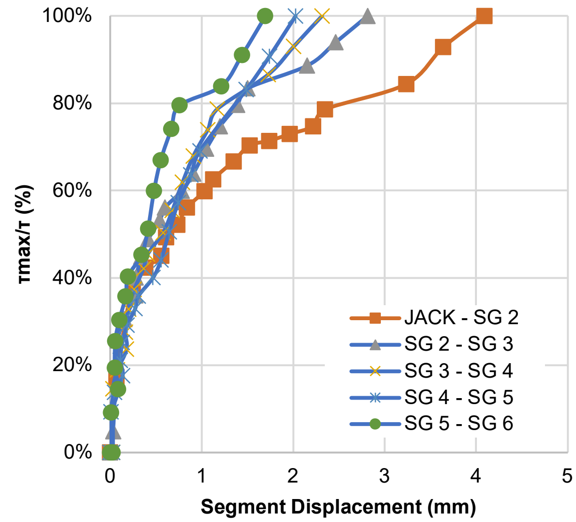

Figure 7 Site A t-z curves

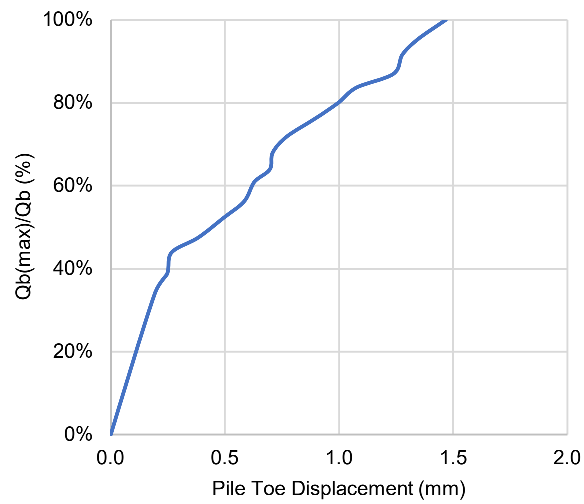

Figure 8 Site A q-z curve

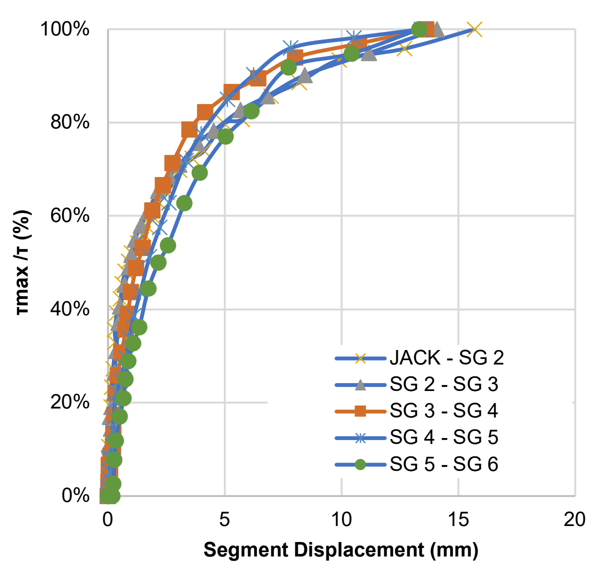

Figure 9 Site B t-z curves

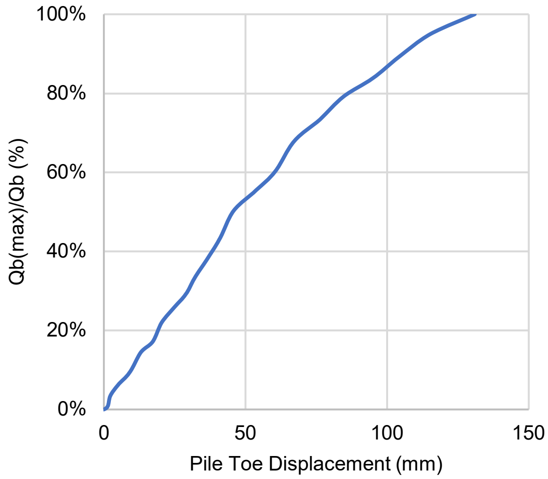

Figure 10 Site B q-z curve

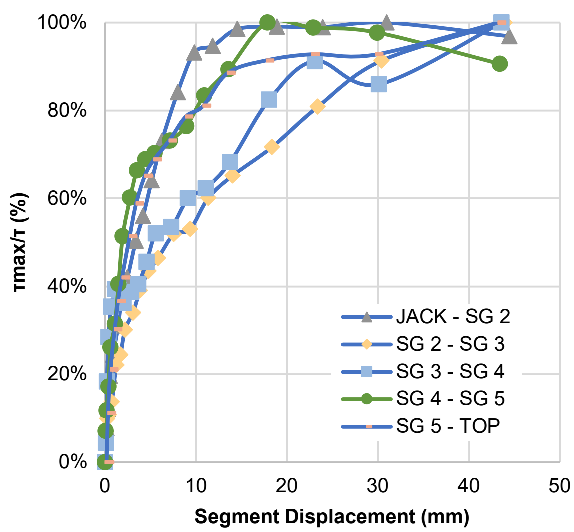

Figure 11 Site C t-z curves

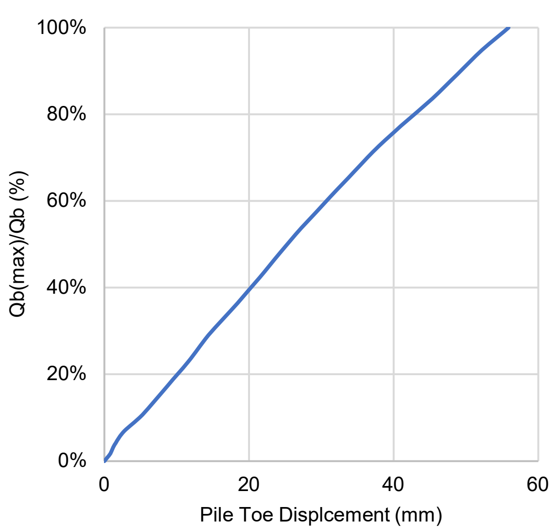

Figure 12 Site C q-z curve

3. NON-LINEAR LOAD TRANSFER (T-Z) METHOD

The T-Z method, also known as the load-transfer method, is widely used for analyzing piles subjected to axial loads. It is particularly useful when dealing with non-linear soil behavior or stratified soil conditions around the pile. This method involves considering the pile as a series of elements supported by discrete nonlinear springs, representing soil resistance. T-z springs represent skin friction, while a nonlinear Q-z spring at the pile tip represents end-bearing resistance. The springs illustrate the nonlinearity of soil reaction by plotting resistance (T or Q) against displacement (z), as shown in Figure 13.

When predicting load displacement for a working pile, it is recommended to use site-specific load transfer curves obtained from the instrumented ultimate test piles. Figures 14, 15, and 16 show the soil profile, length, and SPT-N or RQD values of the three working test piles at different sites. For each working pile load test, site specific load transfer curves (t-z and q-z) are selected based on the soil profile and the maximum parameter for the particular soil is limited to the "adopted" parameter stated in Table 3. The T-Z method allows for simulation of the non-linear stress strain behaviour in soil with the pile capacity computed at each iteration based on the solved displacement values.

The concrete elastic modulus (*Ec)* is estimated by using the American Concrete Institute (ACI) 318-14 equation expressed below.

$$Ec = 0.043 * Wc^{1.5} * \sqrt{f'c} \quad (3)$$

Where *Wc* is concrete unit weight, and f'c is concrete compressive strength. The concrete mix specified for all three project sites are grade 40, having a minimum crushing strength of 40 MPa at 28 days. Hence, the concrete elastic modulus adopted in the simulation analysis is assumed to be 28600 MPa.

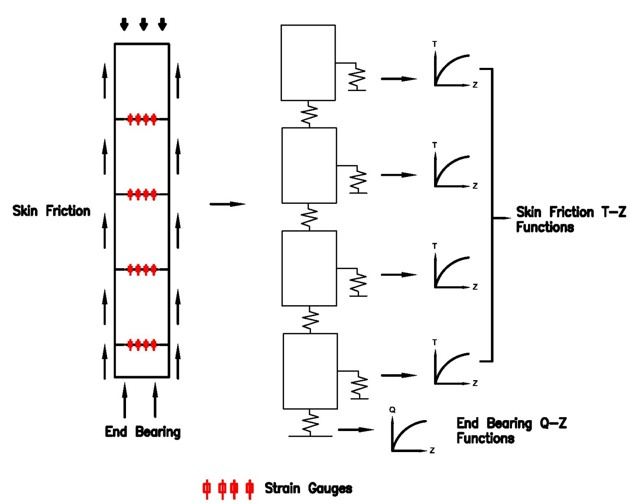

Figure 13 Load Transfer (T-Z) Analyses Model

Table 3 Achieved & adopted soil parameters

Site	Soil Description	f_s (kPa)	q_b (kPa)	Adopted f_s & q_b (kPa)
A	Soil	K_s =2.5-2.9	-	K_s =2.5
	G(III)	600	10,820	600, 10,000
B	Soil N<100	K_s =2.3-2.7		K_s =2.5
	Soil N=>100	K_s =3.0-3.3	10,229	K_s =2.5, 6,000
C	Soil N<100	K_s =2.0	-	K_s =2.5N
	Mudstone	550-830	10,197	500, 9,000

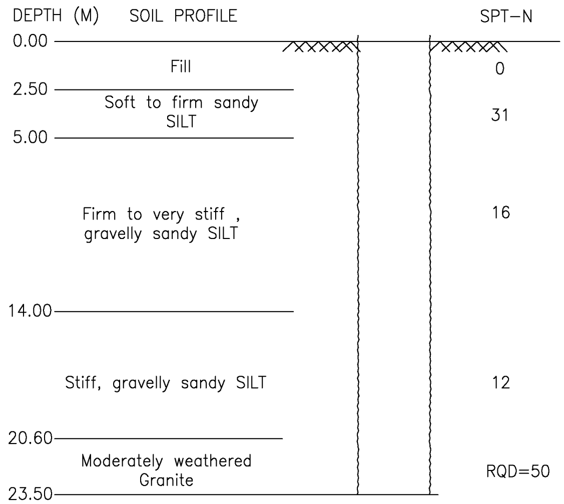

Figure 14 Site A WLT schematic drawing

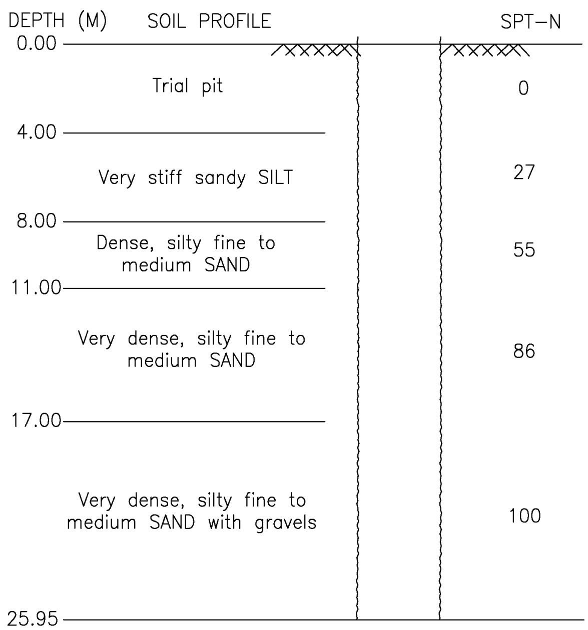

Figure 15 Site B WLT1 schematic drawing

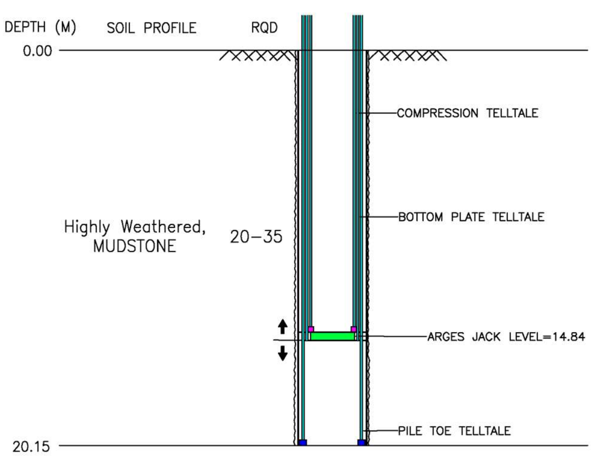

Figure 16 Site C WLT schematic drawing

4. RESULTS AND DISCUSSION

4.1 Comparison between simulation and actual result

Comparison between the simulated test results based on the T-Z method and the actual test results for the working pile at Site A is presented in Figure 17. The results indicate that the calculated pile head displacement is slightly greater than the measured test result. This could be attributed to the relatively conservative adoption of soil parameters, as the ultimate test pile is not fully mobilized. The results also suggested that further optimization of the pile length can be applied to the working piles. For Site B, WLT1 exhibits excellent agreement between the simulation result and the actual test result as shown in Figure 18. The load transfer curves obtained from the ultimate load test closely approach their ultimate values. Hence, the simulation using the load transfer method demonstrates higher accuracy and reliability. Likewise, for Site C, the ultimate test pile conducted using the BDSLT method successfully mobilizes the pile. As a result, the load transfer curve used in the simulation provides better prediction of the upward and downward displacements for the working load test. Figure 19 presents the prediction result and actual test result. From Figure 20, relationship between predicted displacement and measured displacement shows high level of correlation.

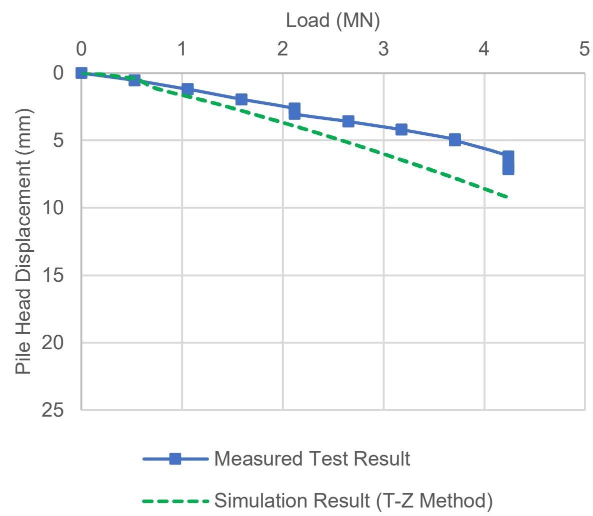

Figure 17 Comparison of result for Site A WLT1

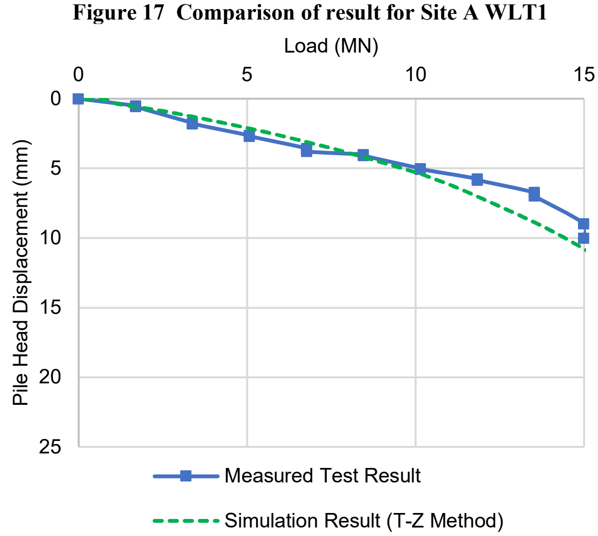

Figure 18 Comparison of result for Site B WLT1

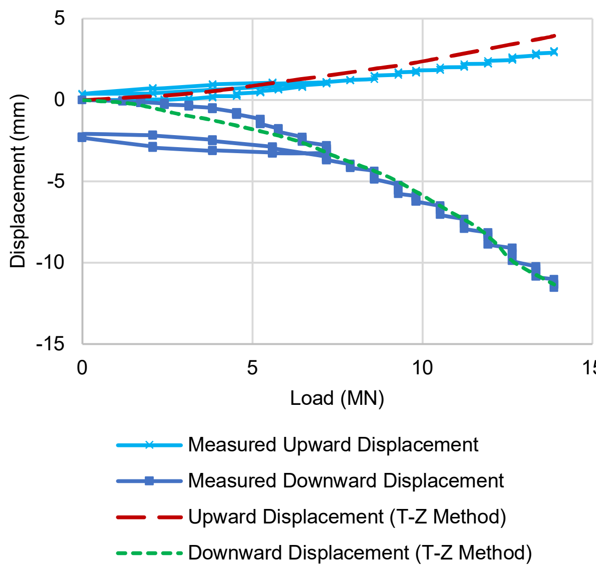

Figure 19 Comparison of result for Site C WLT1

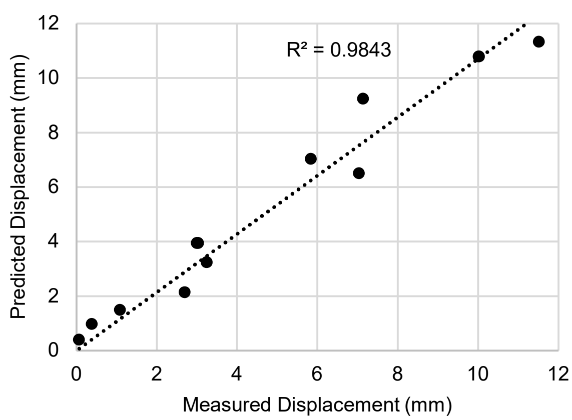

Figure 20 Predicted versus measured displacement

4.2 Equivalent top load displacement curve

While concerns regarding the reliability of the Equivalent Top Loading curve (ETL) constructed from the upward and downward displacement of the BDSLT have been raised, Seo et al., (2016) conducted a review of the original method (Osterberg, 1995), modified method by Schmertmann and load-transfer curve method (Coyle and Reese, 1966). It is concluded that the modified ETL method and load-transfer ETL method exhibited good agreement with the measured top-down load displacement response. Due to the challenges and expenses associated with conducting a direct side-by-side comparison of BDSLT tests, the t-z and q-z curves derived from the ultimate test pile were utilized to simulate and match the upward and downward displacement observed in the results of the Site C working test pile WLT1, as depicted in Figure 21. Subsequently, ETL curves were constructed using the load transfer method and compared to ETL curves constructed using the Schmertmann modified method. Figure 22 illustrates that the difference between the two ETL curves is not significant and, in fact, shows reasonably good agreement.

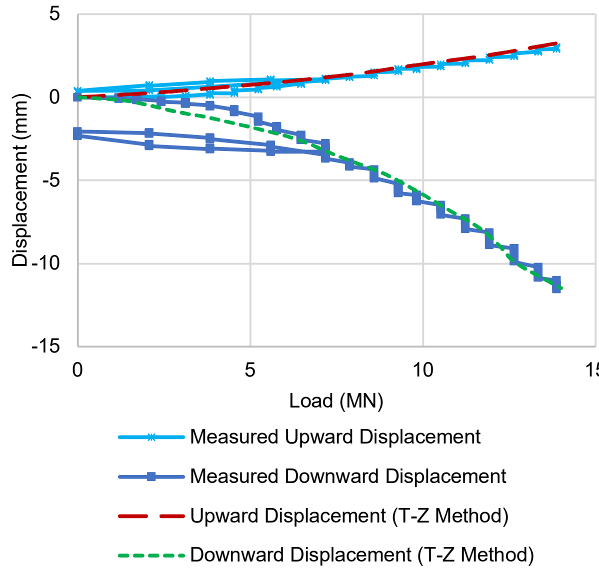

Figure 21 Matching result for Site C WLT1

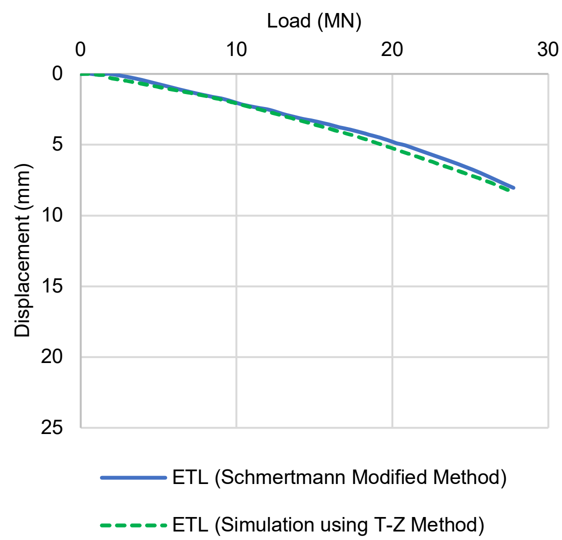

Figure 22 Comparison of ETL for Site C WLT1

4.3 Pile optimization

The construction sector holds a significant responsibility in promoting sustainability due to its substantial resource consumption and contribution to pollution, making it one of the major contributors to both aspects on a global scale. Hence, it is utmost important to ensure that the foundation design is optimized to reduce the wastage while maintaining the safety of the structure (Oh & Mohamad Ismail, 2023)

Measured pile head displacement simulated pile head displacement of different pile lengths for Site B WLT is shown in Figure 23 and Figure 24. It is clearly demonstrated that actual pile design is overly conservative and further optimization can be applied on this pile. Based on the local specification pile settlement acceptance criteria of 25mm at 2 times working load, the pile length could be optimized to 20m with 3m embedded into SPT-N 100 soil.

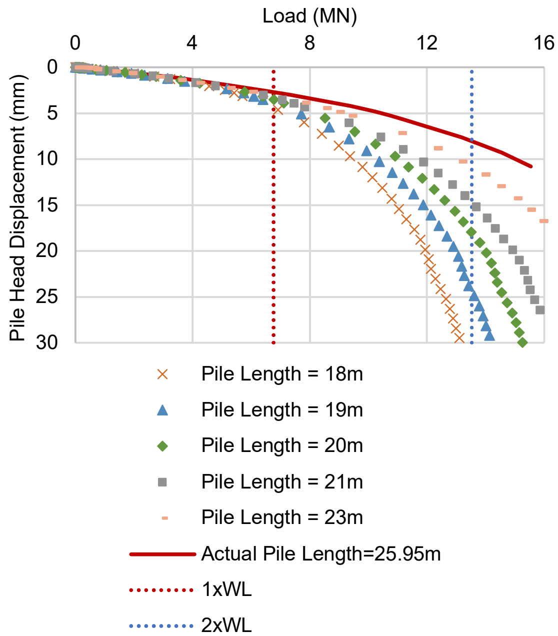

Figure 23 Pile optimization

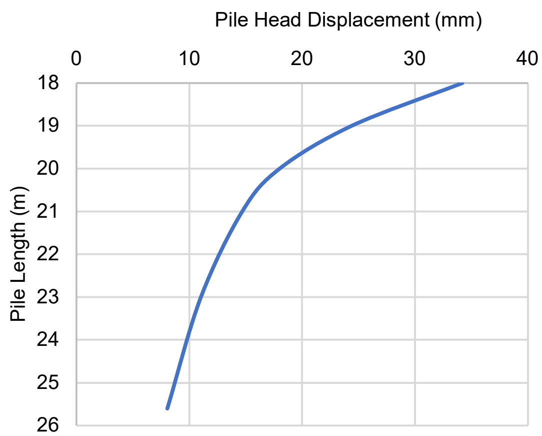

Figure 24 Pile head displacement versus pile length (at 2 x WL)

5. CONCLUSIONS

A well-executed pile testing program holds significant importance in the context of a piled foundation. With the implementation of pile instrumentation, valuable data can be obtained to facilitate further analysis and optimize the length of the piles. This study presents a practical approach to simulate the pile load displacement curve by utilizing t-z and q-z nonlinear load transfer curves. By comparing the results, it is evident that the simulation using the T-Z method aligns well with the actual site pile load test results. This indicates that the adopted t-z and q-z curves are suitable for modelling the remaining working piles and facilitate additional optimization of the pile design. This instils confidence among practitioners that the design is adequate and safe for implementation on-Site.

BDSLT is an excellent alternative method to replace conventional static load test. It can provide a lot more useful data for foundation design, particularly on rock socketed pile. The issue of premature failure and excessive extrapolation on the load test data due to incorrect placement of sacrificial jack location can be solved by carrying out a test simulation using site/soil specific load transfer curves. When optimizing pile length, it is recommended to conduct test simulations using site-specific t-z and q-z curves, as construction-induced variability can impact pile performance.

Different piling contractors have their own unique procedures for constructing piles. To ensure consistency and reliability of the adopted t-z and q-z curves in the analysis, it is important that the piles are constructed by the same contractor using identical drilling tools, stabilizing fluid, and pile cleaning method.

For rock socketed piles, maintaining the cleanliness of the pile base is particularly critical as it directly influences the pile's end bearing capacity particularly the adoption of the q-z curve in the simulation. To address this concern, additional pile cleaning should be performed using the air lifting method. The cleanliness of the pile base can be quantitatively inspected using devices such as SQUID developed by Pile Dynamic Inc. or Sediment Probe by Wuhan Sinorock Technology Co., Ltd. This meticulous approach to pile construction and testing is especially important for piles that heavily rely on their end bearing capacity to ensure reliable simulation resultsPile design encompasses the analysis of geotechnical capacity and settlement.

Additional research can be conducted to gather t-z curves and q-z curves for various types of soil. The gathered data can then be utilized to simulate the load displacement behavior of the ultimate test pile. By adopting this method, there is a greater likelihood of fully mobilizing the ultimate test pile and obtaining accurate values for the ultimate shaft friction and maximum end bearing capacity. By accumulating a substantial database and implementing artificial intelligence and machine learning techniques, geotechnical engineers can enhance the precision, safety, and efficiency in foundation design. This approach empowers engineers to make informed decisions and improvements in their designs based on a wealth of data and advanced computational methods.

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