Analysis of the Taipei MRT Circular Line Pile Load Test: A Case Study and Prospective Developments

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ABSTRACT

This paper presents a comprehensive study on the pile load test results of the Taipei MRT Circular Line Project. The objective is to evaluate the performance and load-bearing capacity of the tested piles. The study analyzes two critical load test results: a compression load test to assess structural integrity and a tension load test to evaluate resistance to tensile forces. The analysis of these tests provides valuable insights into the behavior and performance of the pile foundation under different loading conditions. Such information is crucial for ensuring the stability and longevity of the Taipei MRT Circular Line infrastructure.

Furthermore, this paper outlines future research directions aimed at enhancing the understanding and prediction of pile foundation behavior. One direction involves developing a prediction model using multivariate regression techniques to improve accuracy and reliability in predicting pile performance in similar projects. The findings of this study and the proposed research directions have significant implications for the design and construction of pile foundations in urban transportation infrastructure projects.

Advancing the understanding of pile foundation behavior through this research contributes to the optimization and refinement of foundation design processes. Ultimately, this work seeks to enhance the overall safety, durability, and efficiency of urban transportation systems, benefiting both commuters and city planners. By incorporating the lessons learned from the analysis of load test results, future projects can make informed decisions about pile foundation design, ensuring the structural integrity and longevity of critical infrastructure.

KEYWORDS: pile load test, performance evaluation, load-bearing capacity, pile foundation behavior, prediction model, urban transportation infrastructure

1. Introduction

Drilled shafts, often referred to as bored piles, drilled piers, or caissons, serve as deep foundations with substantial load-bearing capabilities, widely chosen for their strength and versatile design possibilities. Compared to other foundation options, their construction is known for being straightforward. This adaptability empowers engineers to customize shafts to penetrate into underlying rock formations, thus providing superior load-bearing capacity for superstructures. This adaptability is particularly crucial to meet the escalating demand for robust foundation systems, which is driven by the global surge in constructing high-rise buildings for a multitude of applications. Given limited available land, high-rises are increasingly constructed to optimize land use, necessitating deep foundations to manage the weight loads. As the demand rises for drilled shafts socketed into sturdy strata, engineers grapple with the challenge of maximizing both load capacity and strata resistance. This has spurred extensive research into rock behavior and its capacity to withstand superstructure loads supported by drilled shafts. On-site load tests offer vital insights into diverse rock interactions with drilled shafts, aiding in site-specific design adjustments. However, the expense of load tests can be a deterrent, significantly impacting project costs. Consequently, this study seeks to mitigate these challenges, striving to reduce costs while adeptly handling uncertainties. Through a comprehensive analysis of drilled shaft load tests encompassing compression and tension forces, the research aims to unravel the intricate behavior of these test shafts. This exploration is poised to be invaluable to designers and engineers, particularly in cases akin to this case history, providing insights that balance cost-effectiveness and structural reliability.

The Taipei city government’s Department of Rapid Transit Systems (DORTS) planned to undertake the construction of the first phase of the Circular Line Project (CF660B) on the route from Banqiao, New Taipei City (along the North River Road) to Dahanshi and Xinzhuang Siyuan Road. This was spearheaded by the Taipei city government’s DORTS for New Taipei city which sought out the expertise of Moh and Associates, Inc. for this project under the design services. One of the requirements of the project is the commencement of pile load tests. These tests entail employing monitoring systems to evaluate the performance of the pile foundations and conducting integrity tests to ensure the overall quality of the pile construction.

The objective of this study is to evaluate the behavior of two load test results (compression and tension) obtained from the site and determine the load-carrying capacity of these test piles through the utilization of various available interpretation methods. The outcomes of this interpretation will be compared and assessed to assist future designers in determining the suitability and reliability of these interpretation methods for similar case studies. Furthermore, this paper presents future research directions aimed at advancing the understanding and prediction of pile foundation behavior. This includes the development of a prediction model using multivariate regression techniques to enhance the accuracy and dependability of predicting pile performance in comparable projects. The findings of this study and the proposed research directions have significant implications for the design and construction of pile foundations in urban transportation infrastructure projects.

2. Interpretation methods

Pile load tests are typically carried out to validate the design of a foundation and serve as a basis for evaluating the predicted capacity derived from analytical models. These tests are crucial for ensuring the safety of the design and accounting for factors that may not have been considered during the initial design concept. Consequently, it is essential to have a comprehensive understanding of the generalized load-displacement behavior of a specific foundation system and interpret the results of load tests consistently and logically.

The load-displacement curves obtained from axial load tests on deep foundations can exhibit three different shapes, as illustrated in Figure 1 (Hirany and Kulhawy, 1988, 2002). Curve A's peak value and curve B's asymptote value clearly define the maximum load resistance or capacity of the foundation. However, when the load-displacement curve resembles curve C, the maximum resistance of the foundation is not distinctly defined. This particular curve shape is often observed in load-displacement curves of drilled shafts.

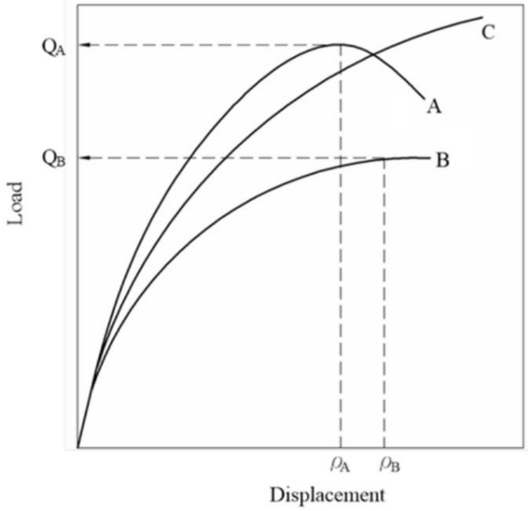


Figure 1. Typical load–displacement curves for drilled shafts under axial compression

A wide range of methods (van der Veen, 1953; Terzaghi and Peck, 1967; Chin, 1970; DeBeer, 1970; Fuller and Hoy, 1970; Davisson, 1972; O'Rourke and Kulhawy, 1985; Hirany and Kulhawy, 1988, 1989, 2002) can be found in the literature for interpreting the results of axial compression load tests. However, there are relatively fewer methods available for interpreting axial uplift load tests. Many of these methods rely on the experience and judgment of the proponents and do not fully meet the requirements of a widely accepted interpretation method (Hirany and Kulhawy, 1988). Detailed evaluations and discussions of potential limitations associated with each method can be found elsewhere (Hirany and Kulhawy, 1988, 1989). It is recommended to use the term "interpreted failure load" instead of "ultimate capacity" to indicate that the load has been derived from test results, as the latter lacks a universally accepted definition and should be avoided (Chen, 2004).

The interpretation methods are summarized in Table 1 and are examined in detail to assess their relative merits and interrelationships for the studied case. The interpreted results are then compared statistically.

3. New Taipei City MRT Circular Line Pile Load Test

This study was based on the Ultimate Load Test Report written in 2013. The location for the test in this project is approximately on the east side of the Dahan Bridge, which connects Xinzhuang District and Banqiao District in New Taipei City. It is situated on the floodplain near the Banqiao end, between PIER P16-25 and P16-26, with the Huanhe Road to the south as seen in Figure 2. Based on the geological investigation data provided by the project party, the depth of the gravel layer in this project is approximately below the ground surface at 55.8 meters. Above the gravel layer, there are predominantly sand and clay layers that make up the general soil layers. Within the maximum drilling depth (60.8 meters), the layers can be divided into nine levels, approximately as described in Table 2.

Table 1. Representative compression and uplift interpretation criteria for drilled shafts

Method	Definition of interpreted capacity, Q
Chin (1970)	Load is equal to inverse slope, 1/m, of line $\rho/L = m\rho + c$ with L = load and ρ = total settlement.
DeBeer (1970)	Load occurs at which change in slope on log-log total settlement curve.
%B	The load that occurs at specific settlements based on the percentage of the diameter of the shaft, B.
Terzaghi and Peck (1967)	Load occurs at 1.0 in (25.4 mm) of the total settlement.
L_1 - L_2 (1988)	L_1 and L_2 designate the elastic limit and failure threshold, respectively. Failure is defined qualitatively as the load beyond which a small increase in load produces a significant increase in displacement.
Slope-tangent (1985)	Load occurs at a displacement equal to the initial slope of the load-displacement plus 0.15 in (3.8 mm) + B (in mm)/120, in which B = shaft diameter.
Davisson (1972)	Load occurs at a displacement equal to the pile elastic compression line, PL/AE, plus 0.15 in (3.8 mm) + B (in mm)/120, in which P = load, L = depth, A = cross-sectional area, E = Young's modulus, B = shaft diameter.

(a) (b)

Figure 2. (a) Load test map location (b) load test site

Table 2. Summary of soil layer

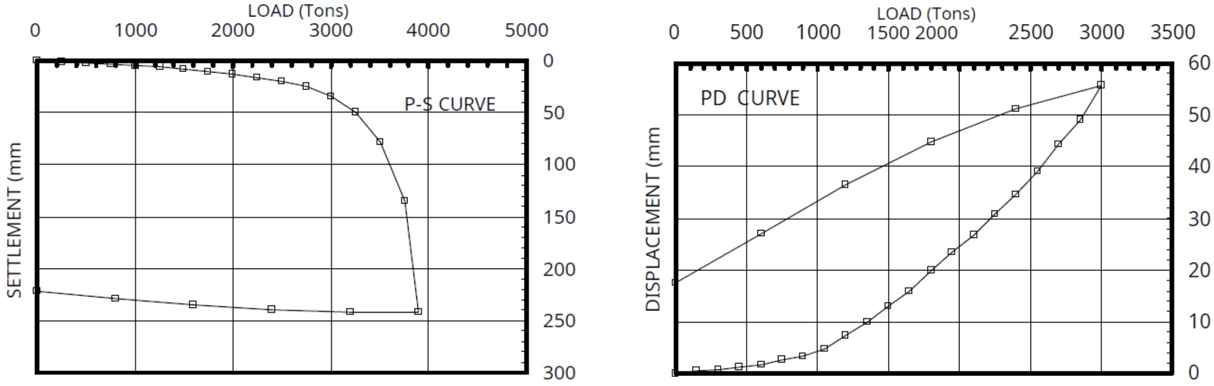
Layer	Soil layer	Depth(m)	N-value (average)
1	Backfill layer	6.3	5~14(8.7)
2	Silty fine sand layer (SM)	14.7	13~16(14.6)
3	Clayey silt layer (CL)	20.4	6~9(7.5)
4	Silty fine sand layer (SM)	30.2	26-38(32.7)
5	Clayey silt layer (CL)	34.3	13 (13)
6	Silty fine sand layer (SM)	45.6	21-35(28.9)
7	Clayey silt layer (CL)	52.3	15~18(16.3)
8	Silty fine sand layer (SM)	55.8	28~40(35.7)
9	Gravel layer with fine sand (GM)	60.8	>100

In addition to the soil layer data, the pile properties are also presented as seen in Table 3. The preliminary load tests for this project were carried out at the construction site. The tests consisted of one set for measuring resistance to tension and another set for measuring resistance to compression. The expected load capacity for the tests is approximately 5000 tons for compression and 3000 tons for tension.

Table 3. Test pile properties

Pile	Diameter (m)	Length (m)	Pile top elev.	Pile bottom elev.	Design test load (tons)	Actual test load (tons)	Gravel socket (m)	Test type
TPC	1.5	60.4	0.6	-59.8	5000	3900	3.0	Compression
TPT	1.5	59.8	0.0	-59.8	3000	3000	3.0	Tension

Besides test pile and soil properties, Figure 3 displays load test outcomes for compression and tension. The load-displacement curve holds significance in pile foundation engineering for multiple reasons. It aids in establishing ultimate capacity and load transfer efficiency to the soil. The curve forecasts pile behavior across various load levels, facilitating assessments of elasticity, plasticity, and failure. This curve validates design assumptions, evaluates pile integrity during construction, and monitors long-term performance. Analysis of the curve guarantees stability and reliability of pile foundations.



(a) (b)

Figure 3. Load–displacement curve for (a) compression and (b) tension load tests

4. Interpretation results

The results of the interpretation methods are presented in Table 4. These results are based on the procedures presented in Table 1 applied to the load-displacement curves from the load test results. It can be seen that the compression test produced higher interpreted loads compared to that of the tension test. The results of the L_1 method are 19,000 kN (1,937 tons) for compression and 13,295 kN (1,355 tons) for tension. The displacement can also be seen to be less in tension than its compression counterpart. This method is recommended for loads at the serviceability of the pile. In comparison to the design load for serviceability, the interpreted service load is greater than but in the same range than the design service load (1,400 tons for compression and 920 tons for tension which are 50% of the design maximum load which are more conservative from the actual results) which makes this interpretation method the recommended method for serviceability.

For the ultimate limit state, interpreted ultimate loads are typically within the 50–70 mm displacement range using Davisson and L_2 interpretations, which are the recommended methods for this state. To ensure maximum ultimate load, suggested design loads are 32,000 to 35,000 kN for compression and 25,000 to 27,000 kN for tension. Other methods fall within the transition region of the load-displacement curve, suitable for conservative design considerations. Chin's method yields the highest interpretation due to its hyperbolic curve asymptote interpretation; use it cautiously in design.

Table 4. Interpretation results for compression and tension load tests

Interpretation Method	Compression		Tension	
	Measured Load (kN)	Displacement (mm)	Measured Load (kN)	Displacement (mm)
L_1	19000	12.6	13295	8.0
L_2	34500	78.2	25300	38.0
Davisson	32400	55.3	27000	51.4
Slope-tangent	28800	34.5	23000	26.8
Terzaghi & Peck	26033	25.4	22606	25.4
DeBeer	26000	25.3	22500	25.0
3%B	30931	45.0	26293	45.0
4%B	32939	60.0	27760	60.0
5%B	34274	75.0	28721	75.0
Chin	40906	>100	33340	>100

5. Future developments for pile behaviour analysis

Understanding pile behavior is vital, yet load tests for site-specific understanding incur extra costs. To counter this, prediction models have emerged from similar load test data, aiding design and construction. Researchers have compiled axial load test databases for drilled shafts, including data relevant to design (Long and Shimel, 1989; Wysockey and Long, 1994; Chen and Kulhawy, 1994; Marcos et al., 2012; Tang et al., 2019; Topacio et al., 2023). Sharing these databases broadly is key. Phoon et al. (2019) deem these as big indirect data (BID), vital in data-centric geotechnics (Phoon et al., 2022), emphasizing the importance of data infrastructure alongside physical infrastructure. Load test analysis aims to construct regression prediction models for efficient pile foundation design by systematically evaluating structure behavior under controlled loads. This process forms a robust dataset, enabling the creation of quantitative frameworks for estimating pile response. Statistical techniques establish correlations between parameters and performance. Designers input project details to foresee foundation behavior, enhancing decision-making. Machine learning and neural networks further refine model development by uncovering hidden patterns and improving correlations between load tests and soil/rock parameters, ultimately enhancing pile capacity predictions. Examples of such databases are listed in Table 5 (Chen et al., 2023).

This on-going research's ultimate goal is to gather extensive data for a robust database akin to Table 5. Through this dataset, the prediction models will offer refined estimations of pile capacities, enhancing structural assessments. The resulting database provides two key advantages: (1) it forms a targeted repository from the company's projects in Taiwan, offering precise insights into local scenarios; (2) it shapes prediction models for specific project use, reducing construction costs by circumventing load tests. This database will underpin advanced machine learning methods like multivariate regression for improved prediction models. These models derive from a thorough analysis of the company's case histories. The process involves:

1. Data Collection and Preparation: Compile load test results; clean data by addressing inconsistencies, missing values, or outliers; select essential variables (features) impacting pile capacity.
2. Model Development with Multivariate Regression: Choose relevant regression technique; train the model; refine it through evaluation.
3. Model Validation and Deployment: Validate model's generalization; apply it to new datasets.

Table 5. Foundation load test databases (Modified from Tang and Phoon, 2021; Topacio et al., 2023)

Database/Reference	Limit state	Soil type	n	Pile geometry		Soil parameters
				B (m)	L/B	
NUS/ShalFound/919	Bearing	Clay	56	0.30–5.00	0–5.7	s_u=9–200 kPa
		Sand	427	0.25–7.00	0–6.1	ϕ=26–53°
	Tension	Clay	123	0.31–3.05	0.8–13.2	s_u=15–300 kPa
		Sand	313	0.10–2.50	0.5–14.5	ϕ=30–49°
NUS/DrilledShaft/542	Bearing	Clay	64	0.32–1.52	1.6–56.0	s_u=41–256 kPa
		Sand	44	0.35–2.00	5.1–59.0	ϕ=30–41°
		Gravel	41	0.59–1.50	6.2–30.0	ϕ=37–47°
	Tension	Clay	32	0.36–1.80	3.4–55.0	s_u=21–250 kPa
		Sand	30	0.30–1.31	2.5–43.0	ϕ=30–45°
		Gravel	109	0.43–2.26	1.8–17.3	ϕ=42–48°
NUS/RockSocket/721	End bearing	Rock	270	0.10–2.50	1.0–31.3	σ_c=0.5–99 MPa E_m=7.82–75113 MPa GSI=7.5–95 RQD=20–100%
CYCU/DrilledShaft/23	Lateral	Sand	23	0.30-1.58	12.8-59.0	ϕ=28–47° D_r=11%– 99%
CYCU/RockSocket/50	Bearing	Rock	50	0.6-2.0	4.0-55.8	σ_c=0.2–79 MPa RQD=0–100%
CYCU/DrilledShaft/143	Bearing	Clay	82	0.18–2.00	3.4–55.0	s_u=41–505 kPa
		Sand	61	0.24–2.50	5.1–73.3	D_r=28–92% ϕ=29–41°

Note: n – number of data; B – foundation diameter; D – foundation embedment depth or thickness of sand layer; s_u – undrained shear strength of clay; ρ – strength gradient; ϕ – friction angle of sand; ϕ_{cv} – constant volume friction angle; D_r – relative density of sand; N_{SPT} – blow count in standard penetration test (SPT); PI – plasticity index; OCR – overconsolidation ratio; S_t – soil sensitivity index; σ_c – uniaxial compressive strength of rock; E_m – elasticity modulus of rock; GSI – geological strength index; and RQD – rock quality designation.

6. Summary and conclusions

Interpretation methods were employed in order to assess the capacity of the chosen load test results and compared with the service load used in the design. Future goals were also discussed. Key findings include:

1. **Serviceability State Interpretation**: The Taipei MRT Circular Line load test, analyzed with the L_1 method, suggests 19,000 kN (1,937 tons) compression load and 13,295 kN (1,355 tons) tension load. The results are in comparable range with the design service loads, thus the method is recommended for serviceability design.
2. **Ultimate Limit State Interpretation**: Both compression and tension load tests in the Taipei MRT Circular Line showed failure loads at 50-70 mm displacement. Davisson and L_2 methods align with this range and are recommended. Other methods fall within the transition region, suitable for conservative assessments.
3. **Future Focus**: The on-going research aims to establish a database beneficial for the geotechnical engineering field. This includes a targeted dataset utilizing Taiwan case histories and conceptualizing cost-saving prediction models using machine learning for Taiwan-based firms, reducing the need for load tests.

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