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VERIFICATION OF LARGE-DIAMETER BORED PILE PERFORMANCE USING FULL-SCALE STATIC LOADING TESTS: A CASE STUDY OF THE ANHSIN BRIDGE FOUNDATION OF THE TAIPEI MRT

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Abstract

Full-scale pile static loading tests provide reliable field verification for large-diameter bored piles supporting long-span bridge structures subjected to extreme axial loads. This study presents a full-scale static loading test conducted for the foundation of the Anhsin Bridge in the Ankeng Light Rail MRT System, New Taipei City, Taiwan. The adoption of an asymmetrical cable-stayed truss-frame system resulted in exceptionally high axial forces concentrated on the main pylon foundation, requiring verification beyond conventional analytical design methods. A 2.0 m diameter cast-in-place bored pile was tested using a hydraulic loading system capable of applying a maximum axial load of 2,881 tons, exceeding both service-level and seismic design demands. The measured load–settlement response was smooth and progressive, with a maximum settlement of 16.67 mm at peak load and a residual settlement of 3.52 mm after unloading, indicating predominantly elastic pile–soil behavior and a safety factor greater than three with respect to service loading. The test results confirm the adequacy and robustness of the foundation design. From a sustainability perspective, the field verification reduced design uncertainty and avoided unnecessary overdesign, thereby supporting efficient material utilization and long-term structural reliability. The findings provide a practical engineering reference for foundation verification in long-span metro bridges subjected to extreme axial loads.

Keywords: pile static loading test; large-diameter bored pile; load–settlement behavior; foundation verification; sustainable infrastructure.

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1. Introduction

Sustainability considerations in civil infrastructure development have attracted increasing attention over the past decades, particularly in response to the growing demand for environmentally responsible, structurally reliable, and socially acceptable engineering solutions. Various sustainability indicators and assessment frameworks have been proposed to support the evaluation of infrastructure projects across their lifecycle, encompassing the planning, design, construction, operation, and demolition stages [1–3]. These frameworks emphasize not only environmental and ecological protection, but also risk mitigation, structural reliability, durability, and long-term functional performance [4–6].

Among these efforts, the Sustainability Assessment System for Green Civil Infrastructure (SASGCI), proposed by Liu, provides a practical and systematic methodology for assessing sustainability performance in civil engineering projects [3]. The SASGCI framework integrates multiple sustainability dimensions and has been successfully applied to various infrastructure types, including

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bridges, tunnels, slope works, and transportation systems [4, 5]. In recent years, sustainability concepts have increasingly been incorporated into early-stage decision-making processes, highlighting the importance of selecting construction methods and verification techniques that minimize environmental impacts while ensuring safety and reliability throughout the infrastructure lifecycle [7–10].

The Ankeng Light Rail MRT System (AKLRM), located in New Taipei City, Taiwan, represents a major urban transportation project developed under these sustainability principles. One of its most critical components is the Anhsin Bridge (AHB), which crosses the Hsindian River and connects the Ankeng and Hsindian districts. Due to strict environmental constraints and ecological protection requirements, the bridge design and construction faced significant challenges at the planning stage [11]. To mitigate potential impacts on river flow and local ecosystems, the originally proposed steel arch bridge scheme was replaced by an asymmetrical cable-stayed design with truss frames (ABCSTF), allowing the bridge to span the river without placing piers within the flow area [11].

The adoption of the ABCSTF structural system resulted in an exceptionally long span and the concentration of substantial dead loads, live loads, and seismic forces on the main pylon pier foundation. As a consequence, the performance of the pile foundation became a governing factor for the overall safety, durability, and sustainability of the bridge. Under such extreme loading conditions, conventional analytical design methods alone are insufficient to fully represent the complex load–settlement behavior and bearing mechanisms of large-diameter bored piles. Therefore, direct field verification through pile static loading tests is essential to confirm design assumptions and to reduce structural uncertainty.

Pile static loading tests have long been recognized as the most reliable method for evaluating the actual bearing capacity and settlement characteristics of deep foundations. Within the sustainability context, such tests play a critical role in risk mitigation and reliability enhancement, as they provide empirical evidence of foundation performance under loading levels exceeding service and seismic design demands. In the case of the Anhsin Bridge, large-scale pile static loading tests were conducted prior to foundation construction to verify the bearing capacity of the designed piles and to ensure that the foundation system could safely support the long-span superstructure throughout its lifecycle [11, 12].

Accordingly, this study focuses on the pile static loading test implemented for the Anhsin Bridge foundation as a key sustainability-oriented verification measure. By examining the test configuration, loading procedures, analytical evaluation methods, and observed load–settlement responses, this paper aims to demonstrate how pile static loading tests contribute to structural safety, durability, and sustainability in major bridge projects. The findings presented herein provide practical insights for engineers engaged in the design and construction of long-span bridges and metro infrastructure subjected to extremely high foundation loads.

Although pile static loading tests are well established, documented full-scale tests at such extreme axial load levels remain limited. This study therefore contributes practical engineering evidence and sustainability-oriented insights for foundation verification of long-span metro bridges.

2. Methodology

To ensure the structural safety, durability, and sustainability of the Anhsin Bridge (AHB) under extremely high loading demands, this study adopts a field-verified engineering methodology centered on a full-scale pile static loading test. The methodology integrates analytical bearing capacity estimation, large-capacity field testing, and performance evaluation based on load–settlement behavior. This approach is consistent with sustainability-oriented foundation verification practices adopted in major bridge projects [11, 13].

2.1. *Role of pile static loading tests in sustainability-oriented foundation design*

Pile static loading tests are widely recognized as the most reliable method for directly evaluating the load-bearing capacity and deformation characteristics of deep foundations. Unlike empirical or semi-empirical design methods, static loading tests provide in-situ measurements of pile–soil interaction under controlled loading conditions, thereby significantly reducing uncertainty in foundation performance assessment. From a sustainability perspective, such tests contribute to risk mitigation, reliability enhancement, and lifecycle durability by validating design assumptions prior to superstructure construction [11].

For long-span bridges employing cable-supported systems, foundation performance governs the safety and serviceability of the entire structure. International design and testing standards recommend full-scale static loading tests when piles are subjected to exceptionally high axial loads or when conservative verification is required due to geological uncertainty [13–15]. Accordingly, a pile static loading test was implemented in the AHB project as a key verification measure before constructing the main pier foundation.

2.2. *Analytical estimation of pile bearing capacity*

Prior to field testing, the axial bearing capacity of the pile was estimated using conventional analytical formulations that consider both end-bearing resistance and shaft friction. The total ultimate bearing capacity,

$$Qu = qbAb + \sum fsAs \tag{1}$$

where Qu is total bearing capacity of the pile; qb is bearing stress of the soil in the pile tip zone; Ab is cross-sectional area of the pile tip; fs is friction stress between the pile side surface and soil; and As is area of the pile's side surface.

The bearing capacity of the pile consists of contributions from end bearing resistance and shaft friction, as expressed in Eq. (1). The conceptual load transfer mechanism is illustrated in Fig. 1.

In addition, the shaft resistance component was independently evaluated using correlations based on standard penetration test (SPT) results:

$$Qs = Ns/3 \cdot 2\pi \cdot As \tag{2}$$

where Ns is N-value of the soil obtained from the standard penetration test (SPT); and As is area of the pile side surface.

Eq. (2) represents an empirical correlation commonly adopted in local engineering practice in Taiwan to provide a conservative estimation of shaft resistance based on SPT N-values. This formulation is not intended to replace rigorous analytical methods but serves as a supplementary verification tool for preliminary assessment and cross-checking of pile capacity. In this study, Eq. (2) was used only as an auxiliary reference, while the governing design verification relied primarily on the full-scale static loading test results.

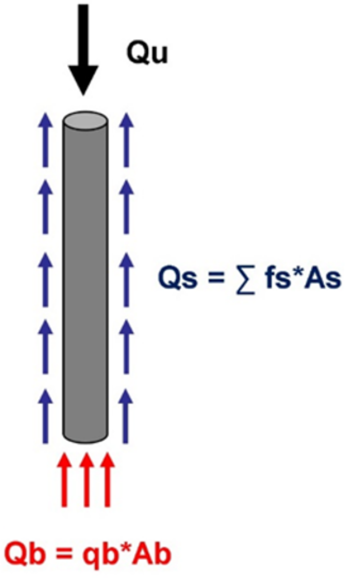

Figure 1. The principle of Eq. (1) $Qu = qbAb + \sum fsAs$

For design verification, the governing pile capacity was conservatively taken as the larger value obtained from Eqs. (1) and (2), ensuring sufficient safety margins under both service-level and seismic loading conditions.

2.3. Configuration of the pile static loading test

Based on the analytical evaluation, a full-scale pile static loading test was conducted on a selected test pile among the permanent foundation piles. The test pile had a diameter of 2.0 m and an embedded length of 35.0 m, with an extension above ground to facilitate load application. Four adjacent piles were designated as anchor piles to provide reaction force during testing [11, 13].

The loading system consisted of eight hydraulic jacks, each with a nominal capacity of 500 tons, assembled to apply a maximum test load of 2,881 tons. This maximum load was determined as the larger of twice the service-level design load and the seismic design load, plus the friction resistance of the pile extension portion, in accordance with conservative verification principles [13–15]. The key parameters of the test configuration are summarized in Table 1.

Table 1. Summary of pile static loading test configuration and design parameters

Item	Unit	Value
Pile type	–	Cast-in-place bored pile
Pile diameter	m	2.0
Pile length (embedded)	m	35.0
Extension length above ground	m	12.5
Total pile length	m	47.5
Design vertical load (service condition)	ton	974
Design vertical load (seismic condition)	ton	2,287
Friction resistance of extension portion	ton	593.96
Maximum applied test load	ton	2,881
Loading method	–	Hydraulic jack system
Number of hydraulic jacks	–	8
Capacity per hydraulic jack	ton	500
Anchor system	–	4 anchor piles
Anchor pile diameter	m	2.0
Anchor pile length	m	47.2
Load transfer system	–	Main and secondary anchor beams
Acceptance criterion	–	Settlement and rebound behavior

2.4. Loading procedure and instrumentation

The pile static loading test was carried out using a staged incremental loading procedure. The applied load was increased stepwise until reaching the target maximum load, with each loading stage maintained for a specified duration to observe settlement stabilization. After maintaining the maximum load, unloading was conducted gradually to evaluate elastic rebound and residual settlement behavior [13–15].

Pile head settlement was measured using dial gauges and displacement sensors mounted on independent reference beams to eliminate the influence of reaction system deformation. During the pile static loading test, the loading system and settlement monitoring instruments were carefully inspected and verified on site to ensure the accuracy and reliability of the measured load–settlement response. Fig. 2 presents representative on-site conditions of the loading assembly and the settlement monitoring instruments adopted in the test. Continuous monitoring ensured accurate capture of load–settlement responses throughout the test.

(a) Assembly of hydraulic loading system and reaction framework

(b) Settlement monitoring instruments installed for pile head displacement measurement

Figure 2. On-site verification of pile static loading test setup

2.5. Performance evaluation criteria

Pile performance was evaluated based on the maximum settlement observed at peak load and the net residual settlement after complete unloading. These criteria are consistent with international standards for pile static loading tests and provide direct evidence of foundation stiffness, bearing capacity, and serviceability performance [13–16].

The verified test results were subsequently used to confirm the adequacy of the foundation design for the main pier of the AHB, thereby supporting the sustainability objectives of structural reliability and long-term durability.

According to the commonly adopted practice for large-diameter bored piles supporting bridge structures, allowable pile head settlement under service-level loading is typically limited to approximately 25~40 mm, depending on structural sensitivity and project-specific criteria. In the AHB project, more stringent internal criteria were adopted to ensure serviceability and durability. The measured maximum settlement of 16.67 mm, therefore, satisfies both general practice and project-specific requirements.

3. Results and discussions

3.1. Load–settlement behavior of the test pile

The pile static loading test was carried out by incrementally applying axial compressive load up to a maximum value of 2,881 tons, following the predefined loading sequence described in Section 2. Fig. 3 illustrates the measured load–settlement relationship at the pile head during both loading and unloading stages. As shown in the figure, the pile exhibited a smooth and progressive settlement response as the applied load increased, indicating stable pile–soil interaction and satisfactory stiffness of the foundation system. The smooth and continuous shape of the load–settlement curve indicates stable load transfer between the pile and surrounding soil throughout the loading process. The absence of abrupt slope changes or inflection points suggests that neither shaft resistance degradation nor end-bearing failure was mobilized within the applied load range. This behavior reflects adequate pile stiffness and uniform mobilization of soil resistance, which is particularly critical for foundations subjected to high axial loads in long-span bridge systems.

At the maximum applied load of 2,881 tons, the measured pile head settlement was 16.67 mm. This settlement level is relatively small for a large-diameter bored pile subjected to such an extreme load and is well within commonly accepted serviceability limits for bridge foundation systems. No abrupt increase in settlement or indication of plunging failure was observed throughout the loading process, suggesting that the ultimate bearing capacity of the pile was not reached during the test [13–15].

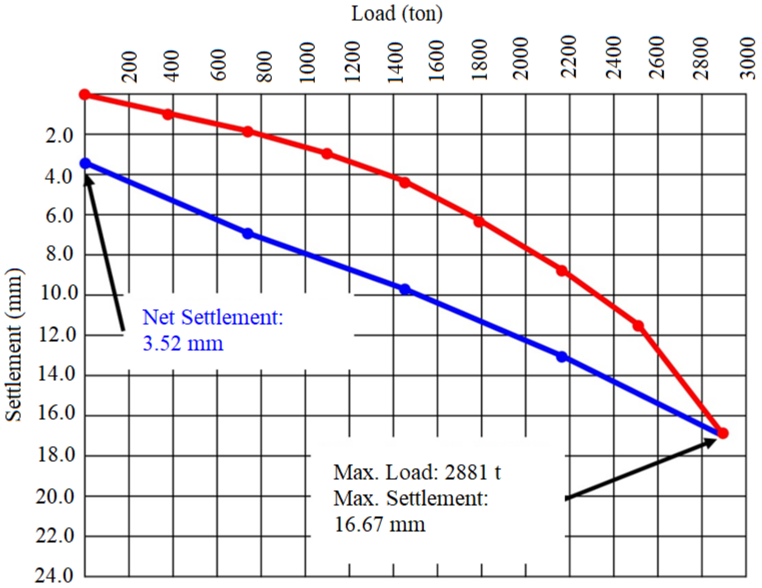

Figure 3. Load–settlement relationship of the test pile obtained from the pile static loading test

3.2. Unloading response and residual settlement

Following the completion of the maximum loading stage, the applied load was gradually released in accordance with the unloading procedure. As shown in Fig. 3, a significant portion of the pile head settlement was recovered during unloading, demonstrating elastic rebound behavior of the pile–soil system. Upon complete unloading, the net residual settlement was measured to be 3.52 mm.

The pronounced elastic rebound observed during unloading indicates that the pile–soil system experienced limited irreversible deformation, even under loading levels exceeding design demands. This elastic-dominant response implies that plastic yielding of the surrounding soil and degradation of shaft resistance were minimal. Such behavior is desirable for long-span bridge foundations, as it suggests favorable long-term serviceability and reduced risk of progressive settlement under repeated or sustained loading.

The relatively small residual settlement indicates that the pile response remained predominantly elastic, even under loading levels exceeding both the service-level and seismic design demands. This behavior confirms that irreversible plastic deformation of the surrounding soil and degradation of shaft resistance were minimal during the test [13]. Such elastic-dominant behavior is particularly desirable for foundations supporting long-span bridge structures, where long-term serviceability and durability are critical considerations.

3.3. Verification of bearing capacity and safety margin

The measured load–settlement response provides direct verification of the analytical bearing capacity estimates presented in Section 2.2. The absence of excessive settlement or instability at the maximum applied load confirms that the ultimate axial bearing capacity of the pile exceeds 2,881 tons.

Considering the design vertical loads of 974 tons under normal service conditions and 2,287 tons under seismic conditions, the test results demonstrate a safety factor greater than 3 with respect to service loading. This level of conservatism satisfies international recommendations for foundation verification in critical transportation infrastructure and long-span bridge applications [14–16]. The verified safety factor greater than three should not be interpreted solely as numerical conservatism, but rather as evidence of robust foundation performance under extreme loading conditions. This margin reflects the combined effects of pile stiffness, favorable pile–soil interaction, and conservative verification through full-scale testing. Importantly, such confirmation allows confidence in the design without resorting to excessive pile dimensions, thereby supporting both structural reliability and sustainable resource utilization.

To facilitate clear interpretation, the key outcomes of the pile static loading test are summarized in Table 2.

Table 2. Summary of pile static loading test results

Item	Value
Maximum applied load (ton)	2,881
Maximum settlement at peak load (mm)	16.67
Holding duration at maximum load (hr)	12
Residual settlement after unloading (mm)	3.52
Dominant pile behavior	Predominantly elastic
Verified safety factor (service load)	> 3

3.4. Implications for durability and sustainability

From a sustainability perspective, the verified performance of the pile foundation contributes directly to risk mitigation, structural reliability, and long-term durability of the Anhsin Bridge foundation system. By confirming the actual bearing capacity and deformation characteristics through a full-scale pile static loading test, uncertainties associated with soil variability and analytical assumptions were substantially reduced prior to superstructure construction [11]. In addition, the pile static loading test directly supports key indicators within the SASGCI framework, including risk mitigation, structural reliability, and efficient material utilization. By verifying actual foundation performance prior to superstructure construction, the project avoided unnecessary conservatism in pile design, thereby reducing material consumption and associated environmental impacts while ensuring long-term serviceability.

Moreover, the field-verified results enabled confirmation of the foundation design without unnecessary over-conservatism, thereby avoiding excessive material usage and associated environmental impacts. This outcome aligns with sustainability principles emphasizing efficient resource utilization, lifecycle performance, and resilience of civil infrastructure systems [3–5].

3.5. Engineering significance

The pile static loading test results presented in this study demonstrate that large-diameter bored piles, when properly designed and verified, can reliably support the extremely high axial loads associated with long-span cable-supported bridge systems. The favorable load–settlement behavior observed in this case study highlights the importance of field-based verification for foundations subjected to exceptional loading demands.

The findings provide a valuable technical reference for engineers involved in similar metro bridge and transportation infrastructure projects, particularly where foundation reliability, serviceability control, and sustainability considerations must be addressed simultaneously.

4. Conclusions

This study investigated a full-scale pile static loading test conducted for the foundation of the Anhsin Bridge, a long-span structure of the Ankeng Light Rail MRT System in New Taipei City, Taiwan. The test was implemented to verify the bearing capacity and deformation behavior of large-diameter bored piles subjected to extremely high axial loads induced by the asymmetrical cable-stayed truss-frame bridge system. The measured load–settlement response demonstrated stable and controlled pile behavior throughout the loading and unloading stages.

At the maximum applied load of 2,881 tons, the pile head settlement was limited to 16.67 mm, and a substantial elastic rebound was observed during unloading, resulting in a residual settlement of only 3.52 mm. These results confirm that the actual bearing capacity of the pile exceeded the design demands with a significant safety margin and that the pile–soil system remained predominantly elastic, even under loading levels exceeding both service-level and seismic conditions.

The field-verified performance of the pile foundation provides direct confirmation of the robustness and conservatism of the foundation design adopted for the Anhsin Bridge. By validating analytical assumptions through a full-scale static loading test, uncertainties associated with soil variability and load transfer mechanisms were effectively reduced prior to superstructure construction. This verification-based approach enhanced structural reliability and long-term durability while avoiding unnecessary overdesign.

From a sustainability perspective, the pile static loading test contributed to risk mitigation and efficient resource utilization by ensuring that the foundation system met safety and serviceability requirements without excessive material consumption. The findings of this study demonstrate the value of integrating full-scale pile static loading tests into the design and construction of long-span bridge foundations subjected to exceptional loading demands, and they provide a practical reference for similar metro bridge and transportation infrastructure projects.

It should be noted that the findings presented in this study are based on a specific geological setting, pile configuration, and loading condition associated with the Anhsin Bridge project. While the results provide valuable engineering insight and reference, direct extrapolation to other sites or foundation systems should be undertaken with caution. The methodology, rather than the numerical results themselves, is intended to be transferable to similar projects.

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