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Challenges and Solutions for Sustainability Practices in Bridge Construction of Metro System: A Case Study of Anhsin Bridge Construction of MRT System in New Taipei City

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Abstract: This study investigates the integration of sustainability indicators into structural system selection and construction-stage decision-making through a case study of the Anhsin Bridge in the Ankeng Light Rail MRT System, New Taipei City. The original steel arch bridge concept posed potential ecological and hydraulic impacts on the Hsindian River due to in-river temporary works. To address this challenge, an asymmetrical cable-stayed design with truss frames was proposed and evaluated using a structured sustainability-based framework. The methodology comprises sustainability indicator identification, comparative structural assessment, construction-stage mitigation strategy implementation, and empirical performance verification. Key sustainability considerations include risk mitigation and reliability, ecological conservation, environmental protection, durability, and constructability optimization. Full-scale pile static loading tests verified a maximum bearing capacity of 2,881 tons with a settlement of 16.67 mm and a net settlement of 3.52 mm, satisfying safety requirements with a safety factor of 3. Wind tunnel testing under wind speeds up to 74 m/s demonstrated a maximum horizontal displacement of 830 mm, confirming structural stability under typhoon-level conditions. The adoption of the truss-frame erection system, heavy-duty tower crane operations, building information modeling–based material traceability for over 30,000 uniquely sized steel members, and ecological monitoring programs minimized environmental disturbance during construction. The results demonstrate that sustainability indicators can function as engineering decision constraints rather than post-design evaluation tools, providing a replicable framework for long-span bridge projects in environmentally sensitive regions.

Author keywords: Sustainability practices; Ankeng Light Rail MRT System; Anhsin Bridge; cable-stayed bridge; sustainable construction

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Introduction

Sustainability indicators for the development of infrastructure projects have been proposed in recent decades,[1–3] with key assessment indicators proposed to evaluate sustainability issues in engineering fields.[4] Tai-Yi Liu proposed a reliable and practical sustainability assessment system for green civil infrastructure (SASGCI) in his doctoral dissertation in January 2020,[3] This provided a new perspective on sustainability practices for developing new infrastructure projects. In recent years, sustainability issues have been widely studied and considered across all engineering fields and construction.[4–7] Sustainability considerations have also been incorporated from the start, such as at the planning and design stages of new projects. The primary goal of the sustainability studies is to identify environmentlly friendly solutions that avoid detrimental impacts on the environment and ecology throughout their life cycle.[8–10] However, the practical integration of sustainability indicators into structural system selection and construction-stage engineering decisions remains insufficiently demonstrated in real-world long-span bridge projects.

The Ankeng Light Rail MRT System (AKLRM) project, which is located in New Taipei City, started in 2016 and was estimated to provide transportation services by 2022. When developing the new bridge of the AKLRM, namely, Anhsin Bridge (AHB), which crosses the Hsindian River, engineers faced significant challenges and needed to find solutions in the planning stage, as shown in Table 1.

To show the technical clarity and precision, the terminology used in Table 1 is presented to more explicitly describe the engineering risks and management challenges associated

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Table 1. Challenges and solutions for the development of AHB

Challenges	Problems faced	Solution (methods)
Prevention of the impact on the Hsindian River	It is a high possibility to cause harmful effects and impacts on the Hsindian River species.	The newly designed ABCSTF for AHB construction, observation for Hsindian River species.
Safety and huge load capacity for the AHB	Huge dead and live loads will be applied to AHB. Verification for AHB's load capacity to guarantee the bridge's safety is essential to be executed by engineers.	Pile static loading tests, wind tunnel tests, a high-quality steel cable system, long-term bridge monitor system.
Risk arrangement during the construction of AHB	The erection work for the AHB's steel members might cause a dangerous situation.	The heavy-duty tower crane system, TFES, with safe working platforms.
Complicated material management for factory manufacture and site installation	The presence of more than 30,000 uniquely dimensioned steel members significantly increases the risk of fabrication errors, misidentification, transportation mismatches, and on-site erection inaccuracies if systematic traceability and verification controls are not implemented.	The management system of extraneous member sizes, using the BIM technique.
Integrate into the local landscape.	An obtrusive structure may severely damage the landscape.	Simulation for the landscape appearance using the BIM technique.

Note: ABCSTF, asymmetrical cable-stayed design with truss frame; BIM, building information modeling; TFES, truss-frame erection system.

with AHB construction. Ambiguous expressions are shown with technically specific descriptions to ensure that the identified challenges reflect measurable construction-stage risks and operational constraints.

In this project, engineers examined all sustainability practices for AHB construction to minimize the possible impact on the environment and human life during the life cycle of the AKLRM.[11] The authors were all involved in this project, and this paper provides references on the development of sustainability research.

Despite the growing body of research on sustainable infrastructure and bridge assessment frameworks, limited studies systematically demonstrate how sustainability indicators can directly inform structural type selection and construction-stage decision-making under real ecological constraints. Existing studies primarily focus on sustainability rating systems, life-cycle carbon accounting, or post-construction performance evaluation,[12–14] while fewer contributions integrate sustainability indicators into comparative structural redesign and constructability-oriented mitigation strategies for long-span bridges.[15,16] Therefore, this study aims to bridge this gap by developing a structured sustainability-based comparison between alternative structural systems (steel arch bridge[17] and asymmetrical cable-stayed design with truss frames[17]) and validating the selected option through empirical full-scale testing and construction-stage performance verification. This approach strengthens the methodological linkage between sustainability theory and practical structural engineering implementation.

Literature Review on the Sustainability Indicators

Efforts in sustainability have drawn attention and public support for infrastructures such as residential houses, roads, highways, bridges, tunnels, water supply systems, sewers, electrical grids, and telecommunication systems, just to name a few. Specifically, sustainable and green infrastructures have been emphasized through design and construction projects that support long-term sustainability. Shau et al. presented good sustainability practices in the Suhua Highway Improvement Project.[17] Sustainable and green civil infrastructure, as mentioned above, may consider the following criteria:[18–21]

- Safety management, risk mitigation, and reliability are maintained during the life cycle.
- CO_2 emissions and harmful impacts on the environment and ecology are minimized during the life cycle.
- The landscape of the project development zone is optimized.
- The benefit/function of project development is maximized.
- Waste production is reduced, and waste recycling is implemented during the lifecycle when possible.
- Energy is saved during the life cycle.
- The durability of the project is extended.
- The local culture is preserved, and a social conscience is maintained.
- Creativity is encouraged.
- A reasonable cost is maintained during the life cycle.

Liu performed research on the evaluation of civil infrastructures, including bridges, tunnels, slope work, and buildings, and determined the weight of each key indicator.[3,4] Certain important issues are considered key indicators of the SASGCI. They comprise the first level of the assessment system. Each indicator should contain related evaluation items as the second level of the assessment system. To consider the entire lifecycle of a project, four stages must be covered, including design, construction, operation, and demolition, which constitute level three of the system.[3,4]

Ten sustainability indicators of bridges were proposed in Liu's research as follows:[3,4]

- Risk mitigation and reliability
- Ecological conservation
- Environmental protection and carbon emissions reduction
- Energy savings
- Waste reduction
- Durability
- Benefit and function
- Landscape
- Social conscience and culture preservation
- Creativity

By adopting the MAVT and TTBT methods in SASGCI in 2021,[5] Liu et al. determined the weights of the 10 key indicators for bridges as follows: risk mitigation and reliability (15.3%), durability (15.1%), landscape (11.5%), ecology (10.6%), benefit and function (9.7%), environmental protection and carbon emissions reduction (9.5%), waste reduction (8.5%), energy saving (7.1%), creativity (7.0%), and humanities and culture preservation (5.6%).[5] The SASGCI provides a practical tool to assess the sustainability achievement of a newly developed infrastructure project.

Methodology

The methodological framework adopted in this study consists of four structured stages: (1) identification of key sustainability indicators based on established infrastructure sustainability assessment systems;[12,22] (2) comparative evaluation of alternative structural configurations using multi-criteria and performance-based decision approaches;[23] (3) implementation of construction-stage mitigation strategies targeting ecological protection, risk reduction, and constructability optimization; and (4) empirical verification through full-scale pile loading tests and wind tunnel testing following recognized geotechnical and structural testing standards.[24–26] This structured approach ensures that sustainability considerations are embedded in technical decision-making and validated through measurable engineering performance indicators rather than treated solely as descriptive attributes.

In this paper, the sustainable construction methods and techniques are adopted, with detailed descriptions provided to present the sustainability achievements of the proposed case study. To avoid redundancy and improve logical progression, overlapping descriptions between structural selection, sustainability indicators, and construction practices have been consolidated. Conceptual evaluation, implementation strategies, and empirical validation are now presented in separate but sequential subsections. The newly designed structure type for AHB, namely, ABCSTF, offers a sustainable solution for the challenge of construction work. The major work and the goals of the AHB construction are listed as follows:

- ABCSTF system: prevents large quantities of piers from being located in the flow area of the Hsindian River.
- Heavy-duty tower crane ST3330 with safe working platforms: significantly increases the safety of erecting the steel members of AHB.
- TFES with safe working platforms: prevents any temporary facility from being set in the flow area of the Hsindian River.
- Pile static loading tests: verify the actual bearing capacity of the designed piles.
- Wind tunnel tests: verify the stability and durability of the ABCSTF structure in extreme wind conditions.
- Management of extraneous member sizes: assists factory manufacturing and site installation under massive quantities of steel member shapes and sizes.
- Steel cable system: provides the primary force for the entire bridge structure, including dead and live loads, to maintain the stability and durability of the ABCSTF structure.
- Landscape design: combined with the pylon and cable-stayed system, resembles a high-flying eagle. Outstanding landscape design reflects the imagination of humans.
- Application of the building information modeling (BIM) technique: assists the entire AHB life cycle, including design, construction, operation, and demolition stages.
- Observation of Hsindian River species: provides the living conditions and status of species in the Hsindian River and its tributaries.
- Long-term bridge monitoring system: monitors the AHB's health condition during the operation stage.

The ABCSTF, constructed using the above-listed sustainable methods, is expected to prevent any harmful impact on the Hsindian River. Fig. 1 shows the schematic of sustainability practices for bridge construction of the MRT system.

Fig. 1 illustrates the whole framework of this study. In this paper, the discussion covers the four stages, design, construction, operation, and demolition, in the life cycle of AHB. The critical sustainability issues, which include risk mitigation and reliability, ecology, environmental protection, carbon emissions reduction, energy savings, waste reduction, and durability, are employed in the study. Therefore, the sustainable construction methods, including the heavy-duty tower crane system, TFES, large-load pile tests, wind tunnel tests, high-quality steel cable system, management system for extraneous member sizes, and BIM application

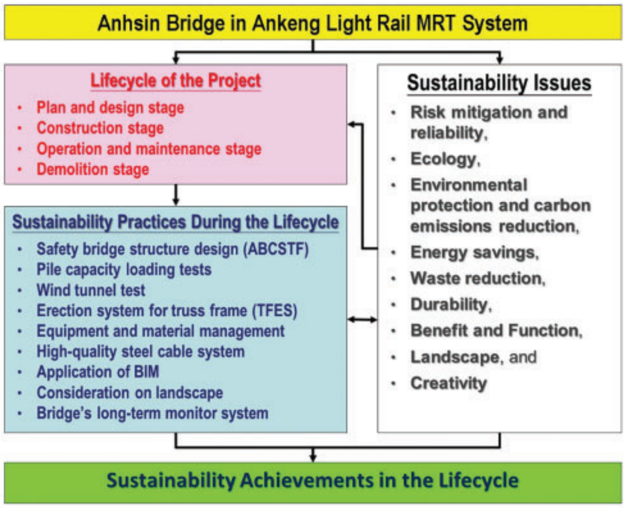


Figure 1. Schematic of the sustainability practices for bridge construction of the MRT system. ABCSTF, asymmetrical cable-stayed design with truss frames; BIM, building information modeling; TFES, truss-frame erection system

for bridge-building, are applied to obtain the sustainability achievements in the AHB life cycle.

To ensure transparency and reproducibility, all essential methodological procedures, including pile load testing protocols, wind tunnel boundary conditions, and sustainability evaluation criteria, are explicitly described in this manuscript. The pile static loading tests were conducted in accordance with established deep foundation testing standards,[24,25] and wind tunnel testing followed recognized aerodynamic modeling practices for long-span bridges.[26,27] While certain project documents originate from internal engineering reports, the analytical procedures and verification methods presented here are fully detailed and consistent with established international standards. Therefore, the findings are reproducible based on the technical descriptions and equations provided, independent of access to proprietary documentation.

In response to concerns regarding accessibility of cited documents, the referencing strategy of this study has been revised to prioritize publicly available standards, peer-reviewed publications, and internationally recognized technical guidelines. Internal project reports are now referenced solely for contextual background or project-specific implementation records, while all critical analytical procedures, equations, testing configurations, and evaluation criteria are explicitly documented within the manuscript. This adjustment ensures that the scientific arguments, engineering calculations, and sustainability assessments presented herein are independently verifiable without reliance on proprietary documentation.

The preceding sections establish the analytical and methodological framework of this study. The following case description applies the structured evaluation approach to the AHB project, presenting practical implementation and verification results without reiterating previously defined sustainability criteria. This separation ensures clarity between theoretical framework development and case-specific application.

Case Study of AHB

Description for the presented project

The AKLRM project started in 2016 and was estimated to provide transportation services by 2022. The client of the AKLRM is the Department of Rapid Transit Systems (DRTS), New Taipei City Government. The DB contractor of the AKLRM is New Asia Construction and Development Corporation (NA), covering the detailed design and construction stages. The AKLRM is designed to have a route length of 7.5 km and contains nine stations (K1–K9), including five elevated stations (K2 and K6 to K9) and four at-grade stations (K1 and K3 to K5). The route of the AKLRM starts with a depot yard near Antai Road and ends at Shisizhang station to connect with the MRT Circle Line. Fig. 2 shows the planned route of the AKLRM project. For clarity and international accessibility, the base map used in Fig. 2 has been simplified and converted to a fully English-labeled format. Nonessential background elements were removed to improve visual focus on the bridge location and route alignment.

Figure 2. Planned route of the AKLRM project. AKLRM, Ankeng Light Rail MRT System

There are three major bridges that cross the Hsiapei Highway, the No. 3 Freeway, and the Hsindian River. The AHB, crossing the Hsindian River, is one of the major parts of the AKLRM and functions as the most critical transportation route to connect the two banks of the Hsindian River (i.e., Ankeng and Hsindian districts).

At the design stage, all of the abovementioned sustainability issues were considered to determine the bridge structure type. Engineers evaluated all key indicators and their evaluation items to select the most sustainable options for detailed design and site construction.

As shown in Fig. 2, the pink area indicates the location of the AHB along the AKLRM route. This bridge connects the two banks of the Hsindian River between the K8 and K9 stations.

Engineers focused on feasible sustainability achievements to select structure-type options suitable for the AHB. The final AHB frame structure is an ABCSTF. Twelve pairs of steel cables are installed between the steel pier column and the top steel box beam of the truss frame. Four different numbers of tendons, namely, 55, 61, 66, and 73, occur in different pairs of cables depending on the required prestressing force.

In this paper, the authors share their experiences with the option decisions and sustainability practices of the AHB in the AKLRM project.

Evaluation and determination of the bridge structure type

The selection of the ABCSTF system was not based solely on structural feasibility but on its superior performance across multiple sustainability dimensions, including elimination of in-river temporary structures, reduction of construction-stage ecological disturbance, improved erection safety, and optimized long-span durability performance. Previous research has emphasized that sustainability in bridge engineering must integrate environmental protection, constructability, and life-cycle reliability considerations simultaneously.[15,28] In contrast to conventional arch systems requiring extensive shoring within river flow zones, the adopted system minimized hydraulic interference and reduced exposure to typhoon-related construction risks. This decision demonstrates how sustainability indicators can function as engineering constraints that directly influence structural configuration rather than being applied solely as post-design evaluation metrics.

When developing the AHB construction design for the AKLRM project, the original concept from the client, DRTS, provided the basic design idea of the AHB as a steel bridge with arch frame (SBAF). Fig. 3 shows the original idea of the construction and design of the AHB.[11]

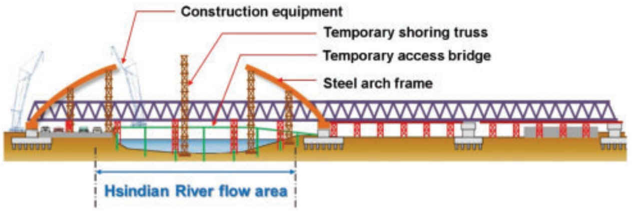


Figure 3. Original idea of the design and construction of the Anhsin Bridge[11]

This option was indicated in the basic design concept of the contract documents provided by the client, DRTS. Construction of the SBAF would be necessary to set the piers in the Hsindian River flow area. As shown in Fig. 3, a temporary shoring truss would be installed in the flow area to support the members of the steel arch frame. Additionally, a temporary access steel bridge would be necessary to operate the construction equipment. Under these conditions, a massive quantity of steel materials would be required, and the total duration would be considerable. In addition, the risk during construction would be substantially increased during the erection of the steel columns. To minimize the possibility of danger, engineers attempted to prevent the pier from being located in the flow area. All these construction methods could yield a harmful impact on river flow. Moreover, the environment and ecological conditions of the Hsindian River could be adversely affected.

Furthermore, Taiwan is a high-typhoon-frequency area during the summer season. All construction machines and equipment at the construction site would be at risk during a typhoon. The equipment would face high-risk conditions within the vicinity of the steel bridge during the typhoon season. Thus, contractor NA proposed an alternative method involving a new, safer structure type, the ABCSTF, instead of the original steel arch frame for this major bridge of the AKLRM. Fig. 4 shows a vertical layout and a simulated picture of the new AHB.

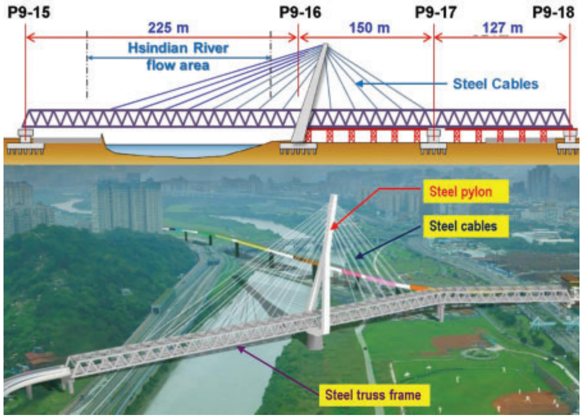


Figure 4. Vertical layout and simulated picture of the new AHB.[11] AHB, Anhsin Bridge

When selecting the structure type for the AHB, engineers compared the performance of SAB and ABCSTF based on the key sustainability indicators listed in Table 2 and provided sufficient information to the decision-maker to reach a final determination. Table 2 lists the performance evaluation results for SAB and ABCSTF. The evaluation covers both the operation/maintenance stage and the construction stage for these two options. Regarding the life cycle of the bridge, reducing the harmful impacts via environmental protection and ecological conservation measures during the construction stage is equally important as during the operation/maintenance stage.

Table 2 indicates that the contractor (NA) obtained comparison results based on the key sustainability indicators, and the ABCSTF option was finally selected as the structure type for the AHB.

Although the pile testing was originally documented in internal project reports, the full calculation procedures, load sequence design, governing equations, boundary conditions, and performance evaluation criteria are comprehensively presented in this manuscript. The reported maximum test load, settlement response, and safety factor verification are derived directly from the described methodology and can

Table 2. Performance evaluation of SAB and ABCSTF based on the key sustainability indicators

Key indicators	Original planning: SAB	Alternative option: ABCSTF
Safety and risk mitigation		●
Reliability	●	●
Environment protection		●
Ecological conservation		●
Durability	●	●
Landscape		●
Construction duration		●
Creativity		●
Final determination		●

Note: ABCSTF, asymmetrical cable-stayed design with truss-frames; SAB, steel arch bridge

be independently reproduced using the provided equations and loading protocol. Therefore, the engineering validation process does not depend on inaccessible documentation.

Sustainability practices for the AHB

Most of the sustainability issues were suitably considered and implemented in the AKLRM project. Since the AHB is part of the entire project, the following focuses on critical items of certain key sustainability indicators, including risk mitigation and reliability, environmental protection, ecology, durability, landscape, and creativity.

Risk mitigation and reliability

In this study, construction-stage risks are defined as identifiable and quantifiable hazards associated with structural instability during erection, heavy lifting operations, temporary load redistribution, wind-induced displacement during installation, and worker safety exposure at elevated working platforms. By explicitly categorizing these risks, the mitigation strategies adopted in this project—such as the heavy-duty tower crane system and TFES—can be evaluated in terms of their capacity to reduce measurable engineering and safety uncertainties.

The safety of infrastructure is always the top priority. Verification and enhancement of safety management during the life cycle are essential to engineers. The alternative structure type of the AHB included three major parts: a 130-m-high steel pylon, a 502-m steel truss frame, and steel cables weighing 1,250 tons. Even though the engineers selected the ABCSTF structure type for the AHB, the construction of every part posed certain risks. Therefore, risk mitigation measures constituted the essential responsibility of engineers to prevent such risks. To resolve and reduce the risks, uniquely designed, reliable construction facilities and equipment were proposed for AHB construction, including a heavy-duty tower crane and a TFES.

A heavy-duty tower crane, ST3330, was installed for erecting 17 segments of the steel pylon. The tower crane was established near the steel pylon and fixed via four tie-in frame layers. Fig. 5 shows the tie-in members connected to the mast tower members.

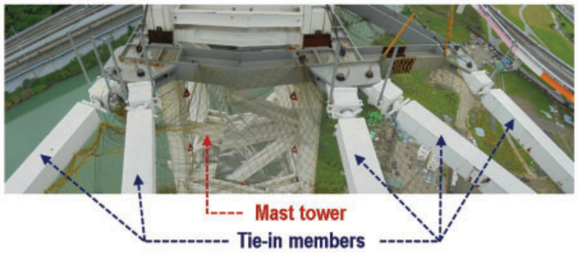


Figure 5. Image of the ST3330 tower crane

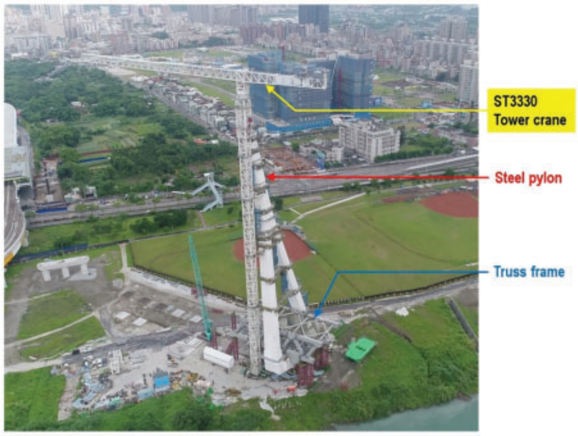
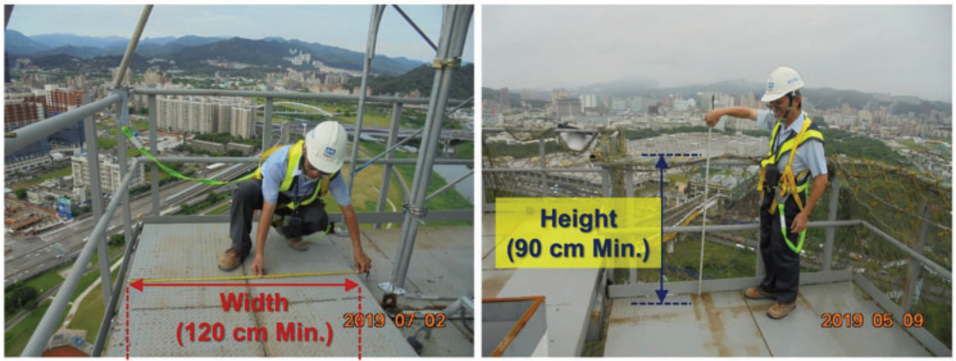


Figure 6. Photograph of the ST3330 tower crane

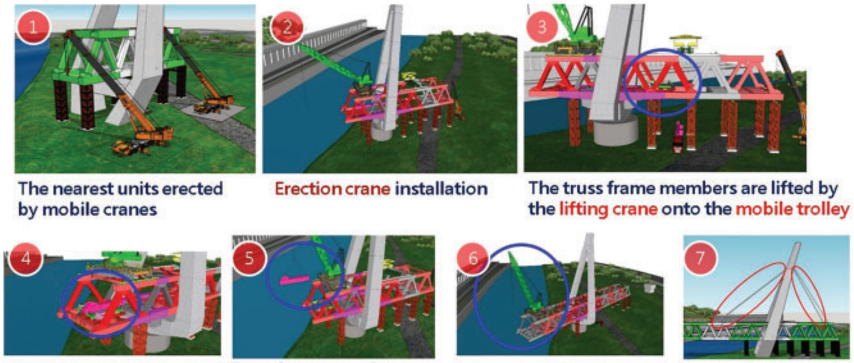
The assembly consisting of the tower crane and AHB steel pylon, which were connected via tie-in sets, reduced the influences of river flow during the typhoon season. A temporary working platform was preinstalled on each pylon segment and lifted concurrently with segment erection. Fig. 6 shows photographs of the ST3330 tower crane. The strict site inspection for all construction facilities, such as the platform's width and the handrail' height, ensures safety to avoid any possibility of damage or injury occurring during the construction stage. This is one of the significant concerns of site risk management. Fig. 7 shows the inspection of the temporary working platform by the responsible engineer.



The width of the platform ensures the sufficient space for the worker to carry the instruments for construction work.

The height of the handrail guarantees the sufficient protection for the worker to execute the installation work on the platform.

Figure 7. Inspection of the temporary working platform by the responsible engineer



The nearest units erected by mobile cranes

Erection crane installation

The truss frame members are lifted by the lifting crane onto the mobile trolley

Truss frame members moved toward the erection zone by the Mobile Trolley

Truss frame members erected by the Erection crane

Erection crane Launching

Installation of steel cables

Figure 8. Erection steps of the truss-frame members

The engineers for the AKLRM proposed a special lifting system, namely, the TFES, as a sustainable solution to prevent the influences of river flow caused by the temporary shoring systems during the erection of the steel members of the AHB. Since the tower crane and other mobile cranes were unsuited for erecting all steel members, the TFES provided lifting, transportation, and erection functions for the assembling the truss-frame members. Thus, the newly designed TFES served as a construction facility containing the devices required for installing the beams and bracing members of the horizontal steel truss. The TFES contains three main installation components:

1. A **lifting crane** with a handling capacity of 48 tons.
2. A **mobile trolley** that can handle steel members weighing up to 35 tons.
3. An **erection crane** with a lifting capacity of 50 tons.

The lifting crane lifted each truss-frame member onto the mobile trolley platform. The mobile trolley then delivered the member, moving at a speed of 6 m/min, to the erection zone, referred to as location (A) in Fig. 8. After the steel members arrived in the erection zone, the erection crane took over all installation work. Fig. 8 shows the erection steps of the truss-frame members.

By adopting the TFES, no temporary facility or equipment needed to be set in the Hsindian River flow area during the construction of the steel truss frame. This notably reduced the possibility of danger. Besides, all erection work, including member connection, bolt penetration and tightening, and site inspection, was performed on the affiliated platforms of the TFES. These facilities provided a safe working environment for the installers and inspectors. Moreover, the overall construction duration was shortened due to the absence of the temporary shoring system and the access steel bridge in the river flow area. Fig. 9 shows site photographs of the TFES. Fig. 10 shows the responsible engineer supervising the bolt penetration of the truss-frame beams.[11]

Proper safety management during the installation of steel cables could guarantee an excellent bridge construction quality. The arrangement of a catwalk with safety guard rails and temporary stairs/ladders provided a safe environment for installing the required steel cables. Fig. 11 shows the safety facilities implemented for the installation work. Fig. 12 shows site photographs of the safety facilities.

Figure 9. Site photographs of the TFES: (a) near the steel pylon and (b) near the P9-18 pier

Figure 10. The responsible engineer supervising the bolt penetration of the truss-frame beams[11]

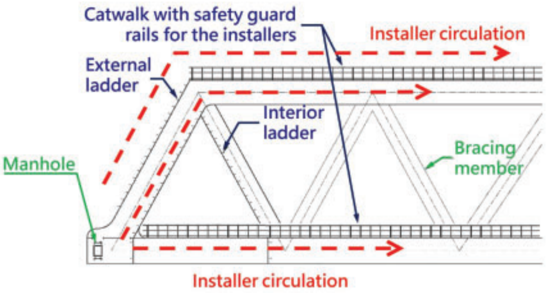


Figure 11. Installed safety facilities for the installation work

Environmental protection and ecology

Considering environmental sustainability, according to the statements in the above sections, the contractor (NA) proposed the newly designed ABCSTF as the frame structure type for the AHB. As a result of this newly well-designed frame structure, the impact on river flow and the ecological environment was prevented as much as possible during the construction and operation stages.[29] Moreover, carbon emissions were reduced through the shortening of the construction duration, and the optimization for the equipment operation and operation management.[30] All these sustainability achievements were obtained under the well-planned ABCSTF.[11] The engineers established an ecological and environmental observation program targeting the Hsindian River and its tributaries to monitor any difference in species population and health during construction.[11] Hsindian River siltation was periodically removed to ensure suitable river flow conditions. The river water quality was also regularly monitored to assess the influence of AHB construction.

The ecological monitoring program referenced in this study was conducted as part of the project's environmental management plan. To enhance transparency, this manuscript summarizes the monitoring scope, observed parameters, frequency of inspection, and evaluation approach rather than relying solely on archived internal reports. The environmental protection conclusions are based on observable construction-stage outcomes and documented monitoring records described within this text.

Although this study does not present a complete life-cycle carbon inventory, the adopted structural redesign inherently reduced embodied material usage associated with temporary shoring systems and minimized heavy equipment operation within the river zone. Life-cycle assessment (LCA) has been widely recognized as an effective methodology for quantifying embodied carbon in infrastructure projects.[31–33] Future research may expand this framework by incorporating standardized LCA methodologies to quantitatively compare embodied and operational emissions under alternative structural scenarios.

Durability

- Very high load on the pier foundation: design, construction, and inspection

The total length of the AHB is 502 m, including four piers (P9-18, P9-17, P9-16, and P9-15), which serve as the substructure of the bridge. There are three spans that occur on these four piers with span lengths of 225, 150, and 127 m, as shown in Fig. 4. Due to the long span length (225 m) of the AHB, attributed to the adopted ABCSTF design, no pier is required in the Hsindian River flow zone. The extended span length can be counted as the longest one for the train

Figure 12. Site photographs of the safety facilities: (a) external stairs and temporary platform and (b) catwalk with the safety guard rails

transportation system in Taiwan. Therefore, most of the load of the AHB, including the pylon, steel truss frame, and train load throughout the bridge's lifetime, is applied to pier P9-16. Thus, the loading capacity of P9-16 must be sufficient to bear extremely high loads. The live and dead loads of the 375-m truss frame are transferred to the pylon of pier P9-16 by the 12 pairs of steel cables. Undoubtedly, most of the bridge load is borne by pier P9-16. Therefore, a high load capacity must be considered for pier P9-16 and the piles of its foundation.[11]

The foundation of P9-16 is designed to be laid on a 5.5-m-thick foundation slab, which is supported by 42 pieces of 2-m-diameter, 35-m-deep borehole piles. To ensure the successful construction of P9-16 and the other piers, a well-prepared construction work plan,[34] as well as strict on-site quality control (QC) procedures for the piles and pile cap, is required,[35] which best guarantees the durability of the bridge.[11] According to the construction and QC procedures, a qualified QC team was established to conduct strict inspections and testing. All tests and inspection results revealed a high quality in the constructed piles and pile cap. Fig. 13 shows the rebar cage welding of the pile under the supervision of the responsible engineer. Fig. 14 shows the inspection of the foundation by QC engineers.

Figure 13. Rebar cage welding of the pile under the supervision of the responsible engineer

Figure 14. Inspection of the foundation by the QC engineers. QC, quality control

Besides, under durability and risk mitigation considerations, the train speed should be less than 120 km/h to guarantee the train safety.

As shown in Fig. 14, the rebar overlap length, rebar placing spacing, concrete cover thickness, rebar development length, etc., are the essential QC requirements for the reinforced concrete (RC) structure. All the inspection work for these RC structures must be rigorous to ensure the quality and durability of the AHB.

- Pile static loading tests

Since extremely high loads will be applied to the P9-16 pier, verification of the pile capacity is necessary before constructing the P9-16 foundation. The authorized engineer randomly selected the test pile from the 42 piles. When conducting the pile static loading tests, the bearing capacity of the test pile and the friction of the anchor piles are obtained from Eq. (1) as follows:

$$Qu = q_b Ab + \Sigma f_s A_s \tag{1}$$

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

Fig. 15 shows the principle of Eq. (1).

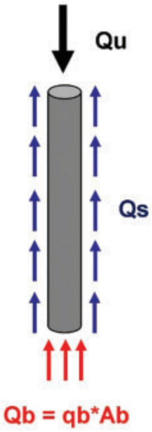


Figure 15. The principle of Eq. (1): $Qu = q_bAb + \Sigma f_sA_s$

In addition, the total bearing capacity of the piles can also be calculated with Eq. (2) as follows:

$$Qs = (Ns/3) * 2\pi * As \tag{2}$$

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

In this case, the total bearing capacity of the test pile and anchor piles was specified by the higher values of Qu and Qs. This also determined the detailed design of the pile diameter and length for the P9-16 foundation/pile cap. The processes below were used to verify that the capacity of the pile satisfied the designed requirements. The engineers established a detailed test procedure for verification of the practical performance of the designed piles.[36] Table 3 lists the above-specified data of the pile test.[11]

Based on Table 3, the maximum test load is calculated with Eq. (3) as follows:

$$max\,\{(2 * normal\ vertical\ load)\,,\, vertical\ earthquake\ load\} + friction\ of\ the\ extended\ portion \tag{3}$$

According to Eq. (3), the maximum test load was calculated as:

Maximum test load = (2,287 + 593.96) tons = **2,880.96** tons = **2,881** tons.

There are two options to apply the test load: concrete mass blocks and hydraulic jack sets. In this case, the engineers selected hydraulic jack sets due to the extremely high load to be provided during the test. Eight 500-ton hydraulic jack sets were assembled to provide sufficient force during the static loading test. Fig. 16 shows the assembly of the pile static loading test.

Testing equipment was placed near the major components, including the hydraulic jack sets, main and secondary anchor beams, reference beams, dial gauges, and monitoring instruments, as shown in Fig. 16. Fig. 17 shows site photographs of the testing equipment.

According to the test procedure,[36] a test pile was selected from among 42 permanent piles, and the neighboring four piles provided the anchor force during the static loading test. The main anchor beam and two secondary beams constituted the reflection members for vertical load transfer, as shown in Fig. 18. A vertical load of 2,881 tons was gradually applied with the hydraulic jack sets. Table 4 lists the pile test sequences along with the loads applied at the 12 specified loading stages.[11,36]

The maximum load was gradually reached after 8 h, and the corresponding pile top measured a settlement of 16.67 mm under the load of 2,881 tons. The load was then slowly decreased after maintaining the maximum load of 2,881 tons for 12 h. At the load release stage, the pile

Table 3. Basic data of the pile test[11,34]

Items	Unit	Values
Length of the piles	Meter (M)	35.0
Diameter of the piles	Centimeter (CM)	200
Length of the extension part	Meter (M)	12.5
Total pile length (including the extension part)	Meter (M)	35.0 + 12.5 = 47.5
Design vertical load (under normal conditions)	Ton	974
Design vertical load (under earthquake conditions)	**Ton**	**2,287**
The friction of the extended portion	**Ton**	**593.96**
Maximum test load	**Ton**	**2,881**
Anchor force during the tests		By the anchor piles
Anchor force supplier		Total of 4 anchor piles, diameter = 2.0 m, length = 47.2 m
Connection rebars to the main anchor beams		SD420W#11-24 × 2 = 48 pieces
Rebar welding length		Fillet weld, length = 16 cm

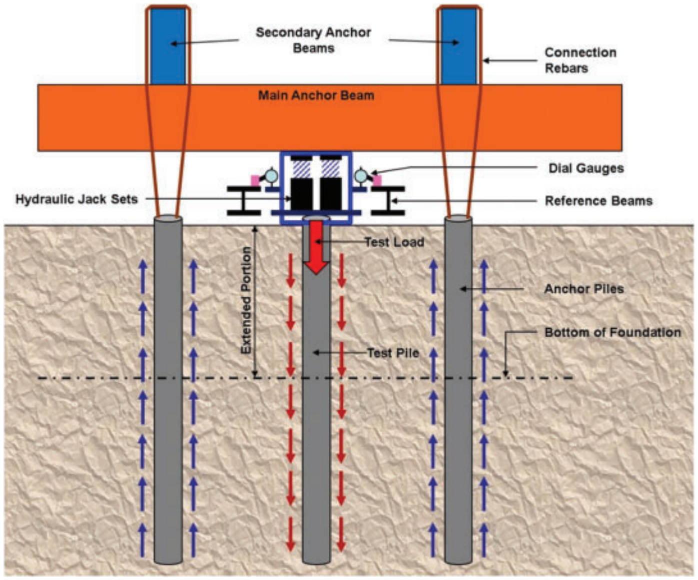


Figure 16. Assembly of the pile static loading test

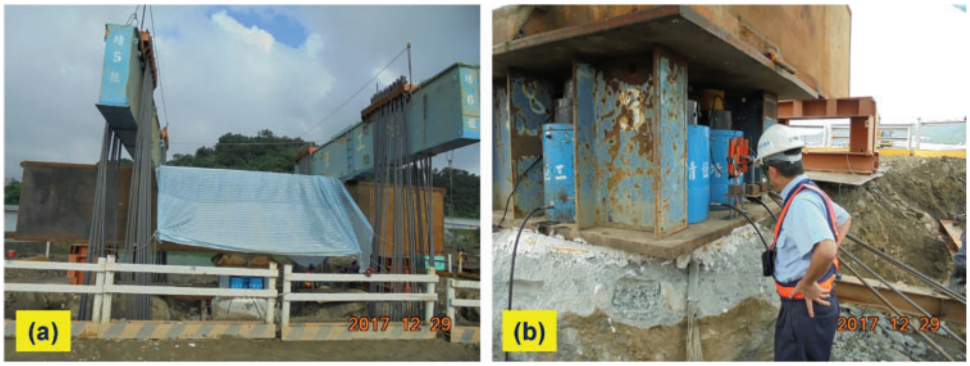


Figure 17. Testing equipment: (a) site test assembly and (b) monitoring instruments evaluated by the responsible engineer

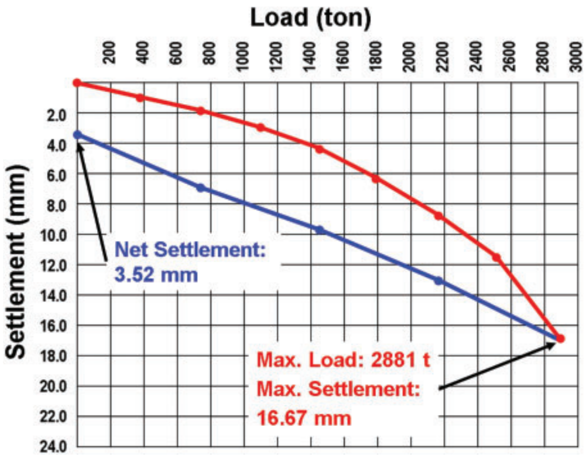


Figure 18. Load-settlement chart of the pile top during the pile static loading test[11]

top settlement was gradually restored. The net settlement, 3.52 mm, was immediately measured during vertical load release. Fig. 18 shows a load-settlement chart of the pile top during the pile static loading test.

The maximum settlement and net settlement verified that the actual pile capacity met the design requirement at a safety factor of 3. The test results indicated an excellent and reliable durability throughout the lifecycle of the AHB.

- Wind force: wind tunnel test

The wind force might cause considerable damage to the bridge structure. To date, bridge collapse has been mainly attributed to an insufficient design considering the horizontal wind force, especially regarding the Tacoma Narrows Bridge collapse. For the AHB of the AKLRM project, the wind force was considered at the design stage. The horizontal force caused by wind, such as that originating from typhoons, might seriously damage the structure of the steel truss frame. The main contractor, NA, conducted the wind tunnel tests[37] to obtain the maximum horizontal displacement caused by such horizontal force. The maximum wind force was calculated using Eq. (4).

$$P = 0.124 * V^2 \tag{4}$$

During the wind tunnel tests, different wind directions, including 30°, 45°, 60°, 90°, 120°, 135°, and 150° relative

Table 4. Pile test sequences along with the load applied at the 12 specified loading stages[11,36]

Specified loading stage	0	1	2	3	4	5	6	7	8
Load percentage (%)	0	12.5	25.0	37.5	50.0	62.5	75.0	87.5	100
Load (t)	0	358	716	1,074	1,433	1,791	2,149	2,507	2,881
The 1st hour		□							
The 2nd hour			□						
The 3rd hour				□					
The 4th hour					□				
The 5th hour						□			
The 6th hour							□		
The 7th hour								□	
The 8th hour									□
The 20th hour							▮		
The 21st hour					▮				
The 22nd hour			▮						
The 34th hour	▲								
Release steps	**12**		**11**		**10**		**9**		**8**

Notes: □: Load increase ▮: Load decrease ▲: Load release.

to the orientation of the steel truss frame, were tested. By adopting the finite element analysis (FEA), the maximum horizontal displacement was computed to be 830 mm under the most critical condition, considering a wind speed of 74 m/s.

The wind tunnel testing methodology, including wind speed selection, directional loading cases, FEA integration, and displacement evaluation criteria, has been described in sufficient detail to ensure methodological transparency. While the original testing plan was archived as an internal engineering document, the aerodynamic loading formulation and performance assessment criteria are fully stated herein and consistent with recognized bridge aerodynamics principles. Consequently, the structural stability verification under typhoon-level wind conditions can be independently assessed based on the information presented.

- Management of extraneous member sizes

The complexity of steel member management in this project arises not merely from quantity but from dimensional variability and geometric similarity among components. Without systematic identification, numbering, and traceability mechanisms, such variability could result in fabrication inconsistencies, incorrect assembly sequencing, and structural alignment deviations. Therefore, the implemented management system was designed to mitigate identifiable fabrication and erection risks rather than solely to improve logistical efficiency.

There is an extremely large number of steel members in the AHB. Every individual piece or steel member is designed in different but similar sizes, shapes, and appearances. This presents an extreme challenge for material management. Thus, a reliable and practical management system for raw materials, covering manufacturing, assembly, transportation, traceability, and erection, should be well discussed and established to perform the construction work without any mistakes.[11] Fig. 19 shows the management concept of materials for AHB.

Engineers established material traceability and steel member management systems for numbering, batching, identification, and verification purposes during the manufacture, transportation, and site installation of the AHB.[38] Implementation of this functional management system resulted in the successful construction of the AHB.

- Steel cable system

The quality of steel cables represents the durability of the AHB. Corrosion protection of cables is the most critical issue in quality assurance processes. Fig. 20 shows the detailed assembly and corrosion protection system for the steel cables. Fig. 21 shows a tendon and an HDPE pipe inspected by the responsible engineer. HDPE, high-density polyethylene.

Landscape and creativity

Based on the 17 sustainable development goals announced by the United Nations in 2015, landscape design is increasingly a concern that must be addressed in new infrastructure projects. In the AKLRM, the shape of the AHB, combined with the pylon and cable-stayed system, resembles a high-flying eagle. This outstanding landscape design reflects the

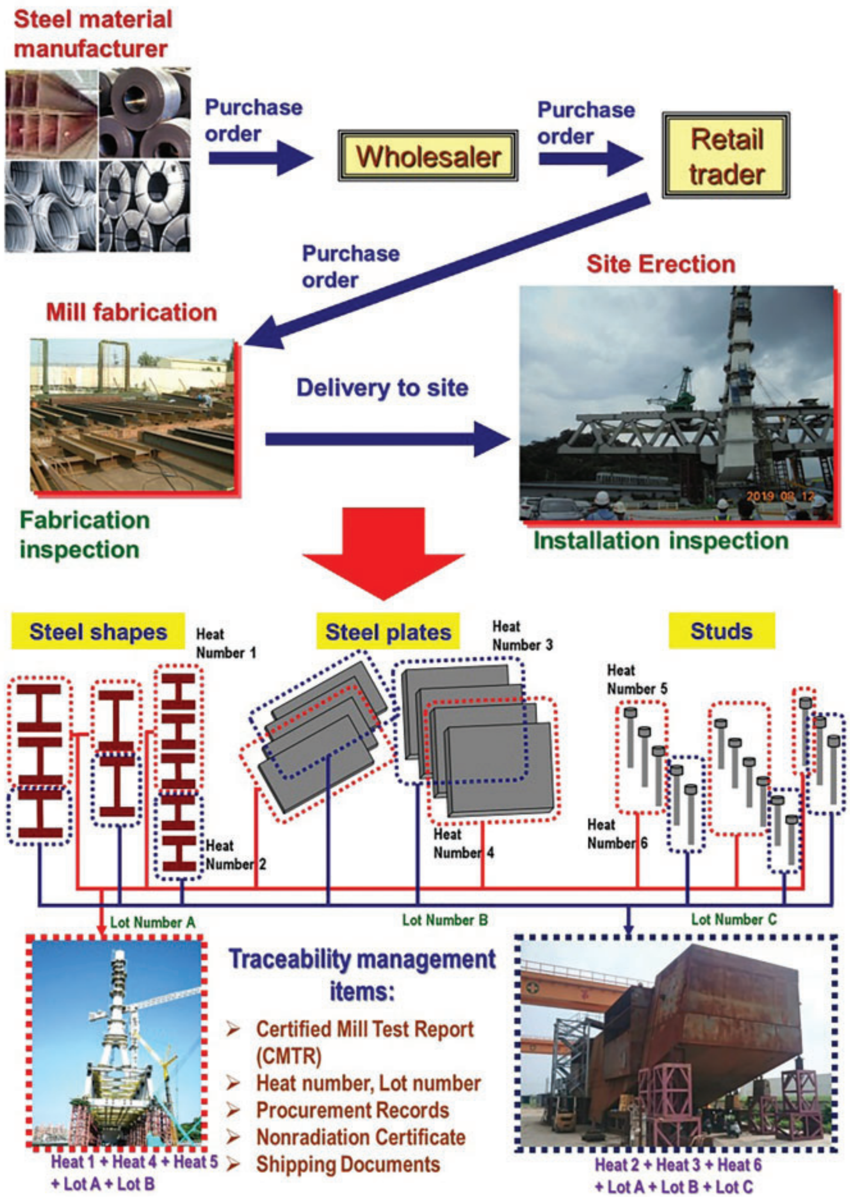


Figure 19. Material management concept of materials for the AHB. AHB, Anhsin Bridge

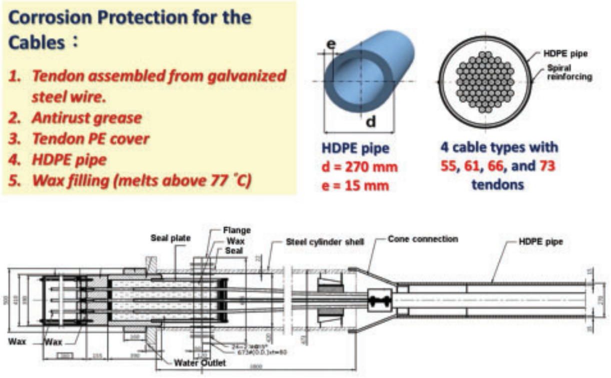


Figure 20. Detailed assembly and corrosion protection system for the steel cables

imagination of humans. Fig. 22 shows the imagined landscape design.

BIM[39] facilitated excellent management of AHB construction by engineers. Every piece was modeled in a 3D format using the BIM technique, including traceable ID numbers, shapes, sizes, installation locations, etc. BIM assisted engineers in efficiently and effectively managing the production, transportation, and erection processes, and enabled the detection of potential conflicts between the different members, which could be resolved prior to installation and/or erection.[11] Fig. 23 shows the BIM-generated images of the AHB and the appearance of the steel truss frame.

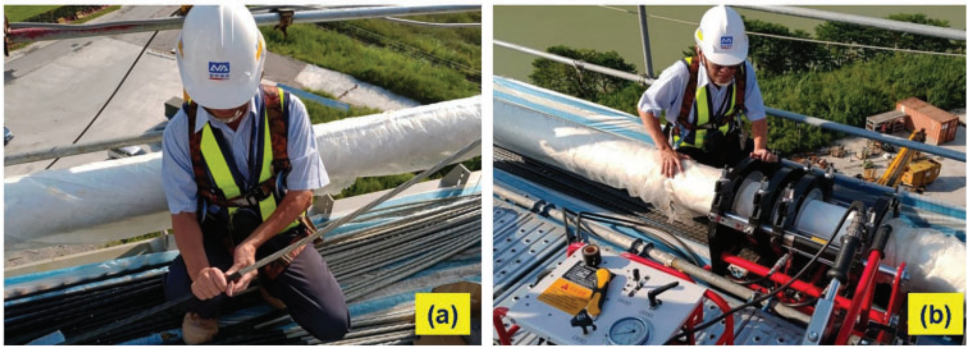


Figure 21. (a) Tendon and (b) HDPE pipe inspected by the responsible engineer. HDPE, high-density polyethylene

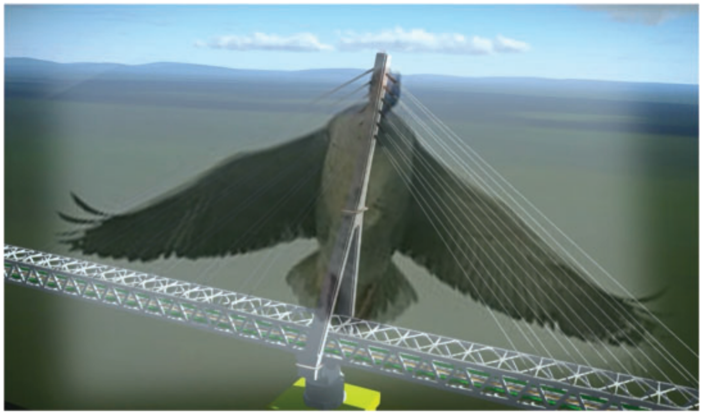


Figure 22. Imagined landscape design

Figure 23. BIM-generated images of the AHB and the appearances of the steel truss-frame. AHB, Anhsin Bridge; BIM, building information modeling

Conclusion

In this paper, the authors conclude that the ABCSTF method for AHB construction successfully achieved various sustainability goals, as follows:

- The newly designed ABCSTF extended the maximum bridge span length up to 225 m. This maximum span length can be counted as the longest one for the train transportation system in Taiwan, and it avoids any pier being located in the Hsindian River flow area.
- The pile loading tests were conducted and obtained a maximum capacity of 2,881 tons with a settlement of 16.67 mm. It is much better than the original design

criteria and guarantees the safety of the AHB during its life cycle.
- The wind tunnel tests present the maximum wind loads up to 74 m/s in different wind directions, including 30°, 45°, 60°, 90°, 120°, 135°, and 150° to the orientation of the steel truss frame, and measured the largest horizontal displacements of 830 mm. This excellent result ensures the safety of the AHB.
- The use of a TFES, with a 48-ton capacity lifting crane, and a heavy-duty tower crane, with the 3,330 m-tons of hanging power, successfully executed the erection of all steel members without any harmful impact on the Hsindian River.
- The application of the material management system and BIM techniques provides traceability for more than 30,000 pieces of member sizes. It assists the construction work without an unexpected mistake during the construction stage.
- The application of the BIM technique also enabled engineers to utilize their talent and creativity in bridge design fully
- The outstanding landscape design of AHB, combined with the pylon and cable-stayed system, resembles a high-flying eagle. It also reflected one of the varied accomplishments of humanity.

Under durability and risk mitigation considerations, the train speed should be less than the speed of 120 km/h to guarantee the train's safety. Therefore, the presented practices successfully adopted in this project in regard to sustainability issues at the design, construction, and operation stages could serve as a valuable reference for other similar bridge projects in the future.

Recommendations for Future Work

Future studies may further investigate long-term structural performance and sustainability outcomes through continuous health monitoring of cable-stayed bridge systems. In addition, quantitative life-cycle carbon footprint assessments under alternative construction scenarios are recommended to enhance comparative sustainability evaluation. The integration of digital twin technologies with sustainability assessment frameworks may also provide advanced decision-support tools for infrastructure planning, construction, and operation.

Availability of the Data and Materials

All data, materials, models, and codes generated or used during the study are provided in the submitted article.

Competing Interests

On behalf of all authors, the corresponding author states that there are no competing interests.

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Disclaimer

Supplementary Materials

None.

Authors' Contributions

- Tai-Yi Liu: Conceptualization, methodology development, sustainability framework integration, case study design, supervision, and manuscript writing.
- Cheng-An Lee: Project data provision, engineering review, validation of construction methods, and technical editing.
- Chao-Pang Wang: Literature review, data analysis, preparation of figures and tables, and draft writing.
- Shih-Ping Ho: Academic guidance, methodological refinement, critical revision, and quality assurance.
- Hong-Kee Tzou: Project implementation support, construction information verification, and review of practical engineering content.

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