Research Report

Research Planning and Experimental Study on Soft Soil Foundation Suspension Bridges

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Abstract: Taking the Jiasong Highway Bridge over Huangpu River in Shanghai as the research background, multiple schemes were proposed for comparison, and detailed scientific research planning was carried out on the basis of the characteristics of soft soil foundations during the project promotion process. Focus on the planning of the scientific research project of the bridge and the implementation of key experiments.

Keywords: soft soil foundation; suspension bridge; scientific research; model test

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1 Overall Design

In recent years, China's bridge construction has made remarkable progress. Suspension bridges have been widely used in river-crossing and sea-crossing projects due to their elegant appearance, excellent spanning capacity and reasonable stress structure. For a long time, people have been looking forward to seeing beautiful suspension bridges such as the San Francisco Golden Gate Bridge and the Oakland Bay Bridge on the Huangpu River. Research on the suspension bridge program began as early as the Yangpu Bridge was constructed.

Conventional ground-anchored suspension bridges require high geologic conditions and large anchorages, making suspension bridges less economical. The presence of creep-slip in the soil body threatens the safety of the superstructure, and the poor mechanical properties of the ultrathick layer of soft foundation even lead to untenable suspension bridge solutions [1,2].

On the basis of the engineering background of the Jiasong Highway Bridge over the Huangpu River in Shanghai, this paper introduces scientific research planning and experimental research on the first suspension bridge on the Huangpu River.

2 Introduction

The project design scope is from Jinping Road in the north to the Songjin Highway in the south, including the intersection of the Jinping Road and the Songjin Highway, with a total route length of 1,825 m.

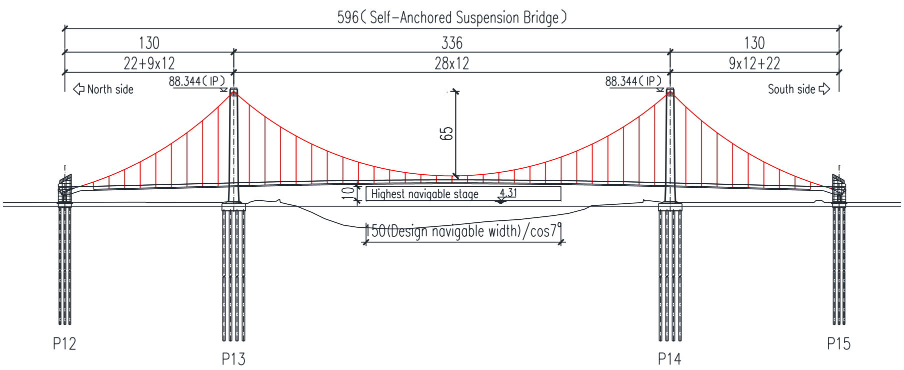

Figure 1 Layout of the Jiasong Highway Bridge over Shanghai Huangpu River (Unit: mm)

The road is designed as a Class II highway with a design speed of 60 km/h. The cross-section consists of 8 lanes in both directions (6 fast lanes and 2 slow lanes) [3]. The total length of the bridge is approximately 1.450 km, including the main bridge and the approach bridges on both sides. The total length of the main bridge is 596 m, and the main span is 336 m.

3 Key Technology

The final recommended scheme for the main bridge of this project is a (130 + 336 + 130) m double-tower, double-cable, composite deck steel box girder self-anchored suspension bridge. In view of the large scale of the bridge project and the unique structural stress, as a key infrastructure project, a series of targeted scientific studies have been carried out in terms of structural safety and reliability.

3.1 Study on the Structural System of Suspension Bridges on Soft Soil Foundations

As the geology of the bridge site is dominated by soft ground, and considering the significant anchorage forces required for traditional ground-anchored suspension bridges, solutions such as partially self-anchored and fully self-anchored suspension bridges were proposed during the project development. The research team proposed for the first time a partially self-anchored suspension bridge structural system suitable for soft ground. Compared with the traditional self-anchored suspension bridge, the partially self-anchored suspension bridge adds a ground anchor structure and an additional anchor cable between the ground anchor and the main girder [4], as shown in Figure 2.

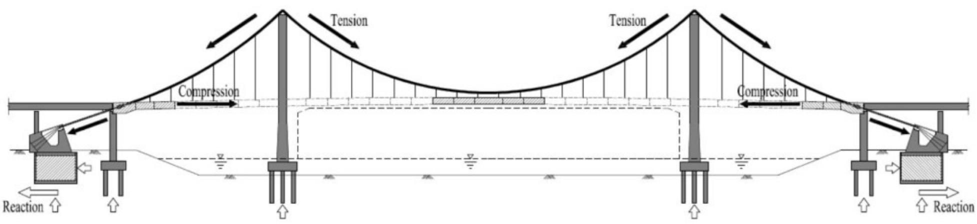

Figure 2 Structural system of the partially self-anchored suspension bridge

During the construction of the partially self-anchored suspension bridge system, ground anchors can first be used to erect the main cable, which is then utilized to lift the main girder (either fully or only for the reserved navigational sections). The tension in the main cable is transferred to the anchorage structures, where the passive earth pressure balances the horizontal forces. After the main girder is closed, the anchor cable can be tensioned to transfer part of the main cable force into compressive forces within the main girder. During both the construction and operational phases, the cable force of the anchor cable is adjustable. This adjustability allows the passive earth pressure to be considered in the anti-sliding stability calculations of the anchorage, thereby reducing the required anchorage weight and offering a novel approach for structural optimization.

As a new type of cable bearing system, the self-anchored suspension bridge not only has the characteristics of the general cable bearing system but also has its own characteristics; that is, it does not need to build a large volume of anchorage, especially when the geological conditions are poor, and this feature is particularly important. Streamlined box girders are used as stiffening girders, and the materials of the stiffening girders can be steel or reinforced concrete materials. The main cables of the self-anchored suspension bridge are not anchored to the anchorages but are directly anchored to the stiffened girders. The force transmission path of the self-

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anchored suspension bridge is as follows (Figure 3): the load is applied to the main girders, the force is transmitted to the main cables through the suspension cables, the vertical force of the main cables is transmitted to the main towers, and the horizontal force is transmitted to the main girders through the anchorage area of the main cables.

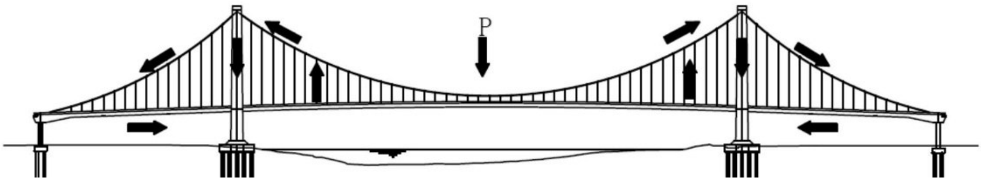

Figure 3 Force transmission path of the self-anchored suspension bridge structural system

In this study, two types of suspension bridge structures are studied in depth from the aspects of structural system mechanics and economic performance, key structural nodes, new stiffening girder structure design methods, key construction technology and intelligent construction technology. It breaks through the traditional suspension bridge structure system and provides a highly competitive alternative for the construction of long-span bridges on soft soil foundations.

3.2 Study on the Wind Resistance Performance of the Main Bridge

In recent years, significant vortex-induced resonance has been observed in many long-span bridges worldwide. To prevent the recurrence of such issues and ensure wind resistance safety during both the completed bridge state and the construction stage, wind resistance performance tests were conducted on the main bridge structure.

A detailed study of the wind resistance performance of the main bridge and aerodynamic improvement measures of the main girder section of the Jiasong Highway Bridge was carried out via finite element analysis, wind tunnel tests of a conventional scale section model and vortex excitation resonance wind tunnel tests of a large-scale main girder section model. After implementing the aerodynamic improvement measures, the flutter stability requirements are satisfied for both the completed bridge and the construction stages. No significant vertical or torsional vortex-induced resonance occurs within a wind attack angle range of ± 5°. The main aerodynamic improvement measures are as follows:

(1) An additional wind nozzle with a tip angle of 64° is used, and the tip of the wind nozzle is level with the top of the sidewalk railing base.
(2) The inspection truss track was relocated 3.625 m to the side of the road centerline.
(3) The central stabilizer plate within the main girder channel has a height of 3.242 m, and its bottom is aligned with the bottom of the service truss car track.

3.3 Study on Seismic Performance of the Main Bridge

Self-anchored suspension bridges are subject to complex stress distributions, which may result in localized damage under seismic loading and consequently compromise the overall structural stability. To investigate this, models of both the semi-floating system and the fully floating system are developed. The dynamic characteristics and seismic phase responses of these two systems are then compared. Nonlinear time history analysis, utilizing E2-level seismic inputs, is conducted to analyze the seismic response of the main bridge. This analysis serves to evaluate the seismic performance of the structure under seismic action and to pinpoint its vulnerable components. Based on the identified vulnerable parts, a feasible solution is proposed to enhance the seismic performance of the structure. Additionally, seismic isolation measures for the main bridge structure are explored.

3.4 Application of Ultrahigh-Performance Concrete in Bridge Deck of Long-Span Self-Anchored Suspension Bridge

Given that the orthotropic bridge deck of steel box girder is prone to fatigue cracking under the repeated action of wheels, steel box girder + high-strength and high-toughness concrete composite bridge deck structure is adopted in this project. Ultra-high-performance concrete (UHPC) materials have undergone rapid development in recent years owing to their exceptional mechanical properties and durability. This project integrates the characteristics of large-span self-anchored suspension bridges by applying UHPC to steel box girder decks, aiming to address the fatigue and durability issues associated with steel bridge decks and their paving. Through research on the material properties of high-strength, high-toughness concrete, reasonable structural parameters for steel bridge decks and high-strength, high-toughness concrete composite bridge decks are proposed.

3.5 Key Construction Technology for Long-Span Self-Anchored Suspension Bridges

A large-span self-anchored suspension bridge has a large structural scale. Initially, the steel beam is constructed, followed by paving bridge deck to form a composite stiffening beam. Subsequently, the system is transformed by tensioning the cables, resulting in the final self-anchored suspension bridge. In this process, the key controlling factors include the construction technology of the steel beam, the alignment of the main beam and main cable, the tensioning of the slings, and the sequence and timing of tensioning. Considering the busy channel and the characteristics of the secondary water source protection area at the bridge site, the construction method of side-span main girder jacking combined with middle-span main girder cable-stayed cables was selected after comparison and evaluation. The process involves first using temporary cables to create the stress state of a temporary cable-stayed bridge to complete the erection and closure of the main girder, then erecting the main cables and tensioning the slings, and finally converting the system into a suspension bridge. The whole construction process is complex, and there are many influencing factors. Finally, a set of advanced key technical achievements in self-anchored suspension bridge construction is formed.

4 Experimental Study

During the project's advancement, a series of experimental studies were conducted, including centrifugal model tests for the self-adaptive anchorage of the suspension bridge and wind tunnel tests for models at different proportional stages of the main girder.

4.1 Centrifugal Model Test of Self-Adaptive Anchorage

The test is aimed at the partial self-anchored suspension bridge structure system proposed in the process of structural system research and comparison.

The current specification is conservative for the checking method of anchorage stability. In fact, the effect of the lateral earth pressure can be reasonably considered in the design of anchorages. Relevant studies have confirmed the positive effect of the soil around the anchorage on improving the stability of the anchorage [5-10], but there is a lack of in-depth systematic research on the design method of anchorages guided by engineering practices considering the lateral earth pressure. At present, most of the research on the stability and displacement of anchorages is carried out via the finite element method and indoor model experiments. To reflect the long-term deformation characteristics of soft soil, centrifuge experiments are needed to improve research in related fields. On this bridge, numerical simulations and static centrifuge tests were conducted to reveal the distribution law and displacement characteristics of the lateral earth pressure on anchorages in soft soil areas. Building

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on the current standard method, a design method for anchorages considering lateral earth pressure is proposed.

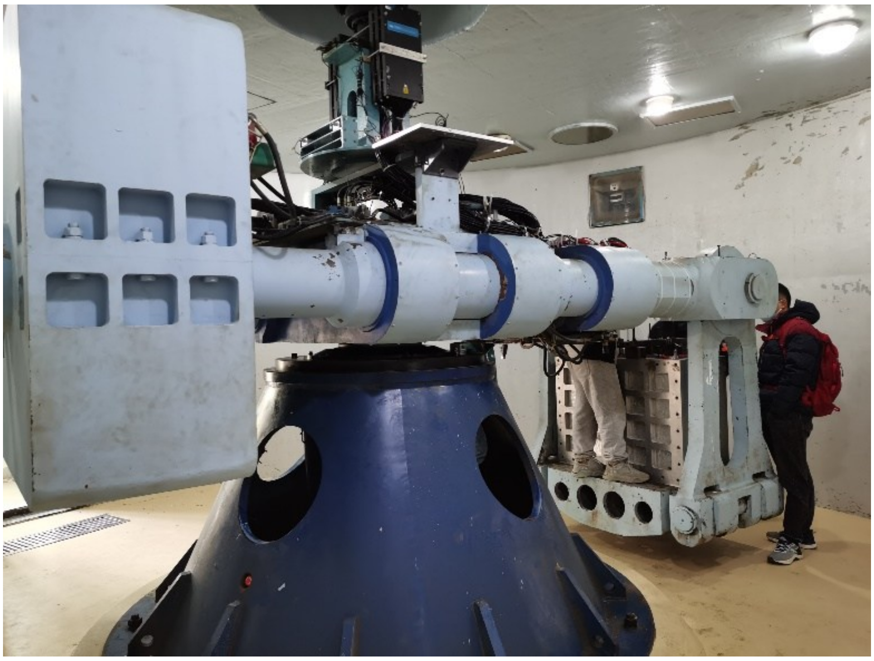
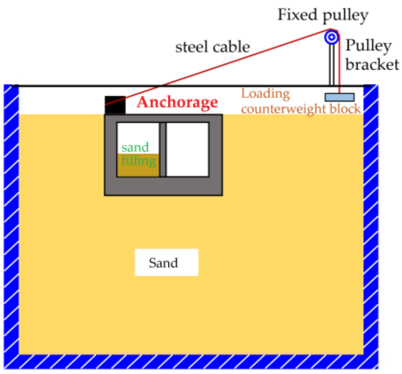
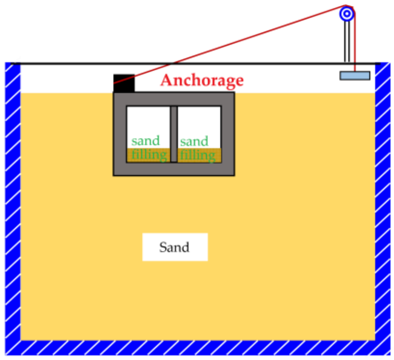


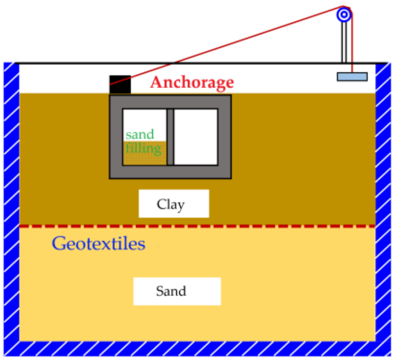
Figure 4 Centrifuge model test conditions



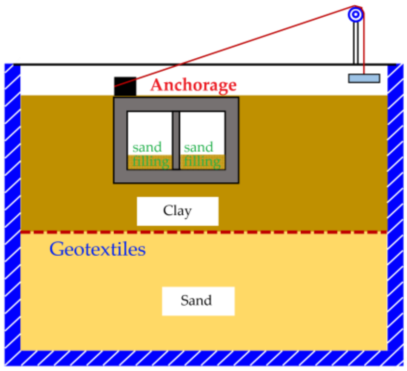
a) Sand around the anchorage, sand filling on the left side (SL)



b) Sand around the anchorage, uniform sand filling (SU)



c) Clay around the anchorage, sand filling on the left side (CL)



d) Clay around the anchorage, uniform sand filling (CU)

Figure 5 Centrifuge model test conditions

The centrifugal model test is illustrated in Figure 4, with four operating conditions considered, as shown in Figure 5: (1) SL working conditions: sandy soil was utilized for the test, with the soil piled on the left side within the anchor anchorage; (2) SU working conditions: sandy soil was employed for the test, with a uniformly distributed mound of soil inside the anchorage; (3) CL conditions: soft clay soil was utilized for the test, with the soil piled on the left side within the anchor anchorage; and (4) CU working conditions: soft clay soil was employed for the test, with the soil uniformly piled inside the anchor anchorage. Before the experiment, several groups of direct shear tests were carried out on the soil samples to determine the strength parameters of the sand used in the test. Representative test results are presented in Figure 6. The results indicate a linear relationship between shear stress and vertical pressure, and the slope of the straight line can be used to approximate the internal friction angle (φ_s) of sandy soils. In the test, the sandy soil was filled and compacted in layers, and the mass density of the sandy soil in each layer was ensured to be approximately 1.62 kg/cm³. The sandy soil filling process is shown in Figure 7.

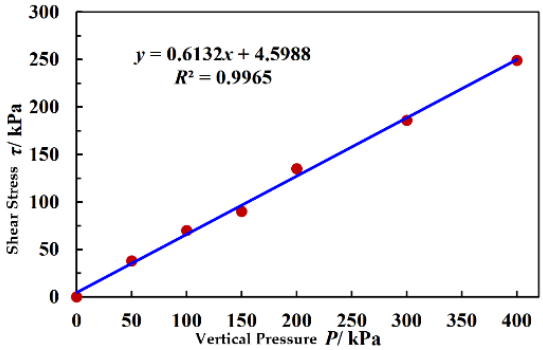


Figure 6 Results of the direct shear test of the sand used in the test

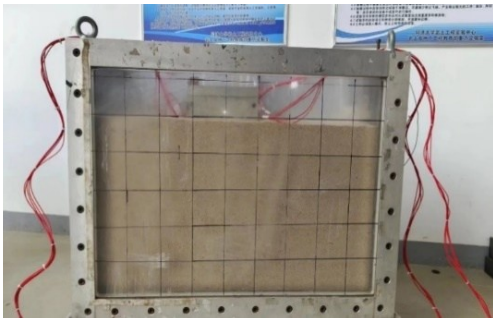


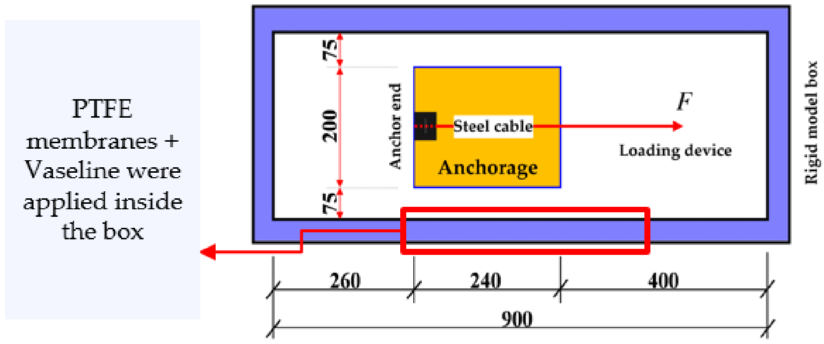
Figure 7 Filling the sand to the bottom of the anchorage

The centrifugal acceleration during the test was set to 100 g. Table 1 presents the scale relationships of the centrifuge model, also referred to as similarity ratios. The preliminary design scheme for the anchorage prototype is a diaphragm wall foundation with dimensions of 24 × 20 × 20 m. The dimensions of the test model were designed based on similarity ratio, and the model was constructed by aluminum alloy. Since this test does not focus on structural internal forces or section stresses, the design primarily ensures that the anchor dimensions and gravity adhere to the similarity ratio relationship.

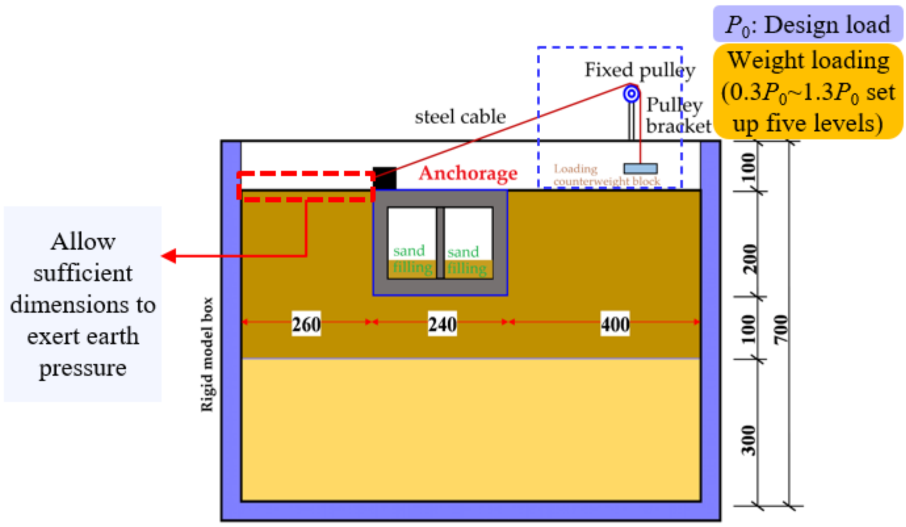
Table 1 Scale relation of centrifuge model

Physical quantity	Dimension	Unit	Scale ratio
Acceleration	LT^{-2}	m/s²	100
Length	L	m	1/100
Area	L^2	m²	1/100²
Volume	L^3	m³	1/100³
Mass	M	kg	1/100³
Earth Pressure	$ML^{-1}T^{-2}$	kPa	1
Pressure	$ML^{-1}T^{-2}$	kPa	1
Concentrated Force	MLT^{-2}	kN	1/100²

The test utilized a 90 × 70 × 70 cm model box, with the relative position of the anchor model to the box illustrated in Figure 8. This ensured sufficient distance on both sides of the anchor to exert earth pressure. To minimize boundary effects, Vaseline and PTFE membranes were applied inside the box to reduce friction. Loading was applied using weights, with five levels of load. 15 earth pressure cells were installed on the passive loaded side at the axis, 1/4 width, and near the edge of the anchor. Additionally, 10 earth pressure cells were placed on the active loaded side (i.e., the left side).



a) Top view



b) Front view

Figure 8 Layout of anchorage model (Unit: mm)

The results of the test revealed the following:

(1) Under the action of the main cable tension, the soil surrounding the soil-facing surface of the anchorage exhibited a passive stress state, with the earth pressure initially increasing and then decreasing with burial depth. Conversely, the soil around the back soil surface demonstrates an active stress state, with the earth pressure increasing with depth.

(2) For gravity anchor foundations embedded in sandy and soft clay soils, the combined earth pressure on the anchor's side can provide significant horizontal resistance.

(3) Eccentric filling on one side of the anchor tension point can effectively reduce the overall horizontal displacement and rigid rotation angle of the anchorage under the main cable tension [11].

4.2 Wind Tunnel Model Test

According to the theoretical analysis results, in the two design schemes of the main bridge, the design scheme of the fully floating system does not meet the requirements of flutter stability, and the design scheme of the semi-floating system barely meets the requirements of flutter stability. Through the improvement of the aerodynamic shape, the stiffening girder of the two structural schemes is changed from the original bilateral rib section to the P–K section, and the flutter critical wind speed of the fully floating system and the semi-floating system is significantly improved. Because the theoretical estimation has a certain approximation, further wind tunnel test verification is needed. The conventional proportional wind tunnel model test of the main beam and the large-scale wind tunnel model test of the main beam are mainly carried out.

4.2.1 Rigid Segment Model Test of Conventional Proportional Girder

Conventional scale main girder rigid body segment model tests were carried out separately for flutter and vortex vibration tests, as shown in Figure 9. The tests were conducted via a spring-suspended binary rigid body segment model, i.e., the segment model was suspended by eight springs on an externally mounted bracket. According to the section size of the main girder of the real bridge, the size of the wind tunnel test section and the requirements of the direct test method, the scale ratio of the conventional proportional segment model of the main girder is taken as $\lambda_L = 1/50$, and the total length of the model is taken as 1.74 m.

Figure 9 Wind tunnel test of rigid segment model of conventional proportional girder

In addition to the geometrical similarity between the model and the real bridge, the wind tunnel test of the spring-suspended binary rigid body segment model should, in principle, satisfy the consistency conditions of the following three groups of dimensionless parameters:

Elastic parameters: $U/(f_v B)$, $U/(f_t B)$ or f_t/f_v (frequency ratio)

Inertia parameters: $m_{eq}/(\rho b^2)$, $J_{meq}/(\rho b^4)$ or r_e/b (inertial radius ratio)

Damping parameters: ξ_v and ξ_t (damping ratio)

where U is the average wind speed; f_v and f_t are the intrinsic frequencies of bending and torsional vibration, respectively; B is the bridge width; b is half-bridge width; m_{eq} and J_{meq} are the equivalent mass per unit bridge length and the equivalent mass moment of inertia, respectively; ρ is air density; r_e is the equivalent slewing radius; ξ_v and ξ_t are the damping ratios of vertical bending and torsional vibration, respectively.

The results show that when the main bridge with semi-closed composite beam scheme is in the finished state, the vertical and torsional vortex-induced resonances with amplitude exceeding the allowable value will occur in the original main girder section under the wind attack angle of ±5° in the uniform flow field. After the combination of aerodynamic improvement measures is adopted, when the bridge is completed, the vertical and torsional vortex-induced resonance with amplitude exceeding the allowable value will not occur at +3°, 0°, -3°, and -5° wind attack angles, but the amplitude at +5° wind attack angle will be slightly larger than the allowable value of vertical vortex-induced resonance.

4.2.2 Large-Scale Rigid Girder Segment Model Test

The purpose of the wind tunnel test of the rigid body section model of the large-scale main girder is mainly to test the vortex-induced resonance performance of the bridge under the action of normal wind when the bridge is completed. In the test, the wind attack angles were +5°, +3°, 0°, -3° and -5° (e.g., Figure 10). The test was conducted via a spring-suspended binary rigid body segment model, i.e., the segment model was suspended on a built-in bracket by eight springs. According to the section size of the main girder of the real bridge and the size of the test section in the wind tunnel as well as the requirements of the direct test method, the scaling ratio of the main girder large-scale segmental model is taken as $L = 1/25$, and the total length of the model is taken as 3.6 m. The skeleton of the rigid segmental model is composed of metal aluminum, and the bridge deck is simulated with aerospace boards to guarantee the geometrical similarity of the shapes. The bridge formation considers the crash barriers, pedestrian railings and service vehicle tracks located on the bridge deck. The crash barriers, pedestrian railings and access rails are computer-generated from Plexiglas and ABS plastic sheets.

Figure 10 Wind tunnel test of rigid segment model of large-scale main girder

The results show that after the combined scheme of aerodynamic improvement measures is adopted, the main bridge does not experience significant vertical and torsional vortex excitation resonance for wind angles of attack in the range of ±5° [12].

5 Conclusions

This article introduces the scientific research project planning at the beginning of the scheme design of the Jiasong Highway Bridge and the experimental research carried out in the later period, which provides a strong support for the scheme comparison and determination, and lays a solid foundation for the promotion of the follow-up project.

Conflict of Interest: All authors disclosed no relevant relationships.

Data Availability Statement: Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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