Scientific Research

Sensitivity Analysis of Construction Control Parameters for Long-Span Hybrid Girder Rigid Frame Bridges

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Abstract: In the actual construction process, there are many factors that affect the alignment and structural performance of bridges, and their influence on bridge structures should not be underestimated. This paper conducts a simulation analysis of a large-span hybrid girder rigid frame bridge using Midas/Civil2020. Deflection values in the completed state are used as evaluation criteria. Sensitivity analysis is performed on construction control parameters such as the self-weight of the girder, girder stiffness, prestressing parameters, environmental temperature, and unbalanced basket weight. This analysis determines the degree of influence of these parameters on the bridge structure, providing a basis for bridge monitoring during actual construction and offering relevant monitoring recommendations.

Keywords: hyper girder rigid frame bridge; finite element calculation; sensitivity parameter analysis

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1 Introduction

With the development of society and advancements in science and technology, various types of bridge structures have been continuously emerging. Compared with the general continuous girder bridge and continuous rigid-frame bridge, the hybrid girder continuous rigid frame bridge not only retains the advantages of a continuous girder, without an expansion joint and smooth running but also maintains the advantages of a T-shaped rigid-frame bridge without the need for supports and system conversion. While facilitating construction, it additionally leverages the low dead weight characteristics of the steel box girder by replacing a section of the main span's concrete box girder with a steel box girder, resulting in a reduction in the structure's overall weight. The structure bending moment distribution of the bridge is more reasonable, and the bridge crossing capacity is significantly enhanced [1]. With its advantages of a simple structure, clear force, a short construction period and a low project cost, the hybrid girder rigid frame bridge has shown broad application prospects in the field of bridge engineering [2]. In 2006, the first large-span hyper girder rigid frame bridge in China, the Chongqing Shibanpo Yangtze River Bridge with a main span of 330 m, was opened to traffic. In 2015, the Wenzhou Ouyue Bridge, located in the Wenzhou section of Zhuyong Expressway in Zhejiang Province, was officially opened to traffic. This bridge features a main span of 200 m, with an 80 m steel box girder in the span. In December 2018, the Yushan Bridge, located on the island of Daishan County, Zhoushan City, Zhejiang Province, was completed. The main span measures 260 m, featuring an 85 m steel box girder. On August 4, 2022, the construction of the ballastless track of A Bay Bridge was completed. The main span measures 300 m, featuring a 108 m steel box girder. It is expected to be completed and opened to traffic in June 2023 [3-5].

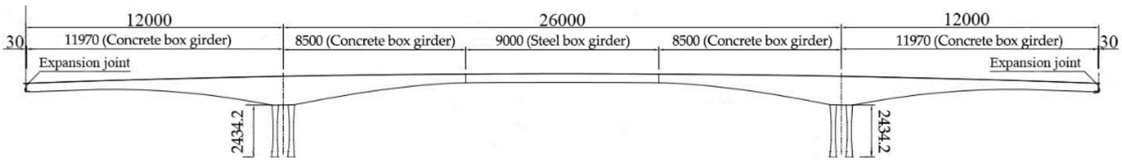
During the construction process, the alignment of the bridge is susceptible to various factors, such as structural weight, main beam stiffness, concrete shrinkage and creep, prestress tension, and temperature effects. These factors can result in certain deviations between the actual alignment of the bridge structure and the theoretical design values. To achieve the theoretical state of the bridge and ensure smooth closure, construction monitoring has become an integral part of the bridge construction process [6-8]. However, in the actual construction process, there are numerous factors that influence the alignment and structural performance of the bridge, making it challenging to accurately identify all these factors during the monitoring process. Consequently, many scholars have conducted research and analysis based on actual bridge projects to investigate the primary factors affecting the bridge's completion state. However, due to variations in bridge design, construction procedures, and environmental conditions, the impact of various construction control parameters on the mechanical properties of bridges also varies.

The main span of a hybrid girder rigid frame bridge is 260 m, ranking among the top in the country, with a 90 m steel box girder used in the middle span. In this paper, Midas/Civil2020 finite element analysis software was used to simulate the bridge, using the deflection value of the bridge in its completed state as the evaluation criterion. Sensitivity analysis was carried out on construction control parameters such as the box girder self-weight, box girder stiffness, prestress parameters, ambient temperature, and weight imbalance of the hanging basket. This study provides a foundation for bridge monitoring work during the actual construction process to ensure the smooth completion of construction monitoring efforts.

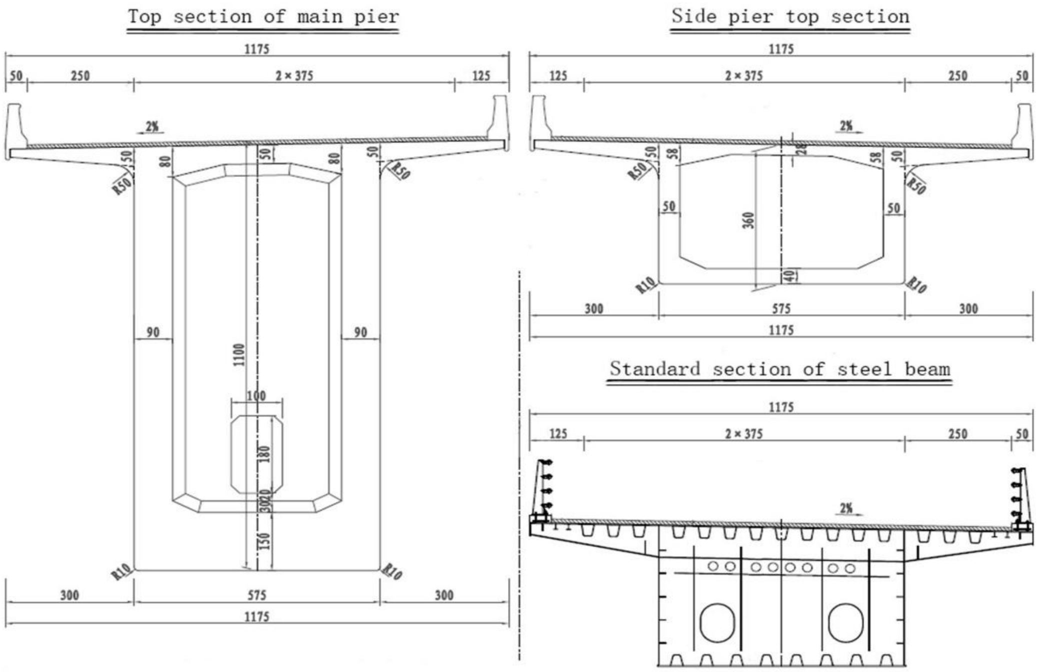
2 Project Overview

2.1 Overview of the Main Bridge Structure

The bridge is a three-span steel–concrete continuous rigid frame bridge, with a 90 m steel box girder used for the main span and concrete girders for the side spans. The bridge span arrangement is (120+260+120) = 500 m. The bridge structure is illustrated in Figure 1.



(a) Elevation diagram of the main bridge



(b) Standard cross section of the main beam

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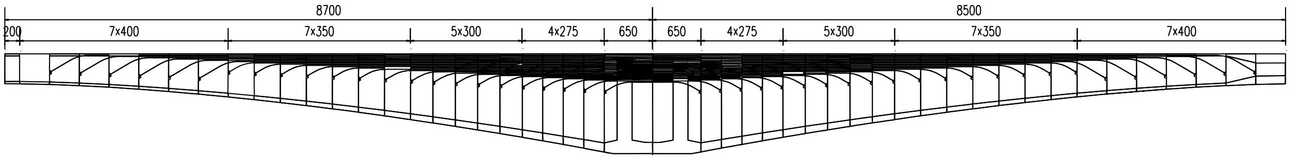
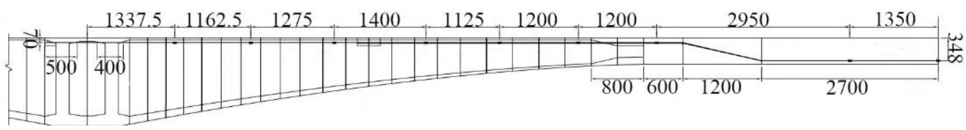


(c) Layout diagram of internal prestressing tendons



(d) Layout diagram of external prestressing tendons

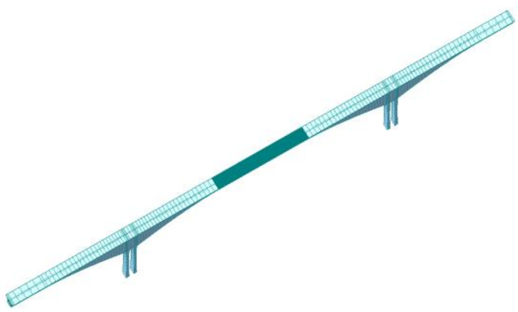
Figure 1 Structural diagram of the main girder (Unit: cm)

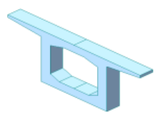
2.2 Material Parameters

The main concrete beams are made of C60 concrete, the primary piers are made of C55 concrete, the main steel box girders are made from Q345qD high-strength structural steel, and the prestressed tendons utilize high-strength, low-relaxation 1860 steel strands. The above material parameters are set according to the Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG 3362-2018) and Specifications for Design of Highway Steel Bridge (JTG D64-2015). The second phase of the dead load mainly includes the bridge deck pavement and anti-collision guardrail. The weight of the bridge deck pavement is 25.8 kN/m in the concrete beam section and 18.06 kN/m in the steel box beam section. The weight of the crash barrier (single side) is 11.7 kN/m in the concrete beam section and 7.3 kN/m in the steel box beam section. The vehicle load class is Highway Class I, and the temperature gradient, braking force and impact force of the vehicle load are calculated in accordance with relevant regulations.

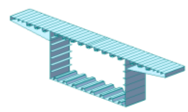
3 Finite Element Model

As shown in Figure 2 and Figure 3, this paper utilizes beam elements for modeling and analysis of the main bridge.





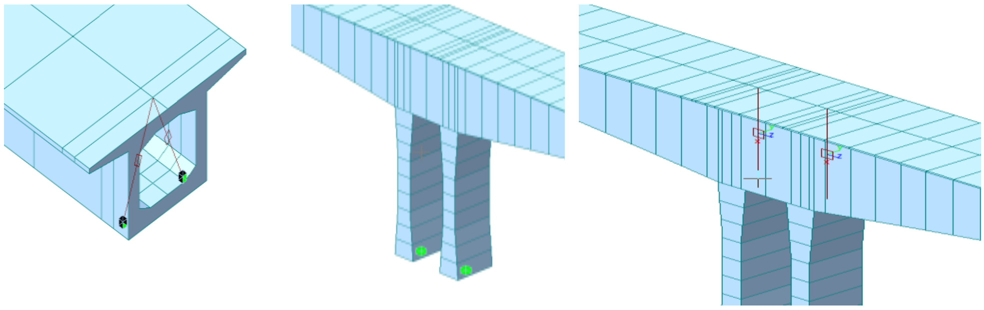
(a) Concrete beam section



(b) Steel beam section

Figure 2 Finite element model **Figure 3** Model cross-section

The overall coordinate system of the calculation model was defined as follows: the x-axis is the longitudinal bridge direction, the y-axis is the transverse bridge direction, and the z-axis is vertical. The main beam and pier were simulated by beam elements. The simulation of the boundary conditions was as follows: (1) block #0 of the box girder and the main pier were consolidated through the rigid connection in the elastic connection; (2) the main pier and side pier were established at the actual position of the support, and the corresponding degrees of freedom were restricted according to the drawings. The support node and beam node of the side pier were set with elastic connection rigidity, as shown in Figure 4 below.



(a) Side pier constraints (b) Main pier bottom constraints (c) Block 0# of girder consolidated with main piers

Figure 4 Boundary conditions

4 Construction Phase Division

The main bridge adopts the construction method of a hanging basket and cantilever pouring. During the finite element analysis of the construction stage, three main construction phases are established, namely, the construction of the main pier and concrete main beam, the construction of the steel main beam, and the second phase. The specific construction procedure settings are shown in Table 1 below.

Table 1 Main bridge construction phase division.

Construction phase	Construction Location	Construction content
CS1	Main pier	Pouring the main pier concrete
CS2~CS4	0#	Pouring concrete for segment 0# block Tensioning the prestressing tendons for segment #0 block Installing hanging basket and adding counterweights
CS5~70	1#~22#、22′#	Pouring cast-in-place concrete segments Tensioning prestressing tendons Moving hanging basket forward and adding counterweight
CS71~CS74	Side span 23#	Pouring cast-in-place concrete segments Tensioning prestressing tendons Moving hanging basket forward and adding counterweight
	Side span cast-in-place segment	Pouring cast-in-place concrete segments
	Side span closure segment	Adding counterweight Pouring cast-in-place concrete for the closure segments Tensioning prestressing tendons Removing side-span hanging baskets
CS75~CS77	Middle-span 23#	Pouring cast-in-place concrete segments Tensioning prestressing tendons Removing mid-span hanging baskets and adding lifting equipment
CS78~CS79	Steel beam section	Hoisting steel beam segments Tensioning external prestressing tendons Removing lifting equipment
CS80	Secondary load	Secondary load
CS81	Shrinkage creep	Ten years of shrinkage and creep

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5 Sensitivity Analysis

5.1 Analysis Procedure

The steps of the sensitivity analysis adopted in this paper are as follows:

(1) The variation range of the parameters is essentially limited to approximately 10%, with the stiffness variation range set at 20%.

(2) The mid-span deflection of the bridge structure is chosen as the control target, and the maximum deflection range of the main bridge is calculated by adjusting the corresponding parameter values using the structural analysis system.

(3) The main design parameters and secondary design parameters are determined based on their influence level.

5.2 Analysis Result

5.2.1 Box Girder Dead Weight

Due to the influence of on-site construction equipment, materials, personnel, and other factors, the actual weight of the box girder during the construction process inevitably deviates from the theoretical value. In this paper, changes in box weight of ± 2%, ± 5%, and ± 10% are considered, and their impact on the final bridge deflection is illustrated in Figure 5 below.

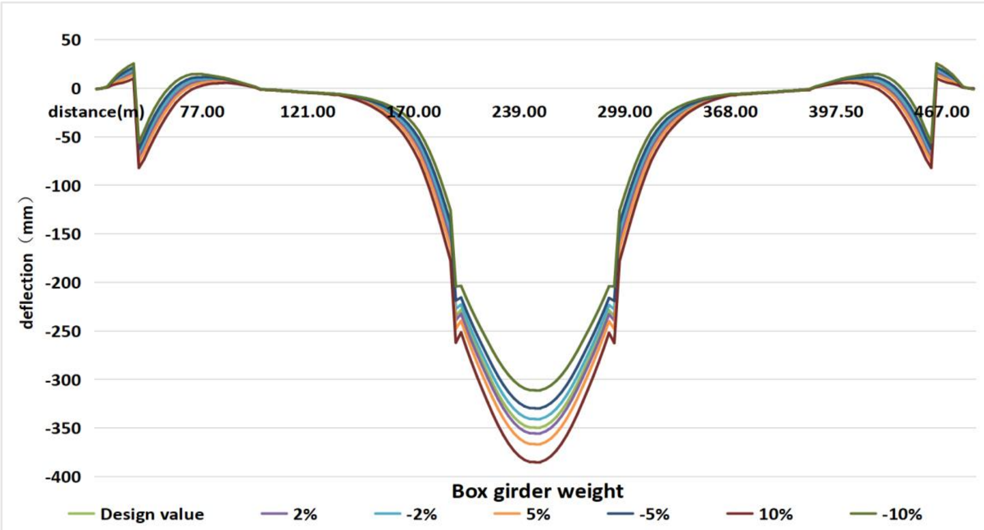


Figure 5 Construction sensitivity analysis results of the box girder dead weight

The calculation results indicate that as the dead weight of the box girder changes, the alignment of the bridge also undergoes variations, with the deflection of the middle span steel beam experiencing the most noticeable alteration. When the self-weight decreases, the bridge deflection decreases upward. Conversely, when the dead weight increases, the bridge's deflection tends to increase downward. Specifically, when the self-weight increases by 10%, the deflection of the mid-span main beam increases by a maximum of 37.93 mm, resulting in a relative change rate of 11% compared to the design value.

5.2.2 Box Girder Stiffness

To analyze the influence of stiffness on the alignment of the long-span rigid frame bridge, the stiffness of the C60 concrete box girder and Q345qD steel box girder was simulated, with stiffness parameter changes of ±5%, ±10%, ±15%, and ±20%. The changes in the deflection of the completed bridge under its self-weight were calculated. The results are shown in Figure 6 below.

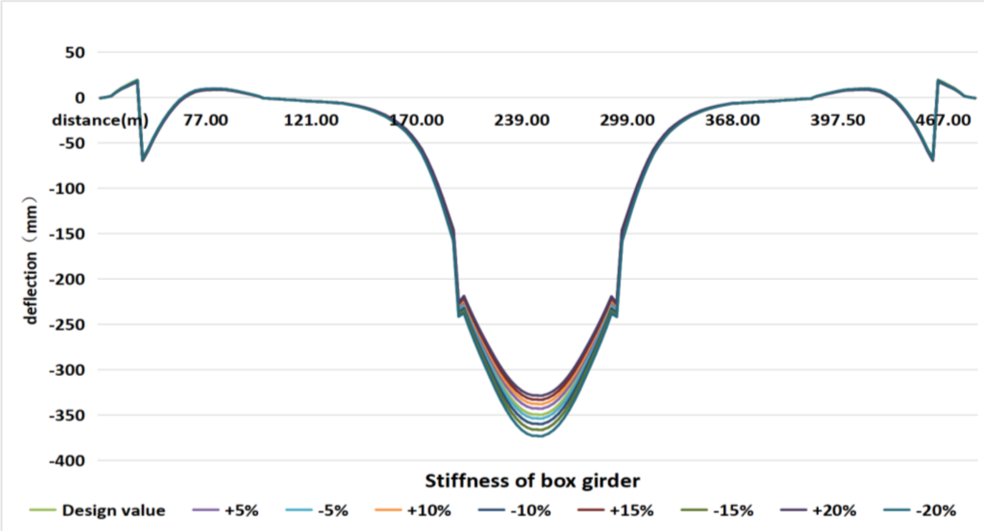
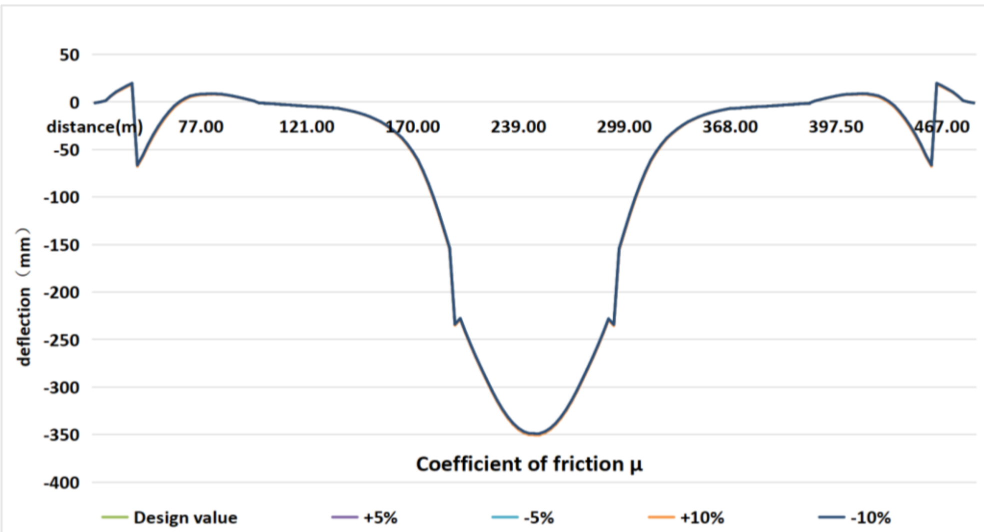


Figure 6 Results of the sensitivity analysis of the box girder stiffness

As seen from Figure 6, as the box girder stiffness increases, the vertical displacement of the main beam gradually decreases. The calculation results show that when the box girder stiffness increases by 10%, the maximum impact on the bridge's deflection is 10.1 mm, resulting in a relative change rate of 3% compared to the design value.

5.2.3 Prestressing Parameters

From the results of previous sensitivity analysis studies, it can be observed that the stress loss in prestressed tendons has an impact on the alignment of the bridge girder [6, 7], with stress loss due to friction being one of the most significant factors. The stress loss due to friction is primarily related to two coefficients, μ (the coefficient of friction between the prestressed tendons and the duct) and k (the coefficient representing the effect of duct deviations on friction). In this paper, both coefficients, μ and k, were simulated with variations of ±5% and ±10%, respectively, to calculate their influence on the deflection of the completed bridge. The results are shown in Figure 7 below.



(a) Sensitivity analysis results for the friction coefficient μ

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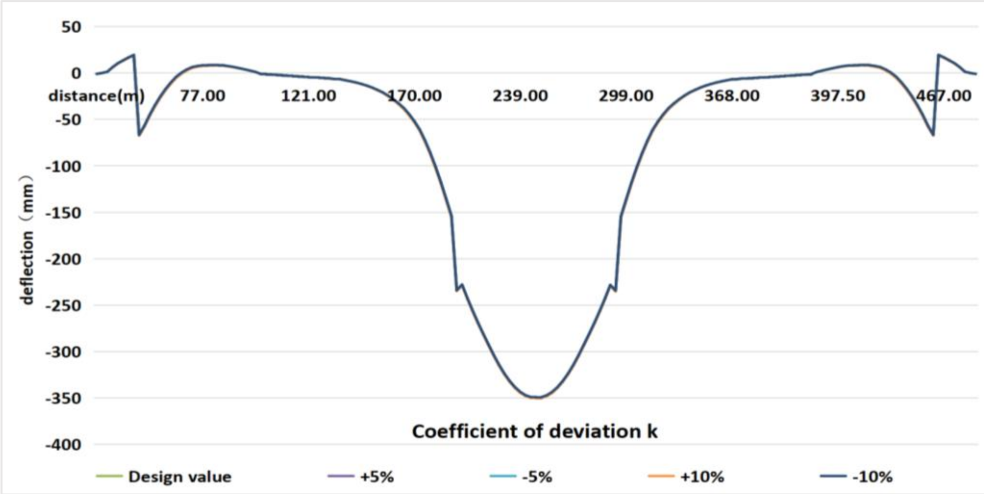


(b) Sensitivity analysis results for the coefficient k

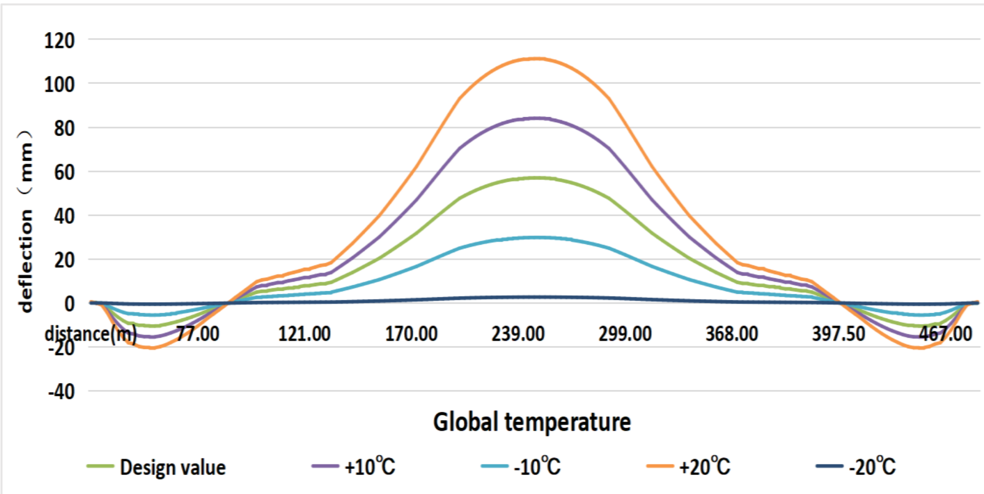
Figure 7 Results from the sensitivity analysis of the prestress parameters

From Figure 7, it can be observed that although the values of the friction coefficient μ and the deviation coefficient k of the passage differ, they have minimal impact on the alignment of the completed bridge, with the maximum deflection change not exceeding 1 mm. When μ is increased by 10%, the maximum deflection change in the mid-span steel box beam section is 0.59 mm, which corresponds to a relative change of 0.2% compared to the design value. Similarly, when k is increased by 10%, the maximum deflection change in the mid-span steel box beam section is 0.58 mm, resulting in a relative change of 0.2% compared to the design value.

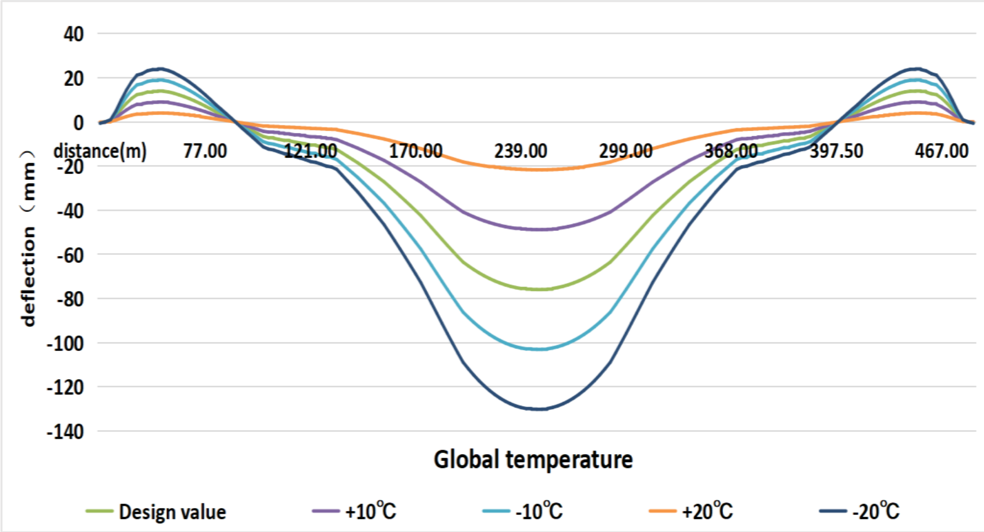
It is worth noting that there are many factors that can lead to changes in prestress steel stress, such as over-tensioning, wedge relaxation, prestress steel stress relaxation, concrete shrinkage, and creep, among others. The loss of prestress caused by friction is just one of the most significant factors, and simply changing the values of μ and k will not lead to significant changes in prestress steel stress. The results in the above figure also confirm this conclusion.

5.2.4 Ambient Temperature

To analyze the influence of ambient temperature changes on bridge deformation, simulations were conducted for both overall temperature increases and decreases of ±10℃ and ±20℃. The design value for the overall temperature increase is +21℃, and that for the overall temperature decrease is -30℃. The calculation results are shown in Figure 8 below.



(a) Sensitivity analysis results for the overall temperature increase



(b) Sensitivity analysis results for the overall temperature decrease

Figure 8 Sensitivity analysis results for the ambient temperature

From Figure 8, it can be observed that under an overall temperature increase, the lateral spans of the main bridge experience downward deformation, while the mid-span of the main girder undergoes upward deformation. Furthermore, as the temperature increases, the deformation values gradually increase. Conversely, under an overall temperature decrease, the lateral spans of the main bridge experience upward deformation, while the mid-span of the main beam undergoes downward deformation. Again, as the temperature decreases, the deformation values gradually increase. In both cases, the maximum deformation occurs at the mid-span. When the overall temperature of the box girder increases or decreases by 10°C, the deformation at the mid-span of the bridge increases by 27.12 mm, representing a change of approximately 36% relative to the design value.

5.2.5 The Imbalance in the Weight of Hanging Baskets

In the actual construction process, due to the need for hoisting the steel box girder segments during mid-span closure, there is a difference in weight between the mid-span and side-span hanging baskets. To analyze the influence on the deformation of the bridge, this paper conducted simulated calculations with weight differences of 10 t, 20 t, and 0 t (uniformly using the mid-span hanging basket weight) for both the side-span and mid-span hanging baskets. The calculation results are shown in Figure 9 below.

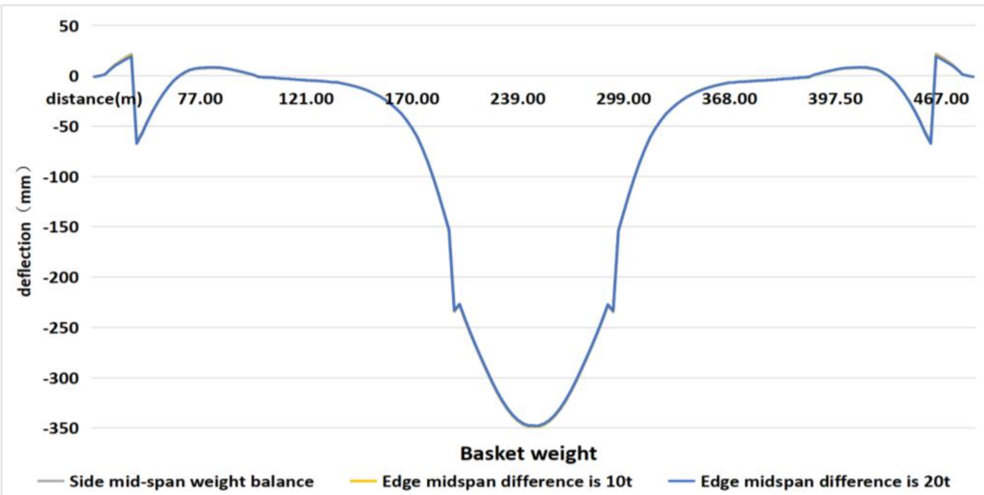


Figure 9 Sensitivity analysis results for the imbalance weight of hanging baskets

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From Figure 9, it can be observed that the imbalance in the weight of hanging baskets between the edge and middle spans has a relatively minor impact on the alignment of the main girder during bridge construction. Notably, there is a relatively larger change in deflection at the side span closure, with a maximum value of 2.2 mm. When there is a 10-ton difference in weight between the side and middle span hanging baskets, the deflection at the side span closure increases by 1.2 mm, while the deflection at the middle span steel beam section decreases by 0.66 mm. The relative change rate in deflection, compared to when the edge and middle span hanging baskets have the same weight (using the weight of the middle span hanging basket as reference), is approximately 0.19%.

6 Conclusions

Through simulation and modeling using Midas/Civil 2020 finite element analysis software, a study was conducted on a large-span hybrid girder continuous rigid frame bridge with a main span of 260 meters. The research aimed to assess the impact of various construction parameters on the alignment of the completed bridge. The main conclusions are as follows:

(1) Among the construction control parameters considered in this paper, changes in ambient temperature have the most significant impact on the alignment of the bridge structure, followed by the self-weight of the box girder, box girder stiffness, and, to a lesser extent, the imbalance in the weight of hanging baskets between the edge and middle spans, as well as prestress losses caused by duct friction. Therefore, during the construction process, it is crucial to monitor temperature closely and rigorously control material parameters such as concrete mix ratios and steel quality to ensure that the actual alignment of the main girder aligns with the theoretical design. The effects of the imbalance in the weight of hanging baskets between the side and middle spans and prestress losses due to the interaction between prestressed tendons and duct friction have relatively minor impacts on the alignment of the main girder and can be appropriately considered during design and monitoring.

(2) Ambient temperature has a significant influence on the deflection of the middle span of the bridge. Therefore, during bridge construction, it is advisable to perform mid-span closure during periods with lower and stable temperatures to minimize the impact of temperature variations on closure accuracy.

(3) During construction monitoring, it is essential to closely monitor the alignment of the main beam. Regularly compare the actual linear shape with the theoretical alignment and assess the degree and location of alignment deviations concerning the influence of various construction control parameters. Collect data on ambient temperature, box girder self-weight, box girder stiffness, hanging basket weight, prestress parameters, etc., in a timely manner during construction monitoring. Update the calculation model and analyze potential influencing factors accordingly. Based on the sensitivity analysis results, implement targeted quality control measures during construction to ensure the smooth closure of the bridge.

The construction control parameters listed in this paper are common and major parameters in the construction process. Parameters that have a minimal impact on construction or are challenging to measure, such as prestressed tendon stress error during tensioning and temperature gradients, were not analyzed in this study.

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