Research on the Influence of Different Design Parameters on the Mechanical Behavior and Deformation of Large-Span Curved Low-Pylon Cable-Stayed Bridges

Zuoqiao You[1, 3,a*], Lu Kuang[2, b], Xuefeng Dou[2,c], Shaohui Xiong[1, 3, d], Chaojie Miao[2, e]

[1]China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., Chongqing, 400067, China
[2]Chongqing Yuxiang Double-line Expressway Co., Ltd., Chongqing, 408599, China
[3]State Key Laboratory of Bridge Safety and Resilience, Chongqing, 400067, China

[a]youzuoqiao@foxmail.com, [b]609717361@qq.com, [c]490863038@qq.com, [d]381234694@qq.com, [e]874098896@qq.com
*Corresponding author

Abstract. To thoroughly analyze the structural behavior and deformation characteristics of large-span curved low-pylon cable-stayed bridges, this study takes the Mo Zhai Wujiang Grand Bridge on the Chongqing Yuxiang Double-line Expressway as the engineering background. A spatial beam-element finite element model is established to investigate the effects of various design parameters on the structural performance and deformation of the bridge. Key parameters, including the side-to-main span ratio, pylon height-to-span ratio, and length of the cable-free zones, are examined for their influence on the structural behavior. The results indicate that rational selection of the side-to-main span ratio, pylon height-to-span ratio, and cable-free zone lengths can optimize the structural performance and deformation control of the bridge. It is recommended to maintain the side-to-main span ratio between 0.52 and 0.57, the pylon height-to-span ratio between 0.13 and 0.15, the cable-free zone length at the pylon base between 24.5 m and 44.5 m, and the mid-span cable-free zone length between 27 m and 67 m. These findings provide valuable guidance for optimizing bridge design and serve as a useful reference for the preliminary design of similar bridges.

Keywords: Curved low-pylon cable-stayed bridge; Side-to-main span ratio; Pylon height-to-span ratio; Cable-free zone length

1 Introduction

Due to their superior structural design and mechanical performance, low-pylon cable-stayed bridges have garnered significant attention in recent years and are now widely applied in highway and municipal bridge construction. Compared to traditional bridge types, such as girder bridges, arch bridges, and suspension bridges, low-pylon cable-stayed bridges represent an innovative design concept. Their analytical frame-

W. Nie et al. (eds.), *Proceedings of the 2024 6th International Conference on Hydraulic, Civil and Construction Engineering (HCCE 2024)*, Atlantis Highlights in Engineering 37,
https://doi.org/10.2991/978-94-6463-726-7_77

work builds upon existing cable-stayed bridge theories, underscoring the necessity for a systematic and adaptable design theory specifically tailored to this bridge type. As the span of low-pylon cable-stayed bridges continues to grow and their girders become increasingly slender, further research is required to address unresolved challenges. Yan Guomin, through studies on several low-pylon cable-stayed bridges in Japan, analyzed their tower configurations, the span ratios of side spans to main spans, and the stress amplitude of stay cables, clarifying the distinctions between low-pylon cable-stayed bridges and conventional cable-stayed bridges [1-2]. Gu Anbang and Xu Junlan further explored the performance characteristics of low-pylon cable-stayed bridges, focusing on factors such as the pylon-to-span ratio, the girder-to-span ratio, the arrangement of stay cables, and stress variations [3]. Studies [4-6] have examined the effects of cable-free zone length and side-to-main span ratio on structural performance. These works highlight that the side-to-main span ratio significantly impacts the overall structural behavior of the bridge, while the cable-free zone length has a minimal effect on the pylons but exerts a complex influence on the girder's stress distribution and mid-span vertical displacement. Reference [7], based on the Huiqing Yellow River Highway Bridge, concluded that the cable-free zone at the pylon base should ideally be approximately 17% of the main span length, and the mid-span cable-free zone should be about 38%, resulting in smoother girder bending moment distributions. Most of the aforementioned studies focus on analyzing design parameters for straight bridges, with relatively little research dedicated to curved bridges. Due to topographical constraints, curved designs are frequently employed in mountain highways, particularly for high-grade highways that require stringent alignment standards, making the application of curved bridges increasingly prevalent [8]. Curved low-pylon cable-stayed bridges integrate the dual advantages of continuous rigid-frame bridges and cable-stayed bridges, with torsional rigidity of their main girders significantly exceeding that of traditional cable-stayed bridges [9-12]. In this context, this study takes the Mo Zhai Wujiang Grand Bridge on the Chongqing Yuxiang Double-line Expressway as its background. By developing a spatial beam-element finite element model, it investigates several key design parameters of curved low-pylon cable-stayed bridges, aiming to provide a reference for the preliminary design of similar bridges.

2 Project Overview

The Mo Zhai Wujiang Grand Bridge is a curved prestressed concrete low-pylon cable-stayed bridge, as shown in Fig. 1. The main girder aligns partially with a straight line and partially with a circular curve, with one side span situated on a circular curve with a radius of R = 1040 m. The structural system of the bridge is an integral pylon-beam consolidation system. The main bridge towers are rectangular reinforced concrete structures, with a total height of 44.0 m for the tower body and an additional 13.5 m for the decorative top. The transverse width of the tower is 3.5 m, while the longitudinal width varies from 12 m at the base to 8 m at the cable anchoring and upper sections. The main girder is constructed from prestressed concrete, featuring a single-cell, three-chamber box girder with straight web sections and a variable depth. The top slab of the box girder has a width of 27.5 m, with cantilever slabs extending 4.0 m on both sides. The cantilever slab has a thickness of 0.2 m at the tip and 0.9 m at the root. The bottom slab width is 19.5 m. The spans of the main bridge are 153 m, 296 m, and 153 m, respectively. The main piers are designed as single-leg hollow thin-walled piers with pile foundations. The girder height varies according to a 1.8th-degree parabolic profile. The stay cables are arranged in a fan pattern, passing through saddle anchors embedded in the bridge tower and are tensioned and anchored at the cantilever ends of the main girder.

Fig. 1. Overall effect of mozhai wujiang super large bridge

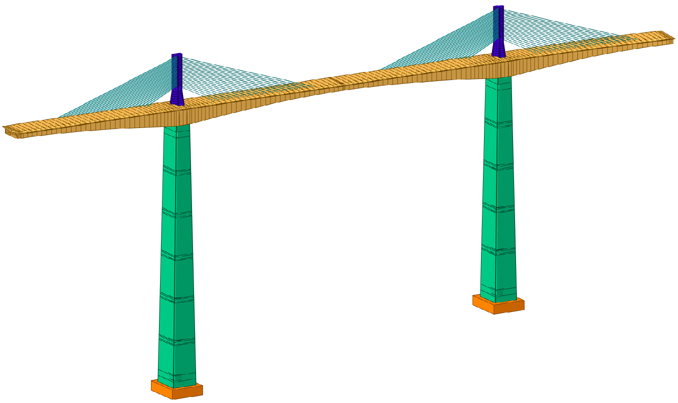

Fig. 2. Finite element model of the mo zhai wujiang grand bridge

3 Finite Element Model

The finite element software Midas Civil was used to establish a spatial beam-element finite element model of the Mo Zhai Wujiang Grand Bridge, as shown in Fig. 2. The model was discretized into 430 elements and divided into 110 construction stages based on the construction sequence. The analysis considered various construction stages, including the foundation, piers, bridge towers, and main girder, as well as stay cable tensioning and the closure of the side spans and mid-span. The loading conditions during the construction stages accounted for the self-weight of the structure, temporary construction loads, prestressing forces, stay cable tension, and the effects of concrete shrinkage and creep. For the operational stage, the loads included vehicular live loads, temperature effects, and the long-term effects of shrinkage and creep over a 10-year period. This modeling approach allowed for the evaluation of the effects of different design parameters on the structural behavior and deformation of large-span curved low-pylon cable-stayed bridges.

4 Analysis of the Influence of Design Parameters

4.1 Effect of Side-to-Main Span Ratio

To study the influence of the side-to-main span ratio on structural performance, the main span length, main girder height, tower height, and stay cable parameters were kept constant. The internal forces and maximum deflection at key points of the main girder were chosen as the analysis targets. The effect of different side-to-main span ratios was investigated under the completed bridge condition. By adjusting the length of the side span cast-in-place segment, the side-to-main span ratio was modified. The analysis was performed for five different side-to-main span ratios ($\gamma = 0.52, 0.57, 0.62, 0.67, 0.72$), and the results are shown in Fig. 3.

Based on Fig. 3, it can be observed that as the side-to-main span ratio (γ) increases, the maximum negative bending moment at the top of the mid-span pier of the main girder slightly increases, while the maximum negative bending moment at the top of the side span pier sharply increases, by approximately 2.68 times. The maximum positive bending moment at the mid-span of the side span also increases significantly, with an increase of about 4.76 times. The main reason for the increase in the maximum negative bending moment at the side span pier and the maximum positive bending moment at the mid-span is the increase in the side span length, which reduces the load carried by the stay cables, thereby increasing the load on the side span girder and ultimately causing an increase in the bending moments in the side span. The maximum deflection and maximum positive bending moment at the mid-span of the main girder gradually decrease, but the reduction is relatively small. The maximum cable force decreases gradually as the side-to-main span ratio increases. In summary, to optimize the design parameters of the main girder, the side-to-main span ratio must be within a reasonable range. It is recommended to control the side-to-main span ratio within the range of 0.52 to 0.57. However, in practical design, the specific value of the side-to-main span ratio should be determined through reasonable calculations and comparisons.

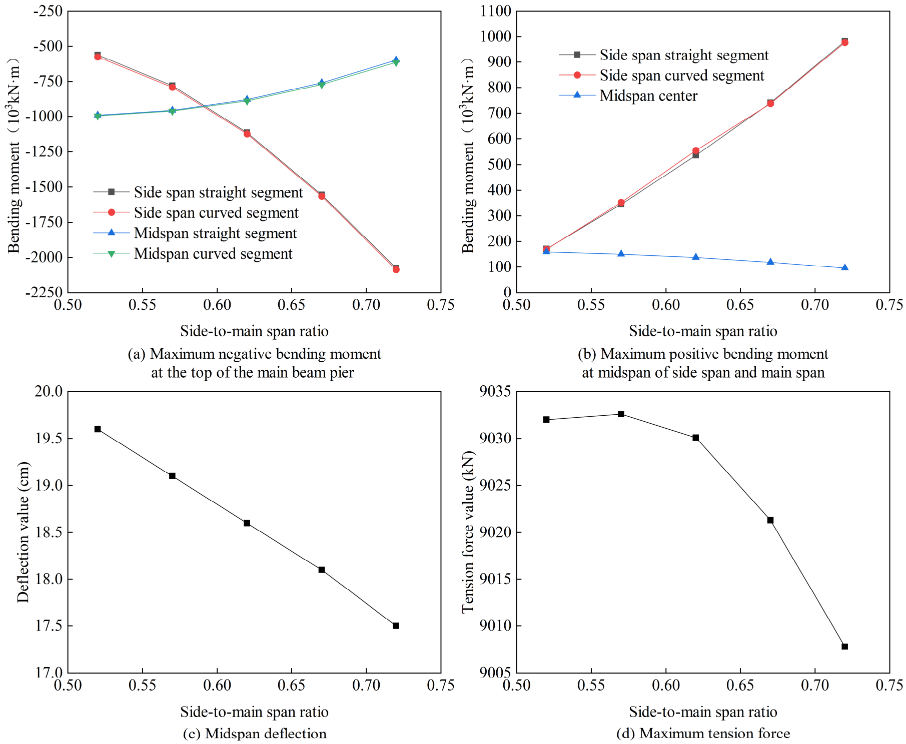

Fig. 3. Effect of side-to-main span ratio on the structure

4.2 Effect of Tower Height-to-Span Ratio

The tower height-to-span ratio influences the structural performance of the main girder by adjusting the angle of inclination of the stay cables. In this analysis, the layout of the side and main spans, the main girder height, and the stay cable parameters were kept constant. The internal forces and maximum deflection at key points of the main girder were chosen as the analysis targets to study the effect of the tower height-to-span ratio on the structural performance under the completed bridge condition. The analysis was performed for five different tower height-to-span ratios (k = 0.12, 0.13, 0.14, 0.15, 0.16), and the results are shown in Fig. 4.

As shown in Fig. 4, with the increase in the tower height-to-span ratio, the negative bending moments at the tops of the piers in both the side span and main span of the main girder significantly decrease. The maximum deflection of the main girder and the positive bending moments at both the side and main spans exhibit a monotonic decreasing trend with the increase in the tower height-to-span ratio, although the reduction is relatively small. At the same time, the maximum cable force also gradually decreases as the tower height-to-span ratio increases. This indicates that the tower height has a significant impact on the overall bridge's mechanical performance. As the tower height increases, the load-bearing performance of the main girder improves.

However, the proportion of live load carried by the stay cables also significantly increases. When the live load factor of the stay cables is approximately 33%, the bridge's structural characteristics approach those of a conventional cable-stayed bridge. Based on the analysis data for this project, it is recommended to control the tower height-to-span ratio within the range of **0.13 to 0.15**. However, in practical design, the specific value should be determined through reasonable calculations and comparisons.

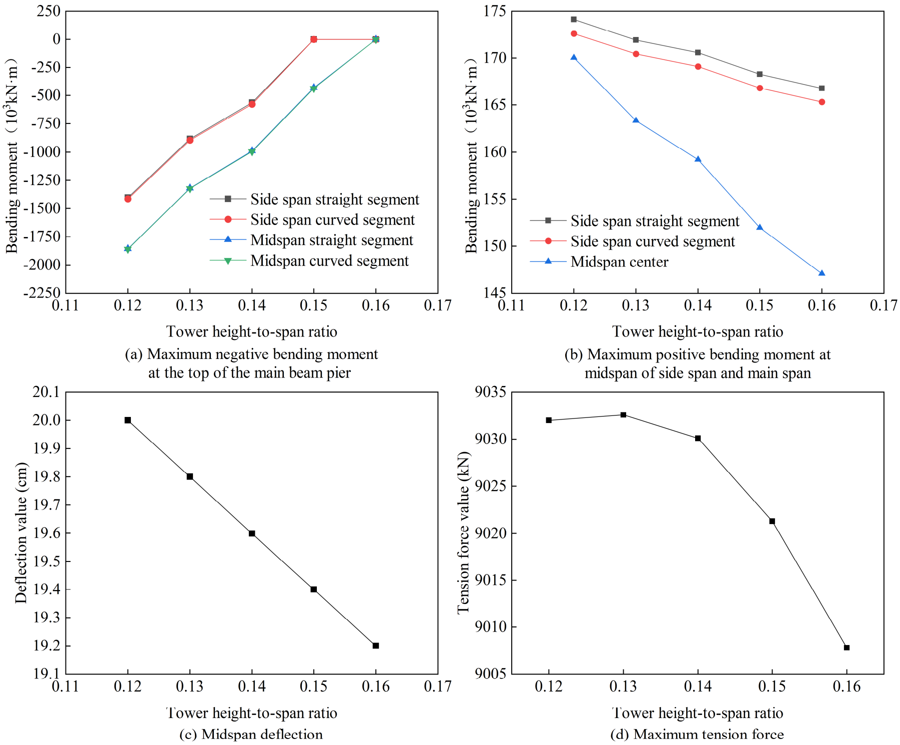

Fig. 4. Effect of tower height-to-span ratio on the structure

4.3 Effect of Length of Cable-Free Zone

The cable-free zone can be divided into the tower base cable-free zone, mid-span cable-free zone, and side-span cable-free zone. By adjusting the spacing of the stay cables on the main girder, the effect of changes in the length of the cable-free zones on the overall mechanical performance of the low tower cable-stayed bridge is analyzed. In the original design, the main span length is L = 296 m, the tower base cable-free zone length is L1 = 34.5 m, the side-span cable-free zone length is L2 = 28.5 m, and the mid-span cable-free zone length is L3 = 47 m. Under the condition that the stiffness of the tower, main girder, and stay cables, as well as the basic dimensions of the entire bridge, remain unchanged, the internal forces and maximum deflection at key points of the main girder are used as analysis targets. The effects of the tower base and mid-span cable-free zone lengths on the structural performance in the completed bridge state are studied. The length of the side-span cable-free zone can be determined jointly by the mid-span cable-free zone length and the side-to-main span ratio.

Effect of Tower Base Cable-Free Zone Length. Based on the original design scheme, with the side-span cable-free zone and mid-span cable-free zone lengths unchanged, the tower base cable-free zone length is altered by adjusting the spacing of the stay cables on the main girder, while other parameters remain consistent with the original design. A bridge completion state analysis is conducted for eight different tower base cable-free zone lengths (L1 = 4.5 m, 14.5 m, 24.5 m, 34.5 m, 44.5 m, 54.5 m, 64.5 m, 74.5 m), and the results are shown in Fig. 5.

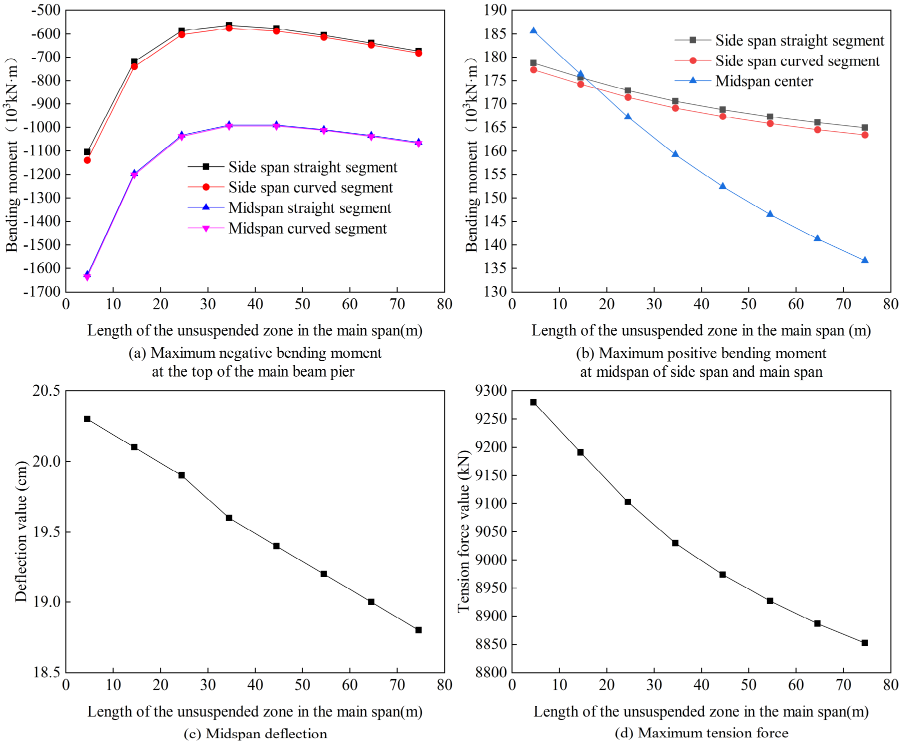

Fig. 5. Effect of tower base cable-free zone length on the structure

As shown in Fig. 5, with the increase in the tower base cable-free zone length, the negative bending moments at the tops of the piers in the side and main spans of the main girder initially increase and then gradually decrease. The negative bending moment reaches its maximum value when the tower base cable-free zone length is 34.5 m. The maximum positive bending moments in the side and main spans gradually decrease as the tower base cable-free zone length increases, with a smaller reduction in the side span and a more significant decrease in the mid-span. The maximum deflection of the main girder and the maximum cable force both show a monotonic decreasing trend as the tower base cable-free zone length increases. In summary, the reasonable range for the tower base cable-free zone length is between 24.5 m and 44.5 m.

Effect of Cable-Free Zone Lengths in the Side and Main Spans. Based on the original design scheme, the tower base cable-free zone length is kept unchanged, and the cable-free zone lengths in the side and main spans are adjusted by modifying the spacing of the stay cables on the main girder, while other parameters remain the same as the original design. The effects of seven different main span cable-free zone lengths (L1 = 7m, 27m, 47m, 67m, 87m, 107m, 127m) and their corresponding side span cable-free zone lengths (L2 = 8.5m, 18.5m, 28.5m, 38.5m, 48.5m, 58.5m, 68.5m) on the bridge performance in the completed state are analyzed. The results are shown in Fig. 6.

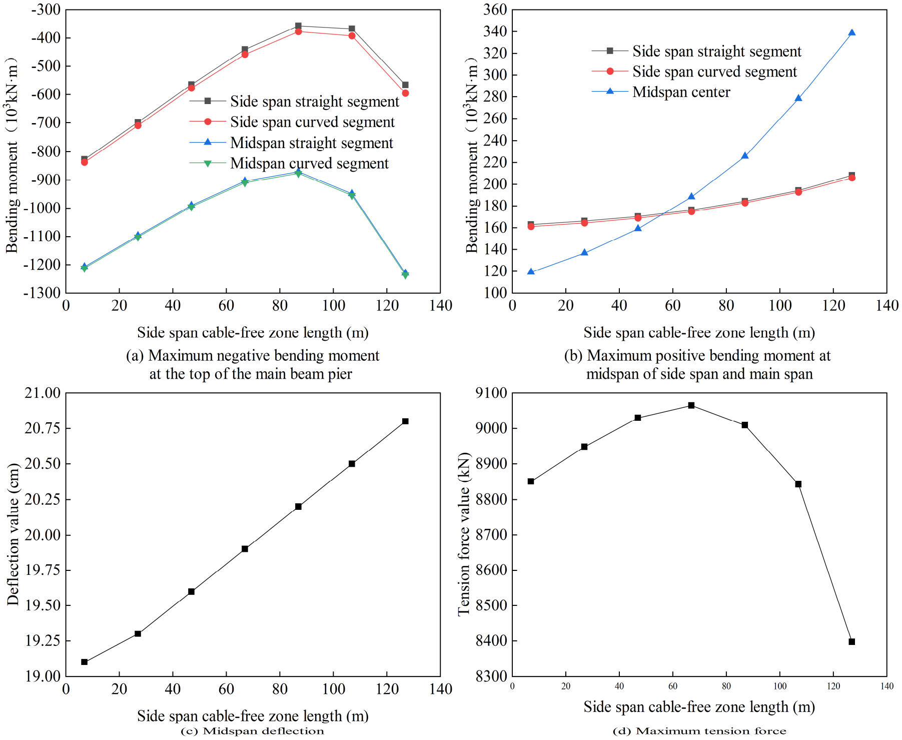

Fig. 6. Effect of cable-free zone lengths in the side and main spans on the structure

From Fig. 6, it can be observed that as the lengths of the cable-free zones in the side and main spans increase, the negative bending moment at the top of the piers in both the side and main spans initially increases and then decreases. The negative bending moment reaches its maximum value when the length of the main span's cable-free zone is 87m and the corresponding side span's cable-free zone length is 58.5m. The maximum positive bending moment in both the side and main spans gradually increases as the tower root's cable-free zone length increases, with the increase in the side span being relatively smaller and the increase in the main span being more significant. The maximum deflection of the main beam increases monotonically with the increase in the cable-free zone length at the tower root. The maximum cable force shows a trend of increasing first and then decreasing as the cable-free zone length at the tower root increases. In conclusion, the optimal length range for the main span's cable-free zone is between 27m and 67m, and the corresponding range for the side span's cable-free zone length is between 18.5m and 38.5m.

5 Conclusion

This study, based on the engineering background of the Mo Zhai Wujiang Grand Bridge on the Chongqing-Xiangxi Expressway, delves into the influence of different design parameters on the stress and deformation characteristics of large-span curved low-tower cable-stayed bridges. Through finite element analysis, the effects of the edge-to-main span ratio, tower height-to-span ratio, and cable-free zone length on the bridge structure's performance are evaluated. The main conclusions are as follows:

(1) The edge-to-main span ratio significantly affects the bending moment and deformation of the bridge. As the edge-to-main span ratio increases, the negative bending moment at the pier tops of the side span and the positive bending moment at the center of the span increase significantly. To optimize the bridge's structural performance, it is recommended to control the edge-to-main span ratio between 0.52 and 0.57.

(2) When the tower height-to-span ratio increases, both the negative bending moment at the pier tops in the side and main spans and the maximum deflection decrease, thereby optimizing the structural performance. It is recommended to control the tower height-to-span ratio between 0.13 and 0.15 to achieve a balance between structural performance and economy.

(3) The lengths of the tower root cable-free zone and the main span's cable-free zone have a significant impact on the bending moment and deflection of the main beam. The study suggests that the tower root's cable-free zone length should be controlled between 24.5m and 44.5m, and the main span's cable-free zone length should be controlled between 27m and 67m to effectively reduce structural deformation.

References

1. Yan, G.M. (1997) Kiso River Bridge in Japan—A Partial Cable-Stayed Bridge with a Main Span of 275m and Four Towers. Foreign Bridges, (02), 1-5.
2. Yan, G.M. (1996) A Brief Discussion on "Partial Cable-Stayed Bridges"—Yashiro South Bridge, Yashiro North Bridge, and Odawara Port Bridge in Japan. Foreign Bridges, (01), 47-50.
3. Gu, A.B., Xiang, Z.F., Xu, J.L., Sun, S.H. (2001) Linear and Nonlinear Stability Analysis of Large-span Concrete Cable-Stayed Bridges. Journal of Chongqing Jiaotong University, (S1), 1-6.

4. Cao, F.Y. (2018) Optimization Study on the Tower-to-Span Ratio and Cable-Free Zone Length of Railway Low-Tower Cable-Stayed Bridges. Lanzhou Jiaotong University.
5. Peng, B., Yang, D.C., Li, W.C. (2020) Influence of Cable-Free Zone Length on Live Load Effects of Low-Tower Cable-Stayed Bridges. Journal of Wuhan University of Technology (Engineering Edition), (04), 324-329. doi:10.14188/j.1671-8844.2020-04-006.
6. Peng, B., Li, W.C. (2017) Influence Analysis of Cable-Free Zone Length on Structural Behavior of Low-Tower Cable-Stayed Bridges. Engineering and Construction, (06), 726-729.
7. Chen, J.M. (2022) Research on the Influence of Different Design Parameters on the Stress and Deformation of Low-Tower Cable-Stayed Bridges. Western Journal of Traffic Science and Technology, (01), 132-134+161. doi:10.13282/j.cnki.wccst.2022.01.036.
8. Wang, W.Y. (2021) Influence of Design Parameters on Stress and Deformation of Main Beams in Low-Tower Cable-Stayed Bridges. Shandong Transportation Science and Technology, (04), 57-59.
9. Jiang, G.L., Zhong, Q.M., Jiang, Y.J., Zhang, D., He, J.L., Fan, X.B. (2023) Study on the Influence of Design Parameters on the Stress and Deformation of Low-Tower Cable-Stayed Bridges—A Case Study of the Nanpanjiang Grand Bridge. Engineering Technology Research, (04), 24-29. doi:10.19537/j.cnki.2096-2789.2023.04.008.
10. Nong, S.W. (2024) Optimization Analysis of Cable-Stayed Cable Design Parameters for Low-Tower Cable-Stayed Bridges. Heilongjiang Transportation Science and Technology, (06), 88-91. doi:10.16402/j.cnki.issn1008-3383.2024.06.020.
11. Liu, S.X., Xu, H.B., Li, L. (2023) Sensitivity Parameter Analysis of Prestressed Concrete Low-Tower Cable-Stayed Bridges. Journal of Nanyang Institute of Technology, (06), 85-89. doi:10.16827/j.cnki.41-1404/z.2023.06.014.
12. Xiao, C.M., Liao, S.R., Zhao, C.G., Xu, P. (2023) Structural Parameter Sensitivity Analysis of V-shaped Low-Tower Cable-Stayed Bridges. Highway, (01), 187-193.