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Analysis on the Improved Calculation Method of Cable Duct Inclination Angle for Cable-stayed Bridges

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Abstract

The inaccurate positioning of a cable-stayed bridge's cable duct can lead to the contact between the stay cable and the conduit's cable outlet and difficulties in the installation of the built-in damper. In turn, this can change the stress state of the stay cable and affect the test of the effective cable force, causing serious security risks to the entire structure. In order to analyze the law of the cable duct inclination angle and reveal the influencing factors of such an angle, an improved method for accurately calculating the inclination angle was proposed based on the influence of several factors, namely, segmental construction, second-stage load, concrete shrinkage and creep, and stay cable sag effect. Referring to the theory of elastic mechanics and concrete geometric nonlinearity, a calculation model was established considering the construction process, secondary load, concrete shrinkage and creep, and the sag effect of the cable stay. Furthermore, the influence of the cable stay duct's inclination angle was analysed. Thereafter, an improved method for calculating the inclination angle of cable-stayed cable ducts was proposed and the correctness of this improved method was verified through the construction of three different types of cable-stayed bridges. Results demonstrate that, the correction value of the cable duct inclination angle caused by the sag effect is negatively correlated with the cable length, and such value controls the trend of the inclination angle correction. The influence of factors such as segmental construction and secondary load cannot be ignored when correcting the cable duct inclination angle of an extradosed cable-stayed bridge. The correction of the cable duct inclination angle of the side span of a high-tower cable-stayed bridge far away from the cable tower can ignore the influence of shrinkage and creep. The correction of the cable duct inclination angle of a single inclined pylon cable-stayed bridge should focus on the influence of the tilt shape of the main tower and the shrinkage and creep. The study results provide a certain reference for the correction of the cable duct inclination angles of cable-stayed bridges.

Keywords: Cable-stayed bridge, Cable duct, Inclination angle correction, Sag effect

1. Introduction

Cable-stayed bridges have a series of advantages, such as large spanning capacity, light weight, reasonable force bearing, and clear force transmission paths. Thus, these are widely used in bridge projects across rivers and seas [1]. The cables of such bridges are anchored on the cable towers and main beams. Given that these are responsible for lifting the main beam at multiple points as well as transmitting the dead load and force of the main beam to the tower columns, it is crucial to ensure the safety of these cables [2]. In recent years, the rising application demand for cable-stayed bridges has resulted in great progress in the research on related technologies of cable-stayed cables. In particular, more and more units are involved in the design, production and application of stay cables. The cable duct is a circular tubular structure of a certain length that is set obliquely on the main beam. The end of the stay cable is anchored on the end of the cable duct, and the cable duct body cannot have any contact with the stay cable [3]. Therefore, the installation angle of cable ducts is one of the core issues in the construction of cable-stayed bridges.

However, due to the influence of external factors, the relative position between the stay cables and the cable duct changes dynamically during the construction of the cable-stayed bridge, causing the center of the stay cable and the center of the cable duct to not coincide. As long as the damping device of the stay cable does not come into contact with the cable duct, the stress state of the stay cable will not be affected by the cable duct. If the cable stay is seriously offset in the duct, the damping device of the stay cable will not be installed properly. As such, the damping device will have to be forcibly installed by pulling the cable with the help of machinery and equipment. The shock-absorbing rubber block undergoes significant deformation once the installation of the shock-absorbing device is completed. At this moment, the stay cable receives a force perpendicular to the cable axis due to the extrusion of the rubber block. As a result, the stress state and boundary conditions of the stay cables change significantly, seriously affecting the safety of the bridge structure and the accurate testing of cable forces [4].

Based on the abovementioned information, technical personnel has conducted numerous studies on the precise positioning of cable ducts during construction from the perspective of surveying [5, 6, 7]. However, they are still unable to effectively solve the problem of the contact

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between the built-in shock absorbing device of the stay cable and the cable ducts. Therefore, accurately predicting the inclination angle of cable ducts during construction as well as clarifying the spatial relationship between cables and cable ducts during bridge construction and operation are problems that require urgent solutions.

To this end, the current study uses influencing factor analysis and finite element methods (FEM) to establish FE calculation models for different bridge types, namely, extradosed cable-stayed bridge, high-tower cable-stayed bridges, and single inclined pylon cable-stayed bridges during the construction stage. We analyzed the sag effect, segmental construction, secondary load, and concrete shrinkage and creep, along with other factors, to correct the cable duct inclination angle. The goal of this study is to calculate the cable duct inclination angle of different types of cable-stayed bridges in a more accurate manner, thus providing a reference for the construction of cable-stayed bridges in the future.

2. State of the art

Although scholars have conducted numerous studies on stay cables, they mainly focused on structural stress, cable force testing technology, vibration of stay cables, and maintenance of stay cables. In comparison, only a few studies have been conducted on the cable duct of stay cables. For example, Li [8] used FE software to simulate the construction of a cable-stayed bridge and obtained the stress on the structure at each construction stage. However, the author did not study cable ducts. Similarly, although Farré-Checa [9] completed the whole-process monitoring of the main beam elevation of the cable-stayed bridge on the basis of calculating the stress of the cable-stayed bridge, the study did not involve cable ducts. Souza Hoffman and Igor [10] numerically simulated a prestressed concrete cable-stayed bridge and obtained the displacement of the main beam and the cable force of the cable stay at each construction stage using the FEM. However, they did not describe the cable duct's inclination angle. By conducting health monitoring and inspection of many cable-stayed bridges around the world, Mehrabi [11] concluded that many problems found in cable-stayed inspections are related to the corrosion and vibration sensitivity of the cables. Thus, the author proposed the anticorrosion and cable force test methods based on laser vibration calculation. However, there was no mention of the impact of the cable duct's status on the cable force test. Arangio, Stefania, and Franco Bontempi [12] took Tianjin Yonghe Bridge as an example and used 15 sensors arranged on the structure to obtain the vibration data of the structure. They also evaluated a cable-stayed bridge on the basis of Bayesian neural network damage detection. However, they did not mention the influence of the cable duct inclination angle. Javanmardi et al. [13] pointed out that the cable stay was one of the key components of the cable-stayed bridge; as such, any vibration could cause fatigue and fracture problems in the structure, thus affecting the structural safety. As with the others, they also did not mention the influence of the cable duct on the vibration of the cable stay.

Ho et al. [14] compared two testing methods of installing sensors directly on the cable-stayed cables HPDE pipe and the steel strands on a cable-stayed bridge with a main span of 200 m. They found that the impact of testing directly on the HPDE pipe on the short cables was 3.11% but it had little effect on long cables. They also reported that the cable force can be measured directly on the protection duct, but did not mention the impact of the spatial relationship between the cable ducts and the cable on the test results. Kim [15] measured the dynamic response of the steel cable by using a vision-based system as a sensor, enabling them to measure the cable force more accurately. Although this method avoided the problem of boundary conditions during cable testing, the inclination of the cable duct affected the cable force testing and structural safety. Huanyu Chen [16] investigated conventional cable-stayed bridges and proposed a calculation method consisting of the pre-camber correction of the cable duct's inclination angle during construction. However, they did not analyze the inclination angle of other types of cable-stayed bridges. Lilong Lin [17] studied the influencing factors of the cable duct installation angle and proposed a calculation method for the cable duct installation angle. The author discussed the correction results of the cable duct installation angle based on an extradosed cable-stayed bridge. Furthermore, the author pointed out that while the cable sag effect had a large influence, the second-stage load, concrete shrinkage and creep, and other factors also had a great impact on the inclination correction value of the cable ducts near the cable tower.

Zhihang Liu [18] took the main bridge of the Peisen Liujiang Bridge as the study object, analyzed the influence of different factors (e.g., sag effect, main beam pre-camber, and cable tower deformation) on the cable duct angle, and calculated the weight of each correction factor for the cable duct inclination angle. The author concluded that the sag effect had the greatest influence when calculating the cable duct's inclination angle and that the compression deformation of the cable tower could not be ignored; however, the horizontal deformation of the cable tower should not be neglected either. Based on catenary theory, Jinquan He et al. [19] conducted a detailed analysis of the cable-stayed cable as a whole and studied the impacts of the sag effect, segmental construction, and other factors on the positioning of cable ducts. However, they did not analyze other types of cable-stayed bridges.

Tongsheng Deng et al. [20] considered the influence of bending stiffness on the sag effect, which was suitable for the accurate calculation of extradosed cable-stayed bridges. However, they found that it was not applicable to the long flexible cable system of conventional high-tower cable-stayed bridges. Furthermore, they did not consider the influence of other factors on the cable duct positioning. Xiaoyu Gu et al. [21] took a composite-hybrid beam cable-stayed bridge as the research object and investigated the manufacturing error limit of steel anchor beam cable ducts from the perspective of steel structure processing, taking the influence of sag effect into consideration. However, they also did not investigate other factors affecting the cable duct inclination angle. Similarly, Mengyun Cao [22] took an asymmetric single pylon partial cable-stayed bridge as the object of study to analyze the precise positioning of the cable duct. However, they did not study the cable duct inclination angles of other types of cable-stayed bridges.

The abovementioned results mainly focused on structural stress and cable force testing and evaluation. In comparison, the calculation of cable duct inclination angle has not been fully investigated. Therefore, the current study establishes a calculation model for the inclination angle of cable ducts based on catenary calculation theory and the elastic mechanics method. Starting from considering the impact of the sag effect of the stay cable on the cable duct's inclination angle, this article focuses on three types of cable-stayed bridges, namely, extradosed and high-tower cable-stayed bridges and single inclined pylon cable-stayed bridges. This study aimed to analyze the impacts of segmental construction on the cable duct's inclination angle, as well as establish an FE model that could take the construction process into consideration. Using this model, we then calculated the influence of the sag effect and the deformation of the main girder and cable tower on the inclination angle of the stay cable's anchorage point, specifically during the construction and completion stages of the bridge. We also determined the positioning angle of the cable-stayed cable duct and the weight of the influence of various factors on the inclination angle, thus providing an important reference for the construction of cable-stayed cable ducts.

The remainder of this study is organized into sections. Section 3 presents an in-depth discussion of the theoretical approach to the calculation of the stay cable duct's inclination angle and proposes a formula for calculating such an angle. The proposed formula considers displacement during the construction stage and the completion stage of the bridge and the sag effect of stay cables. Section 4 presents the use of the elastic mechanics FEM to establish analytical models of different types of cable-stayed bridges, after which we analyzed the factors affecting each inclination angle and obtained the weight of each factor. Section 5 summarizes this study and provides the relevant conclusions.

3. Methodology

The cable duct's inclination angle is determined by the spatial position of the stay cable's anchorage point and the spatial line shape of the stay cable. The stay cable's anchoring point position is affected by several factors, including the construction of the main beam, the secondary load, and the shrinkage and creep of the concrete. Meanwhile, the spatial linear shape of the stay cable is affected by the effective tension and sag effect of the stay cable. The main beam of a cable-stayed bridge typically consists of concrete main beams, steel beams, and steel–concrete composite beams and is generally constructed by hanging basket segments or assembled on brackets. Moreover, each segment construction roughly includes the following three stages: forward movement of the hanging basket, construction of the segmental main beam, and tensioning of the stay cables. The cable ducts are assembled during the construction of the segmental main beam. Once the construction of the segmental main beam is completed, the relative inclination angle between the axis of the segmental main beam and the cable duct within the segment will not change, and no adjustments to the cable duct inclination angle can be made in subsequent segments of the main beam. However, the cable duct's inclination angle changes dynamically due to several factors, such as subsequent segment construction, secondary load, concrete shrinkage and creep, and service load. Therefore, the influencing factors of the cable duct must be analyzed, and the correction amount of the cable duct inclination angle caused by each factor must be accurately calculated. During construction, the correction amount must be added to the cable duct inclination angle to eliminate or reduce the serious deviation between the center of the cable and the center of the cable duct.

3.1 The improved calculation method to obtain the cable duct inclination angle

Factors that affect cable duct inclination include main beam segments, concrete shrinkage and creep, secondary paving, and the sag effect of stay cables.

The formula for calculating the cable duct's inclination angle is shown in (1):

$$\alpha_P = \alpha_d + \theta_1 + \theta_2 + \theta_3 + \theta_4 \tag{1}$$

where α_P is the cable duct positioning angle; α_d is the theoretical design angle of the cable duct in the bridge state calculated based on the design drawings; θ_1 is the correction value of cable duct inclination angle caused by the sag effect of stay cables; θ_2 is the correction value of the cable duct inclination angle caused by the construction of the segment, including the correction value of the inclination angle caused by the deformation of the steel bars and the displacement of the hanging basket during the construction of the main beam of the current segment; θ_3 is the correction value of cable duct inclination angle caused by secondary load; and θ_4 is the inclination correction value of the cable duct after the completion of the bridge is the correction value originated by concrete shrinkage and creep. The calculation method of the inclination angles $\theta_i (i = 1,2,3,4)$ is introduced below.

Table 1. Factors affecting cable duct inclination angle

Main factors	Sag effect	Vertical displacement of tower beam
Construction stage		√
Secondary paving		√
Deformation after completion of bridge		√
Stay cable tensioning	√	

3.2 Calculation of the cable duct inclination angle correction caused by the sag effect of stay cables

Under the action of its own weight, the flexible cable will produce certain sag, which has a nonlinear relationship with the cable force and cable length. When calculating and analyzing the overall effect of a cable-stayed bridge, the Ernst formula is typically used to correct the elastic modulus. However, the Ernst formula is not suitable for calculating the sag of the cable. Given that the stay cable has catenary characteristics, there are two methods for calculating the inclination angle caused by the sag effect depending on the sag of the stay cable and the convenience of calculation. First, for the stay cable with a cable length not greater than 300 m, it can be approximately calculated as a parabola. Second, for stay cables with cable lengths greater than 300 m, the catenary method can be used for calculation, but this method is more cumbersome. The details of the calculation are presented below.

1) Cable length that is less than 300 m

The elongation of stay cables in tension includes the elongation caused by tension and the elongation caused by gravity. For the case of small sag, it can be calculated approximately by a parabola, as shown in Figure 1.

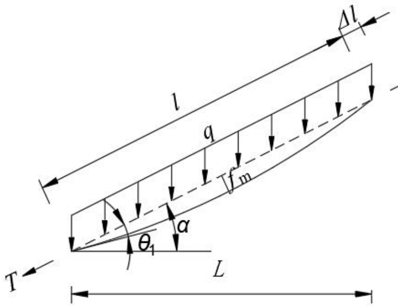

Fig. 1. Stress Diagram of Parabolic Mode Stay Cable

$$Tf_m = \frac{1}{8} q_l l^2 = \frac{1}{8} q l^2 \cos\alpha \tag{2}$$

$$f_m = \frac{ql^2}{8T}\cos\alpha \tag{3}$$

$$\tan\theta_1 = \frac{4 f_m}{l} = \frac{4}{l}\frac{ql^2}{8T}\cos\alpha = \frac{q}{2T}L \tag{4}$$

$$\theta_1 = \arctan\frac{qL}{2T} \tag{5}$$

2) Cable length that is more than 300 m

When the horizontal projection length of the cable is very long (>300 m), the parabola calculation will lead to an error. Thus, it is appropriate to use the exact catenary equation to solve it. In this method, the cable is analyzed as a whole, so that the influence of the sag effect on the angle of the end of the cable can be considered more comprehensively, as shown in Figure 2.

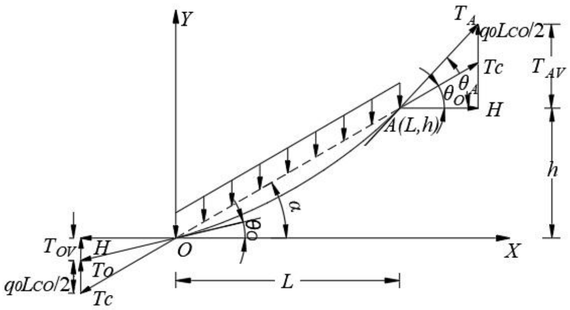

Fig. 2. Catenary mode cable stress diagram

In the figure, α represents the cable duct's inclination angle in the bridge state; T_C is the initial tension force of the stay cable; q_0 is the weight of a meter of the stay cable; H is the horizontal tension force of the stay cable at the anchor point.

From equilibrium conditions:

For horizontal orientation

$$T_c cosa = T_A cosq_A = T_o cosq_o = H \tag{6}$$

For vertical orientation

$$T_{AV} = T_A \sin\theta_A = T_{OV} + \frac{q_0 L_{CO}}{2} = T_O \sin\theta_O + \frac{q_0 L_{CO}}{2} \tag{7}$$

$$T_{OV} = T_O \sin\theta_O = T_C \sin\alpha - \frac{q_0 L_{CO}}{2} \tag{8}$$

From the above relationship, we obtain the following: $H = T_C \cos\alpha$

The lengths of the cable under the stress and unstressed states are represented by L_C and L_{CO}, respectively.

Then: $L_C = L_{CO} + \Delta L$

When the stay cable is under tension, it can be approximately regarded as a rod for stress analysis. From Hooke's law: $\Delta L = \frac{FL}{EA}$, it can be concluded that:

$$L_{CO} = \frac{1}{1 + \frac{T_C}{EA_O}} L_C \tag{9}$$

$$\tan\theta_O = \frac{T_{OV}}{H} = \frac{T_C \sin\alpha - \frac{q_0 L_{CO}}{2}}{H} \tag{10}$$

$$\tan\theta_A = \frac{T_{AV}}{H} = \frac{T_C \sin\alpha + \frac{q_0 L_{CO}}{2}}{H} \tag{11}$$

As such, the tangential angles θ_O and θ_A of the stay cables at the main beam end and the tower end are given by

$$\theta_O = \arctan\frac{T_C \sin\alpha - \frac{q_0 L_{CO}}{2}}{H} \tag{12}$$

$$\theta_A = \arctan\frac{T_C \sin\alpha + \frac{q_0 L_{CO}}{2}}{H} \tag{13}$$

From the above, we can thus obtain the correction angle $\theta_1 = (\theta_O - \alpha)$ under the sag effect of the stay cable.

3.3 Segmental construction

Main beam segment construction includes current and subsequent segment construction. Given that the cable duct and the segmental main beam are welded, the cable duct is considered consolidated with the beam segment to which it belongs. This is calculated as an elastic body to obtain the displacement of each anchor point on the main beam and cable tower. Thereafter, we used the relative displacement between two anchor points of the same cable to determine the impact of segmental construction on the cable duct's inclination angle. Furthermore, because the lateral width of the main beam is much smaller than the span, this study adopts the suggestion of a previous study [22] and ignores the influence of lateral deformation when the stay cables are spatially arranged.

According to the principle of virtual work of the deformable body system,

$$\Delta = \sum\int \frac{\overline{N} N_P}{\text{EA}} \text{ds} + \sum\int \frac{\overline{M} M_P}{\text{EI}} \text{ds} \tag{14}$$

the relative deformation of the same stay cable between the two anchorage points on the main girder and cable tower can be calculated, particularly the relative deformation of horizontal displacement ΔX and the relative deformation of vertical displacement ΔY.

As shown in Figure 3, the cable duct inclination angle correction value θ_2 caused by segmental construction is given by

$$\theta_2 = \arctan\left(\frac{Y_n' - Y_N'}{X_n' - X_N'}\right) - \arctan\left(\frac{Y_n - Y_N}{X_n - X_N}\right) \quad (15)$$

where (X_n, Y_n) and (X'_n, Y'_n) are the coordinates of the anchorage points of the main tower stay cables before and after deformation, respectively, (X_N, Y_N) and (X'_N, Y'_N) are the coordinates of the anchorage points of the main beam stay cables before and after deformation, respectively.

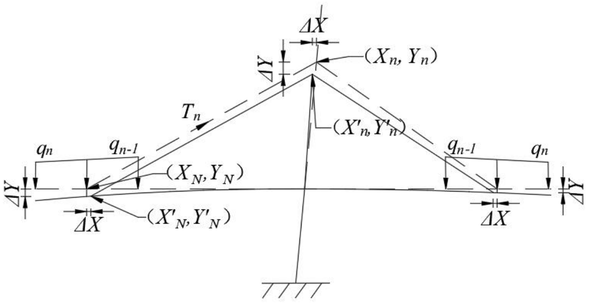

Fig. 3. Calculation diagram of the impact of segmental construction on the positioning of cable ducts

3.4 Secondary load
Once the bridge is closed, it enters the bridge deck pavement construction stage. This second-stage load must be applied to the model, after which the displacement of the cable-stayed anchorage caused by the second-stage load is calculated. Then, we calculate the correction value of the cable duct inclination angle caused by the second-stage load according to Equation (15).

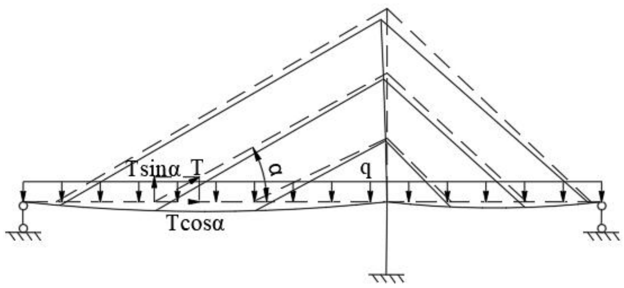

Fig. 4. Analysis diagram of the impact of the second phase paving on the cable duct positioning

3.5 Concrete shrinkage and creep
The shrinkage and creep of concrete continue to exist throughout the life cycle of the bridge [23–29] and have an impact on the structural performance. According to concrete shrinkage theory and creep theory, the deformation value caused by shrinkage and creep is generally smaller in the later stage; thus, only the influence of 10 years' worth of shrinkage and creep is considered in the present study. Here, the interaction between prestressed loss and its secondary effects, the secondary effects caused by structural system conversion, and the relaxation of prestressed steel bars as well as concrete shrinkage and creep must all be considered during calculation and analysis to accurately obtain the deformation value originated by shrinkage and creep. In addition, the impact of shrinkage and creep on the cable duct's inclination angle during construction is included in θ_2, θ_3, where the angle change amount represented by θ_4 refers to the impact of shrinkage and creep on the inclination angle of the bridge pavement layer after 10 years of completion.

4. Results and Discussion

Due to the different structural forms of cable-stayed bridges, the construction procedures and the degree of correction of the cable duct's inclination angle may also vary. This article uses the current large-scale construction of three types of cable-stayed bridges, including extradosed, high-tower cable-stayed bridges and single inclined pylon cable-stayed bridges, as engineering backgrounds to calculate the cable duct inclination angle and analyze the influencing factors.

4.1 Extradosed cable-stayed bridge
The bridge span layout of a double cable plane, prestressed, extradosed cable-stayed bridge made of concrete is 100+170+100 m (tower, beam, and pier consolidation system).

Fig. 5. Photo of the completed extradosed cable-stayed bridge

The main beam is a separated double main box large cantilever with a variable-section PC continuous box girder section and a straight web form that is constructed using the hanging basket cantilever concreting method. The stay cables adopt a flat double cable plane fan-shaped arrangement. The stay cables pass through the cable tower and are anchored on the main beams on both sides of the cable tower. A total of 48 stay cables are used in the whole bridge. The cable anchoring method adopts tensioning at both ends, and the main tower part is fixed with antislip clips. The calculation model is shown in Figure 6.

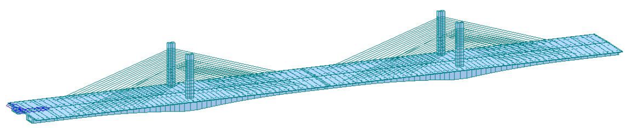

Fig. 6. Calculation model of extradosed cable-stayed bridge

Here, we used the #1 cable stay on the midspan side of pier 1 as an example to introduce the correction calculation of the cable duct inclination caused by the sag effect and other factors during construction.

Cable duct inclination angle in bridge state: $\alpha = 23.93^\circ$

Initial tension of 1# cable stay: $T_C = 5053.3kN$

1# cable stay weighs a meter: $q_0 = 58.49kg/m$

Unstressed cable length of 1 # stay cable: $L_{CO} = 34.71m$

The tangential angle of the 1# stay cable is given below.

$$\theta_o = \arctan\frac{T_C\sin\alpha - \frac{q_0 L_{CO}}{2}}{H}$$

$$= \arctan\frac{5053.3\times\sin 23.93^\circ - \frac{58.49\times 9.7947\times 34.71\times 10^{-3}}{2}}{5053.3\times cos 23.93^\circ}$$

$$= 23.83^\circ$$

Correction value of cable duct inclination angle caused by sag effect: $\theta_1 = (\theta_o - \alpha) = -0.105^\circ$

Through analysis and calculation, the displacement of the tower end and beam end of the 1# cable-stayed cable on the midspan side of the No. 1 pier during the construction process can be obtained using Equation (15). Specifically, θ_2, θ_3, and θ_4 are calculated respectively as follows:

$$\theta_2 = \arctan\left(\frac{Y'_n - Y'_N}{X'_n - X'_N}\right) - \arctan\left(\frac{Y_n - Y_N}{X_n - X_N}\right)$$

$$= \arctan\left(\frac{1366.17-(-1.58)}{-0.78-(-3147.9)}\right) - \arctan\left(\frac{1367-0}{0-(-3150)}\right)$$

$$= 0.028^\circ$$

$$\theta_3 = \arctan\left(\frac{1366.48-(1.3)}{0.93-(-3150.37)}\right) - \arctan\left(\frac{1367-0}{0-(-3150)}\right)$$

$$= -0.029^\circ$$

$$\theta_4 = \arctan\left(\frac{1366.33-(0.19)}{3.88-(-3146.32)}\right) - \arctan\left(\frac{1367-0}{0-(-3150)}\right)$$

$$= -0.07^\circ$$

We calculate the correction angle of each cable duct on the main beam by the same method, and the calculation results are shown in Table 2.

Table 2. Summary table of correction angles of each cable duct

Bridge span	Cable duct number	θ_1 (°)	θ_2 (°)	θ_3 (°)	θ_4 (°)	Design cable duct inclination angle (°)	Revised cable duct inclination angle (°)	Correction amplitude	Cable Length(m)	Height correction (m)
Side span	S1	-0.105	0.028	-0.029	-0.007	23.570	23.457	-0.48%	34.336	-0.062
	S2	-0.115	0.022	-0.026	-0.005	22.790	22.667	-0.54%	37.948	-0.075
	S3	-0.120	0.032	-0.022	-0.004	21.890	21.777	-0.52%	42.028	-0.077
	S4	-0.131	0.036	-0.019	-0.002	21.140	21.024	-0.55%	46.116	-0.087
	S5	-0.168	0.038	-0.016	-0.001	20.510	20.363	-0.72%	50.210	-0.121
	S6	-0.181	0.039	-0.013	0.001	19.960	19.806	-0.77%	54.308	-0.138
	S7	-0.186	0.040	-0.010	0.002	19.510	19.356	-0.79%	58.410	-0.148
	S8	-0.198	0.042	-0.008	0.002	19.150	18.989	-0.84%	62.514	-0.166
	S9	-0.201	0.043	-0.006	0.003	18.820	18.658	-0.86%	66.621	-0.178
	S10	-0.231	0.045	-0.005	0.003	18.540	18.352	-1.01%	70.730	-0.220
	S11	-0.233	0.049	-0.004	0.003	18.290	18.105	-1.01%	74.840	-0.230
	S12	-0.244	0.053	-0.003	0.003	18.060	17.869	-1.06%	78.952	-0.250
Mid span	M1	-0.103	-0.026	0.075	0.066	23.930	23.941	0.05%	34.336	0.006
	M2	-0.112	-0.031	0.077	0.067	23.130	23.131	0.00%	37.948	0.000
	M3	-0.118	-0.021	0.080	0.069	22.210	22.220	0.04%	42.028	0.007
	M4	-0.129	-0.017	0.083	0.070	21.440	21.447	0.03%	46.116	0.005
	M5	-0.166	-0.015	0.085	0.071	20.790	20.765	-0.12%	50.210	-0.020
	M6	-0.179	-0.014	0.087	0.072	20.230	20.197	-0.16%	54.308	-0.030
	M7	-0.184	-0.012	0.088	0.073	19.750	19.715	-0.18%	58.410	-0.033
	M8	-0.196	-0.009	0.089	0.073	19.330	19.287	-0.22%	62.514	-0.044
	M9	-0.200	-0.007	0.089	0.073	18.960	18.915	-0.24%	66.621	-0.049
	M10	-0.230	-0.004	0.088	0.072	18.630	18.557	-0.39%	70.730	-0.085
	M11	-0.232	0.002	0.087	0.071	18.330	18.258	-0.39%	74.840	-0.089
	M12	-0.243	0.008	0.085	0.070	18.060	17.980	-0.44%	78.952	-0.105

Furthermore, the influences of various factors on the inclination angle of the cable-stayed cable ducts are shown in Figure 7 and Figure 8.

From Fig.7 and Fig.8, it can be seen that for the extradosed cable-stayed bridge, the following conclusions are drawn: (1) As the cable number increases (i.e., cable length increases), the sag effect on the cable duct inclination angle correction value θ_1 shows a decreasing trend. The reason is that the longer the cable, the more obvious the sag effect is. 2) As the cable number increases, the correction value θ_2 of the cable duct inclination angle during segmental construction shows an increasing trend, but the correction value of the side span cable duct is always positive, while the correction value of the mid-span cable duct has negative and positive signs; 3) As the cable number increases, θ_3 and θ_4 also show an increasing trend; 4) As the cable number increases, whether it is the inclination correction value of the side-span cable duct or the inclination angle correction of the mid-span cable duct, the value shows a decreasing trend. The reason is that the trend of the sag effect of the cable controls the amplitude of the cable duct inclination angle correction.

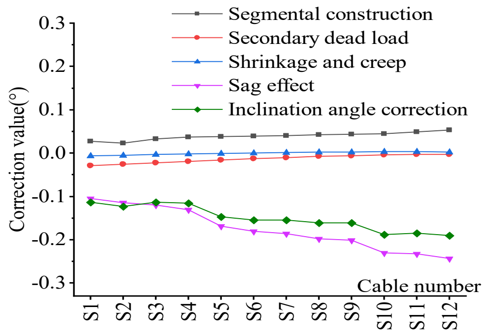

Fig. 7. Side-span cable duct inclination angle correction curve

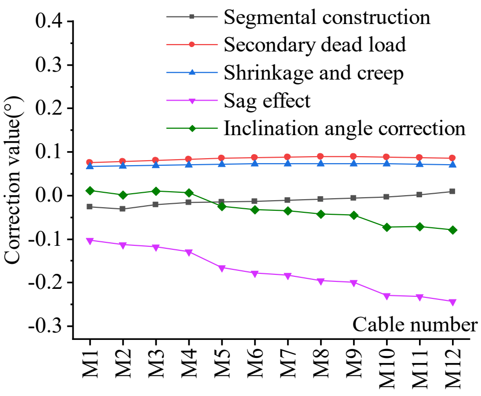

Fig. 8. Mid-span cable duct inclination angle correction curve
Note: Regarding the correction values, a positive sign indicates that the cable duct's inclination angle becomes larger, and a negative sign indicates that the inclination angle becomes smaller.

4.2 High tower cable-stayed bridge

A concrete cable-stayed bridge is a (125+260+125) m twin-tower, double-rib, main beam, concrete cable-stayed bridge. The main beam adopts a concrete π-shaped double-rib section, and the structural restraint system adopts a semifloating system. The fan-shaped double cable plane arrangement is adopted for the cables. The standard cable distance of the main beam is 6 m, and the cable distance of the side span tail cable area is 5.4 m. There are 20 pairs of stay cables on one side of a single cable tower. The tensioned end of the stay cable is located at the bottom of the main beam, and the anchorage is a replaceable cable anchor. The stay cable on the tower is connected through a split wire tube made of multiple sets of steel pipes welded together. The tower end adopts antislip measures. The bridge calculation model is shown in Figure 10.

Fig. 9. Bridge effect diagram

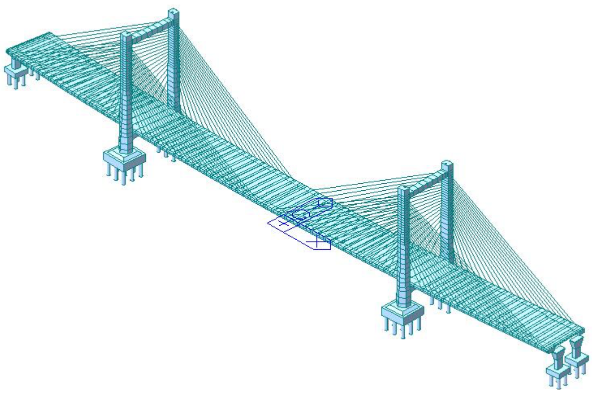

Fig. 10. Calculation model of high tower cable-stayed bridge

Meanwhile, the results of the influence of various factors on the inclination angle of the cable ducts of the high-pylon cable-stayed bridge are shown in Figures 11 and 12.

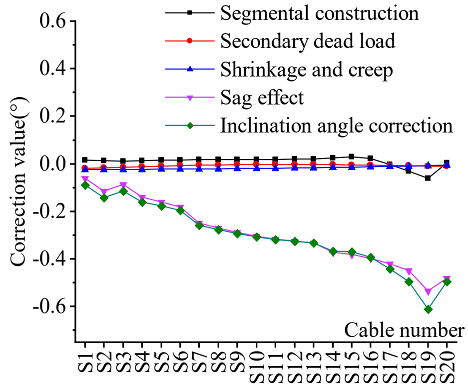

Fig. 11. Side-span cable duct inclination angle correction curve

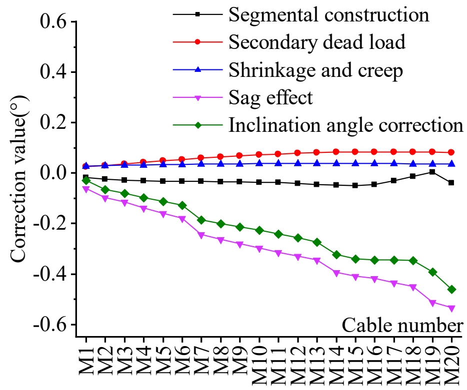

Fig. 12. Mid-span cable duct inclination angle correction curve

Based on Figures 11 and 12, for high-tower cable-stayed bridges, the following conclusions are drawn: (1) As the cable number increases (i.e., cable length increases), the sag effect on the cable duct inclination angle correction value θ_1 shows a decreasing trend. (2) As the cable number increases, the correction value θ_2 of the cable duct inclination angle during segmental construction is very small. However, the correction value of the sidespan cable duct is mostly positive, while the correction value of the midspan cable duct is mostly negative value. (3) As the cable number increases, θ_3 and θ_4 also show an increasing trend, the side span is negative, and the midspan is positive. (4) Finally, as the cable number increases, both the inclination angle correction value of the sidespan cable duct and the inclination angle correction value of the midspan cable duct show a decreasing trend.

4.3 Single inclined pylon cable-stayed bridge

A single inclined pylon cable-stayed bridge is a 59+100 m special-shaped inclined tower hybrid girder cable-stayed bridge. The main beam adopts a steel-concrete composite box girder and a double-sided box structure. The longitudinal stay cables of the cable-stayed bridge are arranged in a fan shape, and the cable planes of the transverse stay cables of the bridge are arranged as double cable planes. The cable distance on the concrete girder is 5 m, and the cable distance on the steel box girder is 9 m. There are 36 cable-stayed cables in the whole bridge, and the cable-stayed cables are anchored on the tower and single-end tensioned on the beam. The bridge calculation model is shown in Figure 14.

Fig. 13. Photo of the completed single inclined pylon mixed-beam cable-stayed bridge

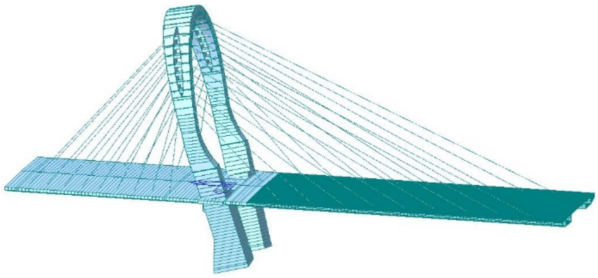

Fig. 14. Calculation model of single inclined pylon mixed-beam cable-stayed bridge

The results of the influence of various factors on the inclination angle of the cable duct of the single inclined pylon cable-stayed bridge are shown in Figures 15 and 16.

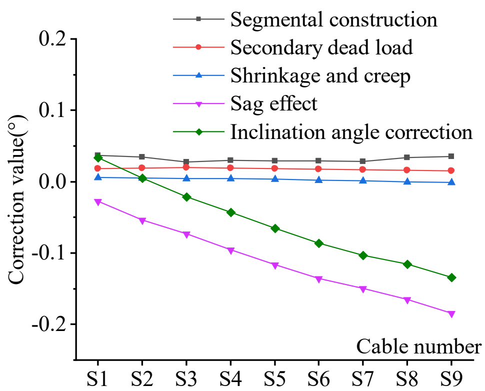

Fig. 15. Side-span cable duct inclination angle correction curve

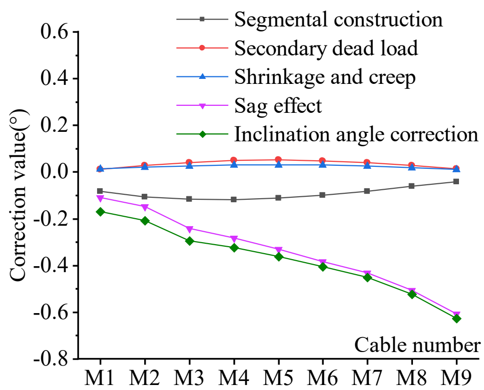

Fig. 16. Mid-span cable duct inclination angle correction curve

Based on Figures 15 and 16, for the single inclined pylon cable-stayed bridge, the following conclusions are drawn: (1) As the cable number increases (i.e., the cable length increases), the sag effect on the cable duct inclination angle correction value θ_1 shows a decreasing trend. (2) As the cable number increases, the θ_2 value of both the side span and the midspan first decreases and then increases; however, the θ_2 value of the side span is positive, while the θ_2 value of the midspan is negative (3) As the cable number increases, θ_3 and θ_4 show a trend of increasing first and then decreasing, and both are positive values. (4) Finally, as the cable number increases, the inclination angle correction values of the side span and midspan cable ducts show a decreasing trend.

5. Conclusions

To explore the law of the cable duct inclination angle of cable-stayed bridges and reveal the relationships among the beam, tower deformation, cable sag effect, and the cable duct inclination angle, this study started the investigation from the influencing factors of the cable duct inclination angle and used the combined numerical simulation technology and theoretical analysis. Using this method, we analyzed the factors affecting the inclination angle of cable-stayed bridge cable ducts. Finally, the following conclusions could be drawn:

1) The cable duct's inclination angle should not only consider the influence of factors, such as the secondary load, the sag effect of the stay cables, segmental construction, etc., but also the effects of the live load and concrete shrinkage and creep after the bridge is completed.

2) Among the different types of cable-stayed bridges, the correction value of the cable duct inclination caused via cable sag effect controls the trend of inclination correction. With the increase of the length of stay cable, the other three factors have less and less influence on the inclination angle of the cable duct.

3) For the same bridge, segmental construction, second-stage loads, shrinkage and creep, and live load after the completion of the bridge have a greater influence on the cable duct near the pylon. However, they have little influence on the cable duct farther away from the pylon. Thus, the influence of the cable sag effect cannot be considered only in the calculation of the cable duct inclination correction.

4) For a single inclined pylon cable-stayed bridge, the correction value of the cable duct's inclination angle is greater than that of a conventional cable-stayed bridge. Thus, the influence of the deviation of the main tower cannot be ignored in calculating the inclination correction of the cable duct.

In this study, we proposed an improved calculation method for cable-stayed cable ducts and applied it to different types of cable-stayed bridges. Good results were obtained. At the same time, considering the influence of the cable sag effect, deformation during construction and pre-camber, it has a certain reference value for the follow-up study of cable duct inclination. However, due to the lack of actual data regarding super-long-span cable-stayed bridges, the application of our proposed an improved method to such bridges still requires verification using measured data. In future research, the study will be revised by combining the monitoring data of super-long-span cable-stayed bridges, with the aim of further improving the calculation method of cable-stayed cable ducts.

References

[1] L. Zhang, G. Qiu, and Z. Chen, "Structural health monitoring methods of cables in cable-stayed bridge: A review," *Measurement.*, vol. 168, Jan. 2021, Art. no. 108343.

[2] A. M. B. Martins, L. M. C. Simões, and J. H. J. O. Negrão, "Optimization of cable-stayed bridges: A literature survey," *Adv. Eng. Softw.*, vol. 149, Jun. 2020, Art. no. 102829.

[3] A. Javanmardi, K. Ghaedi, F. Huang, M. U. Hanif, and A Tabrizikahou, "Application of structural control systems for the cables of cable-stayed bridges: state-of-the-art and state-of-the-practice," *Arch. Comput. Methods Eng.*, vol. 29, no. 3, pp. 1611-1641, Jul. 2022.

[4] H. Yang and S. K. Tian, "A Method for Precise Positioning of Cable Conduit of Cable-stayed Bridge," *Geotech. Invest. Surv.*, vol. 45, no. 1, pp. 69-73, Jan. 2017.

[5] P Lu, "Positioning measurement of anchor plates and cableway tubes of cable-stayed bridges without back-cables," *Bridge Constr.*, vol. 42, no. 2, pp. 134-136, 2007.

[6] C. Q. Liu, M. S. Wang, and H. Yang, "High-precision positioning measurement and error analysis of the main tower cable duct installation of the Fifth Fujiang Bridge," *Munic. Technol.*, vol. 33, no. 3, pp. 166-169, Mar. 2015.

[7] J. S. Hu, X. L. Zhao, Y. Guo, Y. C. Zhu, and P. H. Li, "Research on Installation and Construction Technology of Prestressed Concrete Cable Conduit," *Spec. Struct.*, vol. 38, no. 5, pp. 112-116, May. 2021.

[8] S. Q. Li and X. X. Zhang, "Research on Construction Elevation Control of Wide-with Cable-Stayed Bridge with Low Pylon," in *IOP Conf. Series: EES*, London, GBR, UK, 2021, pp. 1-5.

[9] C. J. Farré, S. Komarizadehasl, H. Ma, J. A. Lozano-Galant, and J. Turmo, "Direct simulation of the tensioning process of cable-stayed bridge cantilever construction," *Autom. Constr.*, vol. 137, May. 2022, Art. no. 104197.

[10] H. I. Souza, L. B. Manica, A. Campos, L. P. Manica, and P. A. Rodrigues, "Finite element numerical simulation of a cable - stayed bridge construction through the progressive cantilever method," *Struct. Concrete.*, vol. 23, no. 2, pp. 632-651, Feb. 2022.

[11] A. B. Mehrabi, "Performance of cable-stayed bridges: evaluation methods, observations, and a rehabilitation case," *J. Perform. Constr. Facil.*, vol. 30, no. 1, Feb. 2016, Art. no. C4014007.

[12] S. Arangio and F. Bontempi, "Structural health monitoring of a cable-stayed bridge with Bayesian neural networks," In *Design, Assessment, Monitoring and Maintenance of Bridges and Infrastructure Networks*. New York, NY, USA: Routledge, 2020, pp. 163-175.

[13] A. Javanmardi, K. Ghaedi, F. Y. Huang, M. U. Hanif, and A. Tabrizikahou, "Application of structural control systems for the cables of cable-stayed bridges: state-of-the-art and state-of-the-practice," *Arch. Comput. Meth. Eng.*, vol. 29, no. 3, pp. 1611-1641, Jul. 2021.

[14] V. L. Ho, T. N. Hoang, R. G. De, T. T. Bui, and M. Abdel Wahab, "Effects of measuring techniques on the accuracy of estimating cable tension in a cable-stay bridge," in *Proc. 13th ICDAS*. Porto, Por, SGP, 2020, pp. 433-445.

[15] S. W. Kim, D. U. Park, J. S. Kim, and J. B. Park, "Estimating tension of a prestressed concrete cable-stayed bridge under construction and traffic use conditions using a vision-based system," *Structures.*, vol. 47, pp. 299-312, Jan. 2023.

[16] H. Y. Chen, "Calculation of pre-camber correction considering the inclination angle of cable-stayed bridges during construction," *Low Temp. Arch. Technol.*, vol. 40, no. 3, pp. 81-83, Mar. 2018.

[17] L. L. Lin, "Angle positioning method of cableway tubes for segmental precast concrete cable-stayed bridges," *Railway Constr. Technol.*, vol. 10, pp. 109-112+117, Oct. 2021.

[18] Z. H. Liu, "Research on the angle correction of the main girder cableway tube of the Peisen Liujiang Bridge," *Western China Commun. Sci. Technol.*, vol. 5, pp. 141-144, May. 2023.

[19] J. Q. He, "Research on key technologies for construction control of single-tower hybrid girder cable-stayed bridge," M.S. thesis, Civil. Eng., SCUT., Guangzhou, CHN, 2017.

[20] T. S. Deng and S. P. Shi, "Correction method for cableway tube installation angle of short tower cable-stayed bridge considering bending stiffness of cable-stayed cables," *Transp. Technol.*, vol. 1, pp. 12-16+26, Jan. 2020.

[21] X. Y. Gu, D. S. Shan, and Q. Li, "Research on manufacturing error limits of steel anchor beam cableway tubes for cable-stayed bridges," *World Bridges.*, vol. 47, no. 1, pp. 48-52, 2019.

[22] M. Y. Cao, "Research on the design of long-span asymmetric high-speed railway single-tower partial cable-stayed bridge and precise positioning of cableway tubes," M.S. thesis, Civil Eng., YTU., Yantai, CHN, 2023.

[23] X. Zhang, H. Xu, M. Cao, D. Sumarac, Y. Lu, and J. Peng, "In-plane free vibrations of small-sag inclined cables considering bending stiffness with applications to cable tension identification," *J. Sound Vib.*, vol. 544, Feb. 2023, Art. no. 117394.

[24] L. Ma, H. Xu, T. Munkhbaatar, and S. Li, "An accurate frequency-based method for identifying cable tension while considering environmental temperature variation," *J. Sound Vib.*, vol. 490, Sep. 2020, Art. no. 115693.

[25] S. Zhang, R. Shen, Y. Wang, G. De Roeck, G. Lombaert, and K. Dai, "A two-step methodology for cable force identification," *J. Sound Vib.*, vol. 472, Jan. 2020, Art. no. 115201.

[26] W. Y. He, F. C. Meng, and W. X Ren, "Cable force estimation of cables with small sag considering inclination angle effect," *Advances in Bridge Eng.*, vol. 2, no. 1, pp. 1-22, May. 2021.

[27] L. Y. Luo, Y. L. Du, T. H. Yi, C. X. Qu, S. H. Zhang, and T. S. Geng, "Piecewise-Fitted Formula for Cable Force Identification Considering Bending Stiffness, Sag, and Inclination," *J. Bridge Eng.*, vol. 28, no. 7, Apr. 2023, Art. no. 04023038.

[28] T. C. Chen, C. Su, and D. j. Han, "Simulation calculation of shrinkage and creep effect of concrete during construction of bridge segments," *J. Chin. Highway.*, vol. 16, no. 4, pp. 56-59, Oct. 2003.

[29] D. H. Yan, Z. C. Tian, X. w. Li, and G. Y. Xu, "Finite element method and application for calculation of shrinkage and creep of concrete bridges,". *J. Chin. Highways.*, vol. 17, no. 2, pp. 56-59, Apr. 2004.