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Calculation Method and Construction Process of Main Cable Alignment of Self Anchored Suspension Bridge

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Abstract: With the development of calculation theory and bridge construction technology, single tower space main cable self-anchored suspension bridge is more and more applied to engineering practice. The purpose of this study is to calculate the main cable shape of self-anchored suspension bridge and analyze its construction process. In this study, the structural model is established firstly, and the plane model of self-anchored suspension bridge is established by using finite element software. The tension scheme of the sling is determined by analyzing the construction stage. Then the main cable alignment is calculated. The initial finished state alignment and internal force of the sling are calculated by nonlinear finite element method. The unstressed length of each cable segment is calculated according to the number of cable segments Value to analyze the results and adjust the model. The results show that the maximum deviation of the main cable alignment is 15mm; the maximum deviation of the sling force is 3%; the non-stress length deviation of the main cable is 4cm, which is 0.8% of the unstressed length of the main cable; the maximum deviation of the unstressed cable length of the sling is 11mm. It is concluded that there is not a simple linear relationship between the displacement of the main cable and the axial force of the main cable. The calculation method of the main cable shape of suspension bridge in this study can ensure that the main cable is formed into the bridge shape, at the same time, the line shape of stiffening beam is smooth, and the engineering acceptance is ensured. It makes contribution to the construction of self-anchored suspension bridge.

1. Introduction

The main cable of the self-anchored suspension bridge is fixed at both ends of the strengthened beam. The reinforced beam bears the horizontal and vertical force of the main cable, and the main beam is compressed vertically. It inherits the beautiful appearance of suspension bridge. Compared with the foundation suspension bridge, it has lower geological conditions, suitable for medium and small span, and has excellent mechanical properties. A bridge with a span of about 300 meters will enhance competitiveness. Suspension bridge is now the largest bridge capacity, the larger the span, the more economical. Therefore, in order to pursue the bridge capacity, new systems and materials must be used. The development of suspension bridges in the future has an inevitable trend.

The main cable shape of suspension bridge is calculated by numerical analysis method and nonlinear finite element method. In the numerical analysis method of cable segment, the shape and internal force of main cable can be calculated correctly according to the known sling force, but the influence of girder stiffness cannot be considered. The nonlinear finite element method can well consider the interaction between the main girder and the cable system, but there are some problems in the modification of the length of the main cable and cable force and the saddle simulation in the calculation process. Different from the situation of the main cable system in the construction stage of the foundation anchored suspension bridge, the strength of the main girder and main cable system in the construction and completion of the self-anchored suspension bridge is closely related. The calculation of main cable shape of self-anchored suspension bridge is very important in the construction process.

In the study of the main cable shape calculation of self-anchored suspension bridge, Kim y proposed two robust methods for 3D analysis of suspension bridge: generalized dead load target assignment method and simplified analysis method. These methods provide an optimal initial state for 3D suspension bridge under dead load. His research is applied to three-dimensional self-anchored suspension bridges with spatial curved main cables and primary camber of main girders. On this basis, he uses two methods to apply the unstressed length method to bridge structure. His method is not stable [1]. The purpose of Li L is to contribute to the probabilistic assessment of bridge VIV response considering the influence of parameter uncertainty. He analyzed the influence of uncertainty on the probability estimation of vibration response. He established the probability density function of the wind speed on the bridge deck. The modal analysis is carried out and the natural vibration characteristics are checked. Then, three performance functions of bridge VIV maximum response model are introduced. He used the second-order fourth moment (SOFM) method to propagate the coefficient of variation (COV), skewness and kurtosis in parameter space, and discussed their influence on the exceeding probability of bridge VIV response. The accuracy of his method is very low [2]. In order to accurately predict the main cable shape of suspension bridge, Zhang W M proposed a new iterative method. In the iteration process, hanger tension and cable shape are input in turn. Considering the saddle arc effect, the shape of the cable is predicted analytically, and the tension of the suspender is calculated by the finite element method considering the joint action of the stiffening beam of the cable hanger. The static equilibrium state of cable is expressed by three coupled nonlinear control equations, which are transformed into the form corresponding to unconstrained optimization problem. His method is too complicated to be practical [3]. Xiao R presents a five-step algorithm for determining the reasonable state of space cable suspension bridges without theoretical derivation or original program design. Based on the conventional finite element analysis method, his algorithm is extended by adding algebraic operation and flow control. First of all, he obtained a set of ideal vertical Suspender Force components by rigid support continuous beam method. Secondly, the shape of the main cable is calculated iteratively according to the specified sag. Thirdly, the reasonable state of side span main cable is determined by the force balance of IP point. Fourth, the anchor span is solved by the balance of the splay saddle. Finally, a full bridge model is activated and special processing is performed to complete the analysis. His method is still in the theoretical stage and not convincing enough [4].

This study first introduces the five basic structures and mechanical characteristics of self-anchored suspension bridge, and expounds the advantages and disadvantages of the current self-anchored suspension bridge. This study also explains the calculation method of the main cable shape and the coordinate calculation formula. In this study, the finite element model is established in the experimental process, and the simulation of self-anchored suspension bridge is completed by combining the calculation steps of the main cable shape and the construction process. After the simulation is completed, the experimental parameters are calculated and analyzed, and the results are compared with the internal force and unstressed cable length of the main cable, the stress characteristics of the main cable and the sling, and the stress-free cable length deviation of the main cable. It is concluded that the research method has advantages in the calculation of the main cable shape of self-anchored suspension bridge, and has certain value in the design of the bridge.

2. Shape Calculation of Self Anchored Suspension Bridge and Main Cable

2.1. Basic Structure of Self Anchored Suspension Bridge

Self-anchored suspension bridge is a flexible suspension system bridge structure with the main line as the main endurance component. The main components include the main line, the main tower, the ring and the reinforcement beam. The dead load and live load of the structure are shared by the main tower, main line and reinforcement beam. The force of each component is distributed according to the ratio of the component to the overall rigidity.

(1) Stiffening beam: the main function of the stiffening beam is to provide the vehicle running channel, bear the bending moment and shear force generated by its own gravity and vehicle load, cluster load and wind load, and transfer the load through the lifting ring. Since the main cable is directly fixed at the end of the strengthened beam, the strengthened beam must bear the huge axial pressure transmitted by the anchoring system after the completion of the bridge. The strength of the strengthening beam is the same as that of the main beam of the cable-stayed bridge, which is a compression bending component [5-6].

(2) Main cable: the main cable is an important load-bearing component of self-anchored suspension bridge. It not only supports its own gravity and the weight of the lifting ring, but also supports the dead load and live load of the bridge abutment transmitted by the lifting ring. When the load increases, the main cable will be elastic deformation, linear change, affect the balance of the structural system, showing the geometric nonlinear mechanical characteristics. This is one of the main characteristics of suspension bridges different from other types of bridges. In the dead path, the main line produces a large initial tension while maintaining a specific geometric shape, which provides a strong geometric stiffness for the subsequent force to resist structural deformation [7].

(3) Main tower: the main function of the main tower is to support the main line. All dead and live loads carried by the main line on the top of the tower, as well as the strength of the strengthened beams supporting the tower, as well as the effects of wind load and earthquake, must be transmitted to the piers and foundations. Under dead load, the main tower mainly bears its own gravity and vertical force, and the main line is transmitted under axial compression. Under live load, the main cable on the upper part of the tower is affected by unbalanced horizontal components, and the main tower is in a bending state.

(4) Sling: sling is an important force transfer component connecting the beam and the main cable. The upper end is connected with the main cable through the cable clamp, and the lower end is connected with the reinforcement beam through anchoring, which is the axial tensile component. Because the main cable is a flexible component, if the reading force changes, the line shape of the main cable will change accordingly. In other words, the sling force determines the shape of the main cable when the bridge is completed. It can be considered that the elastic support is due to the influence of stimulation on the enhanced beam. If the ring force changes, the internal force distribution of the strengthened beam will change. Therefore, by optimizing the ring force, the

appropriate bridge state of the structure under dead load can be determined [8-9].

(5) Saddle: according to its function, the saddle can be divided into tower saddle and slack cable saddle. Tower top saddle is also called main line saddle. That function is to support and restrain the main cable. In order to realize the smooth transition of the main line at the top of the tower, the huge vertical component and unbalanced horizontal force transmitted by the main line will be transmitted evenly. For the main tower, the main function of the loose cable saddle is to guide the main cable and separate the main cable in space, thus promoting the decentralized anchoring of the main cable, resulting in excessive pressure and locking point of local damage to the structure.

(6) Anchoring system: the anchoring system is an important structure to realize the anchoring of the main line at the end of the reinforcing beam, and its function is to realize the smooth transmission of the tensile force from the main line to the reinforcing beam. The anchoring system is not only affected by the large axial pressure, but also by the lifting force generated by the main cable. The complex structural force is the key to the design of self-anchored suspension bridge [10-11].

2.2. Mechanical Characteristics of Self Anchored Suspension Bridge

Self-anchored suspension bridge is a flexible hanging connection system composed of main cable, reinforcement beam, main tower and suspender. The self-weight and external load of the building are supported by the main line, reinforcement beam and main tower. The main cable of self-anchored hanging cable is the main load-bearing component of structural system. The main burden of stretching force is the geometric change of the body. It not only affects the balance of the system through its own elastic deformation, but also is affected by the change of geometric shape. The mechanical characteristics of displacement nonlinearity have a large initial tension under a certain load. The main tower can bear the axial pressure under the action of a certain load. Due to the unbalanced horizontal component of the main line at the top of the tower, the bridge tower is a compression bending member, showing the characteristics of beam and column. The main function of the reinforced beam is to support the bridge abutment and prevent excessive bending and deformation of the bridge abutment. Deformation is an important part of structural system. On the other hand, the dead load and live load of the floor plate of the beam supported bridge are enhanced, and on the other hand, the horizontal component of the main cable supported by the beam is enhanced. Therefore, the reinforced beam is also a compression bending component. The characteristics of the emitted beam and the column. The function of high tide is to transfer the actual load and dead load supported by the enhanced beam as the connection between the enhanced beam and the main line to the main line which can withstand the axial tension [12-13].

2.3. Advantages and Disadvantages of Self Anchored Suspension Bridge

(1) Advantages of self-anchored suspension bridge:

Because there is no need to build a large number of anchors, it is especially suitable for areas with poor geological conditions. Because the terrain is narrow, it can be flexibly configured in combination with the terrain. A suspension bridge with two towers and three piers, or a suspension bridge with one tower and two towers. In the case of long-span suspension bridge reinforced with reinforced concrete beam, the rigidity of the strengthened beam can be improved by the pressure transmitted through the main line. As a result, many press structures and equipments are saved, and the easy buckling of steel under large axial force is overcome. Disadvantages: most self-contained suspension bridges are an important part of the city. The novel and elegant appearance is in harmony with the surrounding environment. After completion, it will become a local landmark and amusement facilities. The solutions between medium and small bridges are very competitive and suitable for urban bridges with high landscape requirements [14].

(2) Disadvantages of self-anchored suspension bridge:

Because the main cable is directly fixed on the stiffening beam, the main beam is subjected to large axial force. Therefore, it is necessary to enlarge the beam cross section. The cost of reinforced beam increases greatly, and the main beam of reinforced concrete beam increases. The weight of the beam increases the amount of steel used in the main cable. As a result, the span of these two materials is limited and the construction process is limited. After the reinforcement beam and bridge tower are completed, the main cable and lifting ring need to be suspended. In order to install the reinforcement beam, several temporary supports were constructed. Therefore, if the span of the self-propelled suspension bridge becomes longer, the additional engineering cost will increase, the local force of the mooring part will become more complex, and the design and construction will become difficult. Compared with the ground type suspension bridge, the construction management when the tension is applied on the suspender will become more complex [15].

2.4. Calculation Method of Main Cable Shape of Completed Bridge

The design of suspension bridge generally determines the rise and span ratio of the main cable of the main span of the bridge state, the coordinates of the control points of the main cable (the theoretical vertex and anchor point), the setting position of the ring and the main cable clamp. It is known that the coordinates of control points are the geometric boundary constraints of the main cable. The span of each main cable section can be determined according to the setting position of lifting ring and cable clamp. For the span of each main cable section and the main cable with special elevation, its linear shape and internal force can be uniquely determined. For the main cable with side line span and anchor span, the height of the middle span is not clear, but the alignment and internal force can be determined according to the balance condition of internal force that the horizontal component of the main cable at the vertex is equal to the adjacent span. Therefore, in the linear calculation sequence of main cable, the main span is usually calculated first, and then the side span and anchor span are calculated. Then, considering the linear calculation of main cable, the separation algorithm of main cable and saddle is adopted.

(1) The parabola theory is used to infer the horizontal and vertical components of the left end of the main cable.

(2) Based on the span of No.1 main cable section and the left end assembly of cable section, the difference between the unstressed length and the height at both ends of No.1 cable section is calculated. The vertical coordinates of a node can be determined [16-17].

(3) According to the unstressed length of No.1 main cable and the sling force in point 1, the horizontal component and vertical component at the left end of No.2 cable section can be calculated. The unstressed length of cable part N2 and the vertical coordinate of node 2 can be obtained by the same method.

(4) Using the method of (3), the unstressed length of each cable section and the vertical coordinates of each node are calculated in turn to obtain the coordinates of the central cable and the right end of the main cable.

(5) Calculate the error between the vertical coordinates of the right end of the main cable and the vertical coordinates of the middle span. If the accuracy requirements are met, the calculation is finished; otherwise, iterative calculation is repeated before the end of (2) after the horizontal and vertical components at the left end of the main cable are corrected [18-19].

From the shape exploration calculation of the main span, the horizontal component of the main cable at the theoretical vertex can be obtained. At the theoretical vertex of the main cable, the horizontal component of the side span adjacent to the main span can be obtained from the constraint condition that the horizontal component of the side span and the middle span are equal. Because of the horizontal force, the shape detection of the main cable with side span is a variable problem. In the shape detection calculation of side span main cable, the shape detection process of main span can be referred to. In the iterative calculation of shape detection, it is necessary to repeatedly calculate the planned vertical reaction force until it is completed to determine the shape and internal force of the side distance. According to the above process, the unstressed length, internal force and geometric coordinates of each cable section of the bridge main cable are obtained [20].

2.5. Calculation of Main Cable Bridge Completion Coordinates

The shape determination of bridge is not only the basis of main line design, but also the goal of construction management. Since the unstressed length of the cable, the shape of the erection line of the main line, the pre bending of the conductor, the position of the cable clamp in the state of the empty cable and the length of the non-stress clamp are determined by the position alignment of the bridge, so the correct calculation of the position alignment of the bridge of the main line is the premise of the construction [21-22].

The main cable is composed of high-tension steel wire with low bending rigidity and flexibility. The calculation assumption of main cable of suspension bridge is as follows [23].

Flexible cables can only bear tension, but not bending moment. After bridging, the rings will be vertical. The cross-sectional area of the main cable will not change even under load [24-25].

When the force applied to the cable is only its own weight q1, according to the coordinate system shown in Figure 1, the equation of the cable curve is as follows:

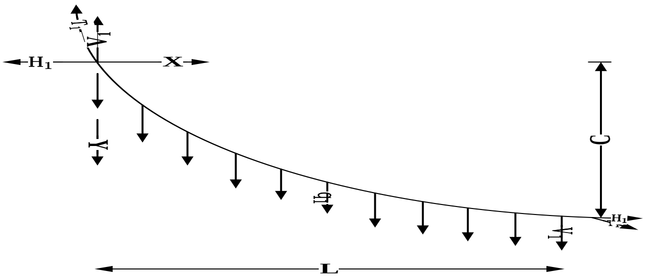

Figure 1. Catenary stress diagram

$$H \cdot \frac{d^2 y}{dx^2} + q_1 \cdot \sqrt{1+\left(\frac{dy}{dx}\right)^2} = 0 \quad (1)$$

Formula (1) is integrated twice with boundary conditions as follows:

$$x=0, y=0; x=L, y=C \quad (2)$$

The result is as follows:

$$y = -\frac{H}{q_1} \cdot ch(\frac{q_1 \cdot x}{H} - \alpha) + \alpha_1 \quad (3)$$

$$\left.\begin{aligned} \alpha_1 &= \frac{H}{q_1} ch\alpha \\ \alpha &= arsh(\frac{\beta \cdot C}{L \cdot sh\beta}) + \beta \\ \beta &= \frac{q_1 \cdot L}{2 \cdot H} \end{aligned}\right\} \quad (4)$$

When the heights of the two towers are equal, C = 0, $\alpha = \beta = \frac{q_1 \cdot L}{2 \cdot H}$, equation (3) becomes:

$$y = \frac{H}{q_1} \cdot \left[ch\alpha - ch\left(\frac{q_1 - x}{H} - \alpha \right) \right] \tag{5}$$

When x = L/2, y = f, then:

$$f = \frac{H}{q_1} \cdot (ch\alpha - 1) \tag{6}$$

The geometric length s and unstressed length S0 of the cable are as follows:

$$S = \frac{H}{q_1} \left[sh\left(\frac{q_1 \cdot L}{H} - \alpha \right) + sh\alpha \right] \tag{7}$$

$$S_0 = S - \Delta S = S - \frac{H}{E \cdot A \cdot q_1} \left[\frac{1}{2} \cdot q_1 \cdot L + \frac{1}{8} \cdot H (e^{-2(\alpha - 2\beta)} - e^{2(\alpha - 2\beta)} - e^{-2\alpha} + e^{2\alpha}) \right] \tag{8}$$

3. Simulation Experiment of Main Cable Shape Calculation of Suspension Bridge

3.1. Establishment of Finite Element Model

(1) Main cable and sling

The main cable can be compressed, but cannot be tensioned. There are 38 main lines in the whole bridge, which only accept tension groove elements. The sling is simulated by trajectory elements. The lifting ring is a vertical component. Because of its very small nonlinearity, the general trajectory elements are used, and a total of 33 truss elements are used.

(2) Stiffening beam and main tower

The stiffening beam is simulated by beam element. The locking end section is used at the edge of the beam, and the standard section is used for the central span. The beam element is allocated its own weight according to the linear load. There are 170 elements. According to the principle of equal rigidity, the main tower is simulated as a single column tower, and the upper and lower beams are replaced by concentrated force. There are 30 elements in total.

3.2. Calculation Steps of Main Cable Shape

(1) The prepared shape of the bridge and the internal force of the lifting ring are calculated by nonlinear finite element method. The suspension cable and main cable are discretized by catenary lead element, and the main girder and bridge tower are simulated by beam element.

(2) According to the obtained main cable shape, sling force and control point height, the cable section numerical analysis method is used to recalculate the main cable shape, correct the position of tower saddle joint, and calculate the unstressed length of each cable section.

(3) If the linear error is greater than the allowable value, the node position of the finite element model and the initial internal force of the element are adjusted according to the numerical analysis results of the cable segment, and then the finite element calculation is carried out again.

(4) When the error is less than the allowable value, repeat, output the cable system, and calculate the linearity and internal force.

3.3. Analysis Steps of Construction Process

The first step: using the numerical solution of the empty cable, the shape of the main grid and the elevation design value of the main tower, the model is established, the specific construction steps are formulated, and the sling is stretched according to the specific tension sequence, and the unstressed cable length of the sling is made, and the length and grasping force basically reach the design value.

Step 2: correct the length of main girder and main tower. In general, the design values of the coordinates of the main girder and the main tower are used for calculation, but the results are not consistent with the design values. This is because the main beam is shortened due to the axial force, and the height of the main tower is reduced, so the longitudinal compression of the main beam is required. The main tower is vertically compressed to replace the main beam and the modeling coordinates of the main tower. Both ends of the main cable are anchored on the main beam, and the anchor point of the main line becomes the anchor point on the main beam. Therefore, the X coordinate of the anchor point of the main line must be prefixed at this time.

Step 3: adjust the tension of the sling, extend the sling to the designed stress-free length, put the main grommet back to its position, and confirm whether the height of the main beam is consistent with the design value. When the main cable height and the length of the main cable reach the design value, whether the main cable should reach the design value or not. After the suspender is extended, the main beam deviates from the original elevation, so it is necessary to change the elevation of the main beam, subtract the vertical displacement value of the main beam from the design standard height, and then revise the model calculation again.

Step 4: when the bridge is completed, if the alignment and internal force reach the design value, the calculation in the construction stage is completed. When the error is large, continue to modify the modeling coordinates and adjust the tension, so that the target value error between the calculation results and the design value is within a certain range. The structural calculation of this paper is mainly linear control, supplemented with cable force control. The error of coordinate and length is within 1cm, and the internal force of lifting ring is controlled within 2% of the design value.

3.4. Main Beam Construction Technology:

The main construction method is to use the steel pipe pile as the temporary support under the main beam, install the truss beam on the temporary support, and install the sliding frame on the beam. After the construction of the main girder is completed, the columns and frames will be transferred to the distribution beams. The temporary buttresses are arranged at a longitudinal interval of 10 m under the transverse diaphragm of the main beam. In order to prevent the temperature crack of the box girder under the condition of large temperature difference, in addition to the fixed support on the upper part of the temporary support of the main span, other temporary pillars are also equipped with bidirectional sliding support. The upper steel plate of the sliding bearing is embedded under the main beam.

4. Calculation of Main Cable Alignment and Analysis of Construction Process of Self Anchored Suspension Bridge

4.1. Calculation Model and Geometric Parameter Analysis of Main Cable Linear Structure

In this study, the finite element model is established by using the general finite element program ANSYS. The structure is composed of stiffening beam, bridge tower, main cable and suspender. The main cable and suspender are simulated by the cable element linkl0 with tension only, and the stiffening beam and tower column are simulated by beam element beam3. The bottom of the tower is connected by fixed end, and the bottom of the main beam is a basin type sliding support. The cable tower and side pier provide vertical support for the main beam, but do not provide horizontal and angular constraints. The connection between the main beam and the bridge tower is realized by vertical coupling; the vertical coupling between saddle and tower top simulates the pushing of saddle. As shown in Table 1, unit parameter number. As shown in Table 2, the structure of the main data table.

Table 1. Unit parameter number

Component name	Unit type (ET)	Material properties (MP)	Real constant
Main cable	LINK10	MAT1	R1
Sling	LINK10	MAT2	R2
Stiffening beam	BEAM3	MAT3	R3
Main tower	BEAM3	MAT4	R4

Table 2. Main data table of structure

Component	Elastic modulus($\times 10^8$kN/m^2)	Cross section area(m^2)	Moment of inertia(m^4)	Weight per unit length(kN/m)
Main cable (single)	1.2	0.1205	0	9.451
Sling	1.95	0.00467	0	0.368
Stiffening beam	0.35	16.4118	14.9953	426.706
Main tower	0.35	8.77	4.5572	227.7
Phase II dead load	170.4			

4.2. Comparative Analysis of Internal Force and Unstressed Cable Length of Main Cable Sling

(1) Internal force of sling

The error range between the result of scheme 1 and the design value is - 2% - 1%, scheme 2 is - 0.4% - 1.4%, scheme 3 is - 0.4% - 1.5%, scheme 4 is - 0.5% - 1.3%, all within the error range, so the four schemes are feasible. The design values of Suspender Force and cable force in each scheme refer to the internal force of four suspenders.

(2) Unstressed cable length of suspender

The unstressed length of the sling and the unstressed length of each segment of the main cable serve as the basis for the subsequent erection and system conversion of the main cable. The unstressed length of the main cable mainly controls the alignment of the empty cable and the main cable of the completed bridge. As the connecting member of stiffening beam and main cable, the sling is affected by the shape of stiffening beam and main cable. On the contrary, the unstressed length of sling and the stress state of sling will also affect the alignment of stiffening beam and main cable. Accurate unstressed cable length of sling can ensure that the main cable is in line with the bridge, and the alignment of stiffening beam is smooth, so as to ensure the acceptance of the project.

The modification of the unstressed cable length of the sling should be taken into account the influence of the pre camber of the completed bridge. The pre camber value of the stiffening beam of the bridge is 1 / 2 live load + 10 years shrinkage and creep, which is not introduced here. The stress length of the sling in the finite element model should be modified according to the structure of the upper and lower edges of the sling

According to the formula for calculating the unstressed cable length of the suspender of suspension bridge, the total length between the lifting point of the main cable and the anchorage point minus the length of the cable clamp and the elongation of the sling is equal to the unstressed length of the sling. As shown in Table 3, the comparison values between the unstressed cable length and the design value of the suspender under each scheme are listed.

Table 3. Comparison of unstressed cable length and design value of each scheme (m)

Boom No	Scheme 1 LO$_1$	Scheme 2 LO$_2$	Scheme 3 LO$_3$	Scheme 4 LO$_4$	Scheme 5 LO$_5$
39	5.425	5.424	5.423	5.424	5.426
40	8.190	8.189	8.187	8.190	8.193
41	11.384	11.383	11.381	11.383	11.388
42	14.819	14.818	14.816	14.816	14.823
43	18.737	18.733	18.732	18.732	18.737
44	23.011	23.008	23.007	23.008	23.010
45	23.773	23.775	23.772	23.774	23.772

It can be concluded from Table 3 that the difference range of unstressed cable length in scheme I is -0.004mm~0.006mm; scheme II is -0.005mm~0.005mm; scheme III is -0.007mm~0.005mm; scheme IV is -0.007mm ~ 0.005mm. It can be seen that the error of each scheme is very small, and the four schemes are feasible from the stress-free length of the sling. As shown in Figure 2, the stress-free length of each scheme is compared. The schematic diagram of the difference between the stress-free length of the sling and the design value is shown in Figure 3.

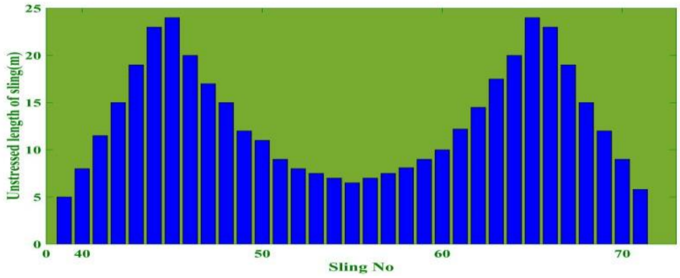

Figure 2. Comparison between the unstressed length of the sling and the design value

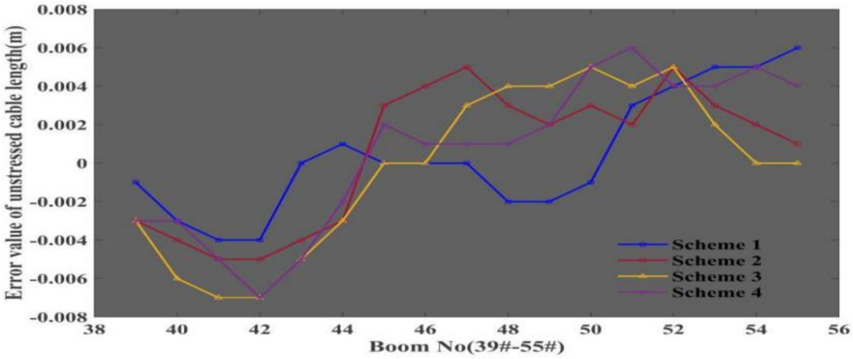

Figure 3. Comparison of stress-free length and design value error value of sling in various schemes

According to Figures 2 and 3, the maximum deviation of the main cable alignment is 15mm; the maximum deviation of the sling force is 3%; the non-stress length deviation of the main cable is 4cm, which is 0.8% of the unstressed cable length of the main cable; and the maximum deviation of the unstressed cable length of the sling is 11mm. The unstressed length of main cable and sling will be used as invariants for component installation and construction when the unstressed state method is used for empty cable erection and sling tension scheme. When the boundary of component installation process does not change and material nonlinearity does not occur, the structure will reach the predetermined target state.

4.3. Stress Characteristics Analysis of Main Cable and Sling

Under the condition of bridge empty cable, the vertical sling force is applied in the main cable span, and the nonlinear finite element analysis is carried out to observe the deformation and stress characteristics of the main cable.

The deflection curve of the middle point of the main cable span under different sling forces decreases with the increase of the sling force. When the sling force is 2000kN, the deflection of the middle point of the main cable is 2.1lm. When the sling force reaches 500kN, the deflection of the main cable in the middle of the span is more than half of the value. When the sling force continues to increase by 1500KN, the mid span deflection of the main cable only increases by 0.97M. In the process of deformation, the vertical stiffness of the main cable changes constantly. As shown in Figure 4, the deflection of the middle point of the main cable span of the bridge under different sling forces.

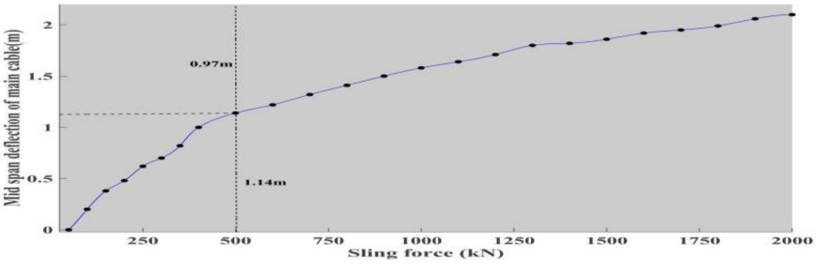

Figure 4. Deflection of main cable span under different sling forces

It can be seen from Figure 4 that, different from the deflection curve of the middle point of the main cable span, the axial force of the cable and the sling force are linear, and the axial force of the main cable increases linearly with the increase of the sling force. It can be seen that the displacement of the main cable and the axial force of the main cable is not a simple linear relationship.

The main cable shows a unique stress law only under the action of the mid span sling force. Under the joint action of multiple slings, the coupling between the main cable and the sling makes the stress state of the main cable extremely complex. The research on the mechanical characteristics of the main cable and sling will be helpful to the calculation of the sling force and the shape of the main cable and the construction monitoring of the sling tension.

It can be seen that the geometric nonlinearity and large displacement deformation of the interaction between the main cable and the sling are the difficulties in the calculation from the tension simulation of a single sling to the optimization calculation of the whole bridge system conversion sling tension scheme, and the optimization of the sling tension scheme needs to consider the constraints of the bridge construction conditions. It is also difficult to accurately and accurately simulate the stress and deformation state of the sling and the main cable when the sling is tensioned by the commonly used finite element software. In order to calculate the system transformation process of self anchored suspension bridge, it is necessary to conduct theoretical analysis and derivation and combine with structural finite element calculation software to calculate the shape of main cable and the cable force of sling in the process of sling tension.

4.4. Stress Free Cable Length Deviation Analysis of Main Cable

The curve length of the main cable is the sum of the unstressed cable length and the elastic deformation of each catenary lead section. Therefore, it is necessary to analyze the empty cable alignment deviation caused by the unstressed cable length deviation. One is to correct the target value of the empty cable erection, and the other is to measure the main cable alignment after the completion of the empty cable erection. When the empty cable alignment deviation is large, the unstressed cable length can be adjusted, that is, repeatedly tensioning the main cable strand.

(1) The principle of non-stress cable length deviation

According to the anchoring method and the structural form of anchor head, the adjustment amount of the reserved length of the anchor head is generally 30-50 mm. In principle, the reserved length should be long rather than short. Therefore, the deviation is a positive tolerance, and the value range is 30-50 mm. The manufacturing deviation is 1/15000 cable length. The unstressed cable length of the main cable of the bridge is 554.116m, and the length of 1/15000 cable is ± 37mm. In addition, the factory processing temperature deviation of the strand is 1 ℃, which causes the stress-free cable length deviation of ±5.5mm, and the factory processing temperature deviation range is generally ±2 ℃, which will cause the unstressed cable length deviation of ±11mm. Under the joint action of the above factors, the stress-free cable length deviation range of the main cable is - 48 ~ 98mm. In error analysis, the error range should be greater than the possible error range. Therefore, the value of the unstressed cable length deviation of the bridge is - 10cm, - 8cm, - 6cm, - 4cm, - 2cm, 2cm, 4cm, 6cm, 8cm, 10cm, and the empty cable alignment analysis is carried out.

(2) Analysis results of vertical deviation of empty cable caused by unstressed cable length deviation

The analysis results of vertical deformation of empty cable caused by the change of unstressed cable length are shown in Figure 5.

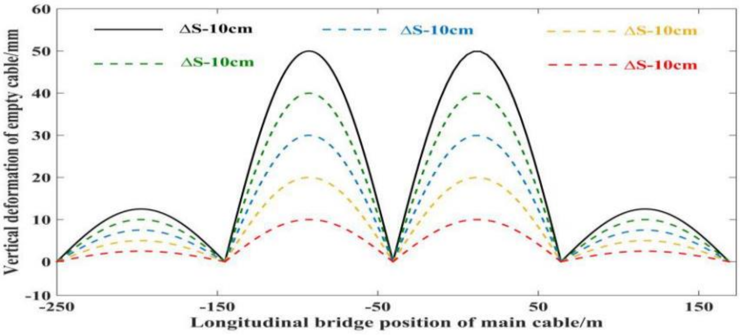

Figure 5. Vertical deformation of cable without stress tolerance

As shown in Figure 6, the relationship between the unstressed cable length deviation and the vertical deformation of the main cable vertical point is shown.

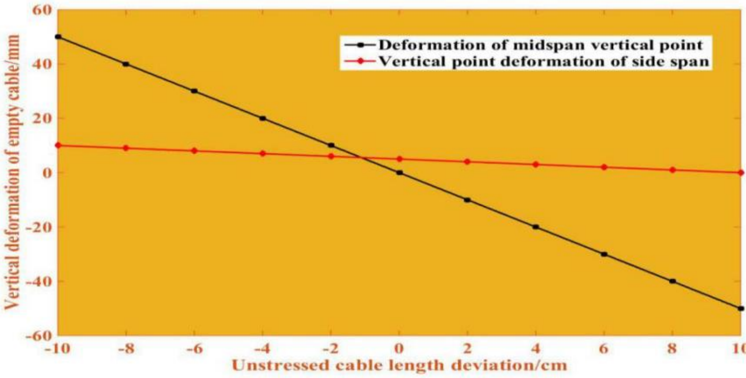

Figure 6. The relationship between the unstressed cable length deviation and the vertical deformation of the cable sag point

It can be seen from Figure 5 that when the main cable has no negative tolerance of stress cable length, the main cable is lifted up; when the main cable has no positive tolerance of stress cable length, the main cable deflects downward, and the deformation value increases with the deviation.

It is shown in Figure 6 that there is a linear relationship between the unstressed length deviation of the main cable and the vertical point deformation of each span. The change rate of the sag deformation of the middle span is -0.512, and that of the side span is -0.1. The mid span is more sensitive than the side span. The vertical span ratio of the main cable in the middle span of the bridge is 1/5, and the ratio of the non-stress length of the main cable of the side span is close to 1:2. When the unit deviation of the non-stress length of the main cable in the middle span occurs, the deformation of the vertical point of the middle span is -1.535cm; when the unit deviation of the non-stress length of the main cable of the side span occurs, the deformation of the vertical point of the middle span is -0.599cm.

5. Conclusion

Self-anchored suspension bridge is gradually favored by people because of its beautiful appearance, strong adaptability to topography and geology, flexible span layout and so on. The section catenary theory is used to calculate the shape and internal force of the main cable, and the unstressed length of the main cable and sling under the completed state of the main cable by programming. According to the internal force of the main cable in the completed state, the position of the main cable saddle in the completed state is solved, and the correction formula of the unstressed length of the main cable considering the friction force at the position of the main cable saddle is established, and the actual cutting length of the main cable is determined. Combining nonlinear finite element method with numerical analysis of cable segment, the main cable shape of self-anchored suspension bridge is calculated, which has the characteristics of clear mechanical concept and high calculation accuracy.

Through the analysis of the mechanical characteristics of the main cable and the sling, the main cable shows geometric nonlinearity and large displacement in the process of sling tension. The tension force and the length of the sling are not linear proportional relationship, and the tension force varies with the stiffness of the main cable. The tension of the new sling changes the alignment of the whole main cable and the cable force of the original sling. The initial state of the cable tension is empty cable state and the target state is the bridge state. The position coordinates, unstressed length and internal force of the main cable in the completed bridge state are analyzed. On this basis, the main cable at the saddle is corrected and calculated. Then, the position coordinate and internal force value of the main cable in the state of empty cable are determined by reverse analysis method, and the main cable at the saddle is corrected and calculated.

The main cable of self-anchored suspension bridge is catenary in the state of empty cable. After a series of turning processes, the bridge is finally completed. The shape of main cable changes. When the bridge is completed, the shape of main cable is neither parabola nor catenary, but between the two. The rigid support continuous beam method is used to determine the reasonable bridge cable force of the sling. The calculation is convenient. Except for the sling close to the side pier, the other sling cable forces are relatively uniform. According to the known geometric parameters of main cable such as design sag, sling position, bridge deck design alignment and so on, the target state is established. Through the iterative method of hypothesis calculation comparison correction hypothesis, the completed bridge alignment of empty cable and main cable meeting the design requirements is obtained, and the geometric shape and internal force of the structure in each construction stage are output. The method is effective and feasible.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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