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Research Article

Parametric Updating of Steel Strand Stay Cable Force Calculation Model Based on Response Surface Method

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In order to solve the problem that the calculation result of cable force deviates from the measured value because the parameters of steel strand stay cable are not exactly equal to the designed value in practical engineering, a model updating method selecting the steel strand stay cable parameters as the updating parameters and using more measured data as the objective function was proposed. This method selects the central composite design in the response surface method. In the fine-fitting model affected by the cross-term and high-order terms between parameters, the value of the parameter to be corrected is optimized according to the measured data. Using the above method, taking a cable-stayed bridge without a backstay as the engineering background, the model updating is carried out by using the cable force monitoring data during the construction monitoring process. The results show that using this method, the updated values of the parameters of the cable can be obtained according to the measured data, and the updated values of the parameters are consistent with the reality. The deviation between the calculated value of cable force and the actual cable tension obtained according to the parameter updating decreases significantly, and most of the deviation is reduced from 30% to 50% before the updating to less than 5%. The updating effect is obvious and meets the engineering requirements.

1. Introduction

Cable is the key mechanical component of cable-stayed bridges, and the accuracy of cable force measurement directly affects the construction safety and service status of cable-stayed bridges. The frequency method is an effective method to measure the cable force indirectly, and the accuracy of cable force identification by the frequency method depends on the cable force calculation formula and the specific values of parameters of each cable, so it is especially important to get the actual cable force calculation formula and the parameters of the cable force calculation. The main factors affecting the cable force calculation results are cable length, unit cable weight, bending stiffness of the cable, boundary conditions, shock absorber, and high density polyethylene (HDPE) casing [1–4].

At the present stage, many scholars have carried out research on the calculation of cable force and derived the formula for calculating the cable force considering the influence of various factors. Yi-Fan and Shuan-Hai [5] equated the cable model with two ends fixed to the model with two ends hinged and further deduced the formula of cable dynamic calculation length. Weixin and Gang [6] derived the formula for the calculation of the cable force considering the influence of the cable sag and bending stiffness by analyzing the axially tensioned beam with two ends fixed and gave the applicable range of the formula considering the cable sag and bending stiffness, respectively. Zui et al. [7] derived the calculation formula of cable force with fundamental frequency and second-order frequency for cables with fixed ends by numerical fitting method. Shao-Ping et al. [8] used the energy method to derive the formula for calculating the cable force and eliminated the bending stiffness as an implicit function, which effectively avoided the problem of difficult identification of the bending stiffness. Xu-Dong et al. [9] used the energy method to derive the segmentation formula between the fundamental frequency and the cable force and give the limit value of the segmentation formula. Jianfei et al. [10] obtained a cable force calculation formula based on the first five natural frequencies under the condition of both ends being fixed by combining the numerical solution with the analytical solution and considering the bending stiffness of the cable. Most of the above formulae highlight the influence of one factor and deviate too much when used in specific bridge cases.

Parallel steel strands or wires are in a discrete state, which will contact together due to cable tension, cable sag, and cable hoop, and are not integral. Therefore, there is a big deviation between the bending stiffness calculated by taking multiple parallel steel strands as a whole and the actual stiffness. For different cables under different anchorage types, the real bending stiffness shall be determined in combination with the actual situation [11]. The diameter of the HDPE casing outside the cable is larger than that of the cable, so it will contact with the cable under its own gravity, and the length of the contact area will vary with the cable length, but it is difficult to measure directly. The HDPE casing itself is almost force-free but will generate forced vibration due to contact with the cable. Therefore, the HDPE casing will have a certain effect on the cable frequency measurement and cable force calculation with its different contact area with the cable, and the size of this contact area cannot be measured directly, but the effect on the cable force calculation can be done by modifying the cable linear density. The currently proposed calculation formula considering the impact of the damper still requires substitution of the damper stiffness value, but the specific value of the damper stiffness is more difficult to measure. Considering the difference in damper stiffness, installation location, and damping coefficient, the method of correcting the calculated cable length can be used to reduce the error caused by the damper on the cable force measurement. The boundary conditions become very complicated after the two ends of the cable are anchored by the anchorages, which are neither fully fixed nor fully hinged [12].

The existing research mostly adopts the method of modifying sensitivity parameters, which selects the parameters that have a significant influence on the objective function to modify during the model updating process and makes the modified parameters have clear physical significance by restricting the value range of these parameters. The objective function is mostly constructed based on the joint measured data of the static load test and dynamic load test of the bridge, and finally, the modified finite element model can accurately reflect the stiffness information, mass information, boundary information, and static and dynamic properties of the structure [13]. Sensitivity-based correction method and the response surface method are the most commonly used methods in the process of model correction. Based on the central composite design (CCD) experimental design of response surface method, Yanqiang et al. [14], respectively, fitted the response surface equation for the parameters to be corrected and the objective function with or without consideration of the parameter cross-term, obtained the explicit equation between them and obtained the optimal value of the parameters to be corrected by the optimization solution, indicating that the correction effect on the cable force is more obvious when considering the influence of the parameter cross-term during correction. Yinping et al. [15] first established a finite element model of an arch bridge and carried out the model correction based on the response surface method, and finally obtained the explicit response surface equation between the objective function and the parameters to be corrected by combining the results of the parameter significance analysis, and the structural parameters were corrected by combining the measured data.

According to different scholars deriving the calculation formula under different conditions, in order to get the actual value of various influencing factors under different cable types, this paper puts forward the finite element model modification of stay cable based on the response surface method. By using the response surface method combined with field measurement data, the actual calculation parameters of the stay cable can be obtained more accurately to improve the calculation accuracy of the cable force.

2. Engineering Background

This paper is based on the Yingcheng Bridge, whose span arrangement is 35 + 60 m. The bridge elevation is shown in Figure 1. The main girder is a separated single box double chamber corrugated steel web integral box girder, as shown in Figure 2. Stay cables are made of filled epoxy-coated parallel steel strands with XL15-43 specifications, whose standard tensile strength is 1,860 MPa and the modulus of elasticity is 1.95e5 Mpa, with HDPE casing protection on the outer side and FSM15-43 anchorages on both ends. One stay cable is set every 6 from 16 m away from the main pier, and seven pairs of stay cables are set in parallel on the left and right sides. Each stay cable consists of 43 parallel steel strands. The horizontal inclination angle of the cable is 30°. All stay cables are of the same type. The specifications and parameters of the stay cable are shown in Table 1, and the sectional drawing and structural drawing of the stay cable are shown in Figures 3 and 4, respectively.

2.1. Cable Force Monitoring Field Test. After each group of stay cable tensioning is completed, the tensioning jack cable force value is recorded, and the frequency measurement of the former cable is also carried out after the subsequent cable tensioning is completed in order to combine with the stress and deformation monitoring in the field to corroborate each other. The initial cable force is recorded after the completion of tensioning of the stay cable construction. In the subsequent construction stage, the frequency measurement of the constructed cable is measured by the cable force dynamometer, which is tied to the outside of the HDPE casing against the middle of the cable, where the HDPE casing and the cable fit together, as shown in Figure 5.

The cable force dynamic tester wirelessly transmits the collected vibration acceleration signal to the computer end for Fourier transformation analysis to obtain the frequency of each order of the cable, as shown in Figure 6, which is the frequency result displayed after analysis and processing. The abscissa value corresponding to each wave peak displayed in Figure 6 is the frequency value of each order of the stay cable.

Figure 6 shows the cable force measurement results of S5, S6, and S7. According to the cable force measurement results obtained from Figure 6, the fundamental frequency value and frequency order can be judged according to the principle

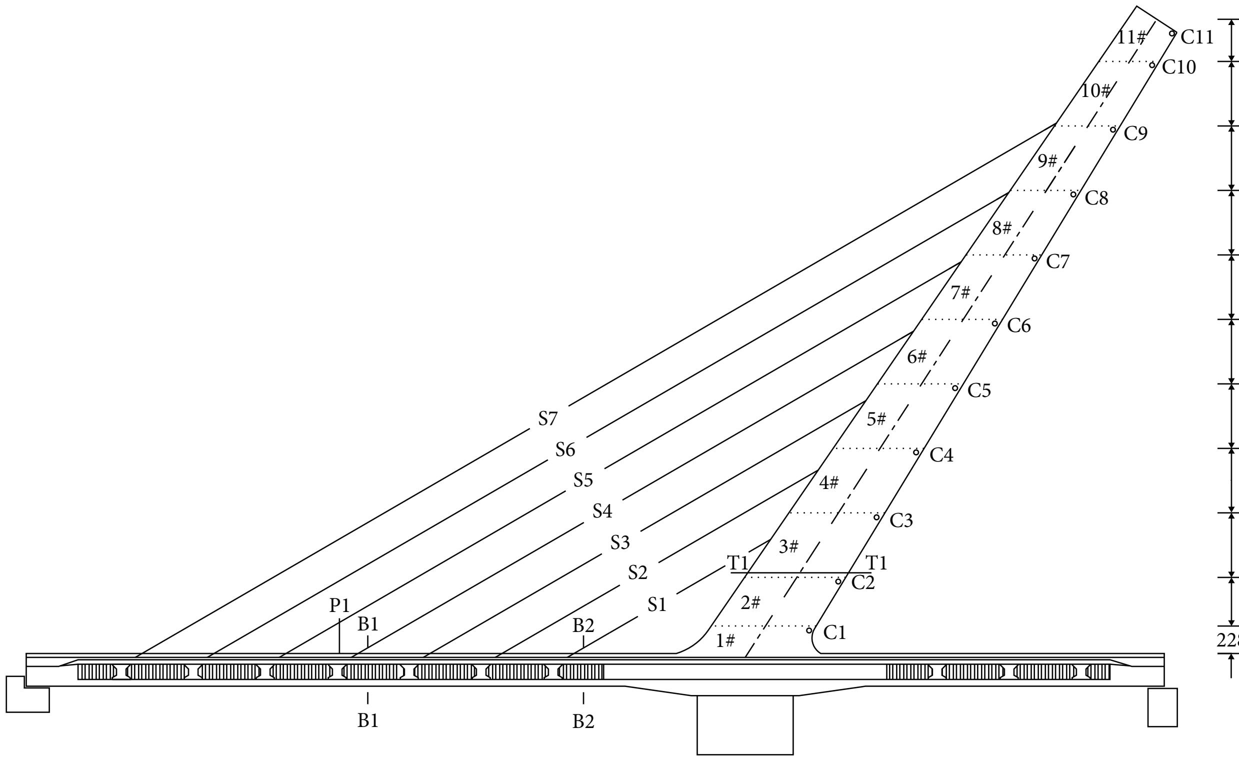

Figure 1: Layout of bridge elevation (unit: cm).

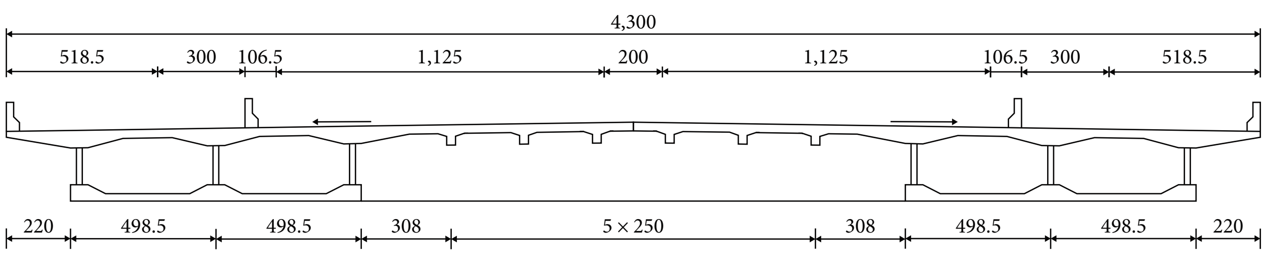

Figure 2: Box girder section (unit: cm).

Table 1: Cable specifications and parameters.

Cable number	Number of parallel steel strands of single-stay cable (piece)	Length of single cable L (m)	Unit cable weight (kg/m)	HDPE casing unit weight (kg/m)
S1	43	34.2	47.257	9.943
S2	43	44.9	47.257	9.943
S3	43	55.5	47.257	9.943
S4	43	66.2	47.257	9.943
S5	43	76.8	47.257	9.943
S6	43	87.5	47.257	9.943
S7	43	98.1	47.257	9.943

of similar frequency difference. The fundamental frequency and each order frequency can also be directly judged for the result with a large frequency amplitude. For the result with a small amplitude, it is necessary to calculate the fundamental frequency value by several high-order frequency values with large amplitude according to the principle of similar frequency difference.

2.2. Calculation Results of Practical Formula of Cable Force. Taking the seven cables listed in Section 2.1 as an example, the seven cable force calculation formulas were used in combination with the field-measured frequency values of the seven cables and compared with the theoretical tensile force of the cables to analyze the size of the deviation produced by each formula when applied to the bridge. The possible values

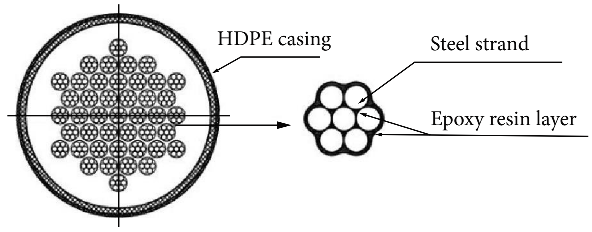

Figure 3: Cable section view.

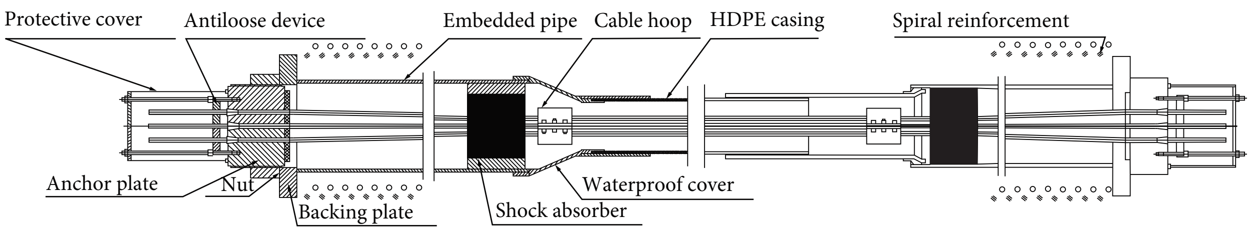

Figure 4: Diagram of cable structure.

Figure 5: Field binding of cable force dynamic meter.

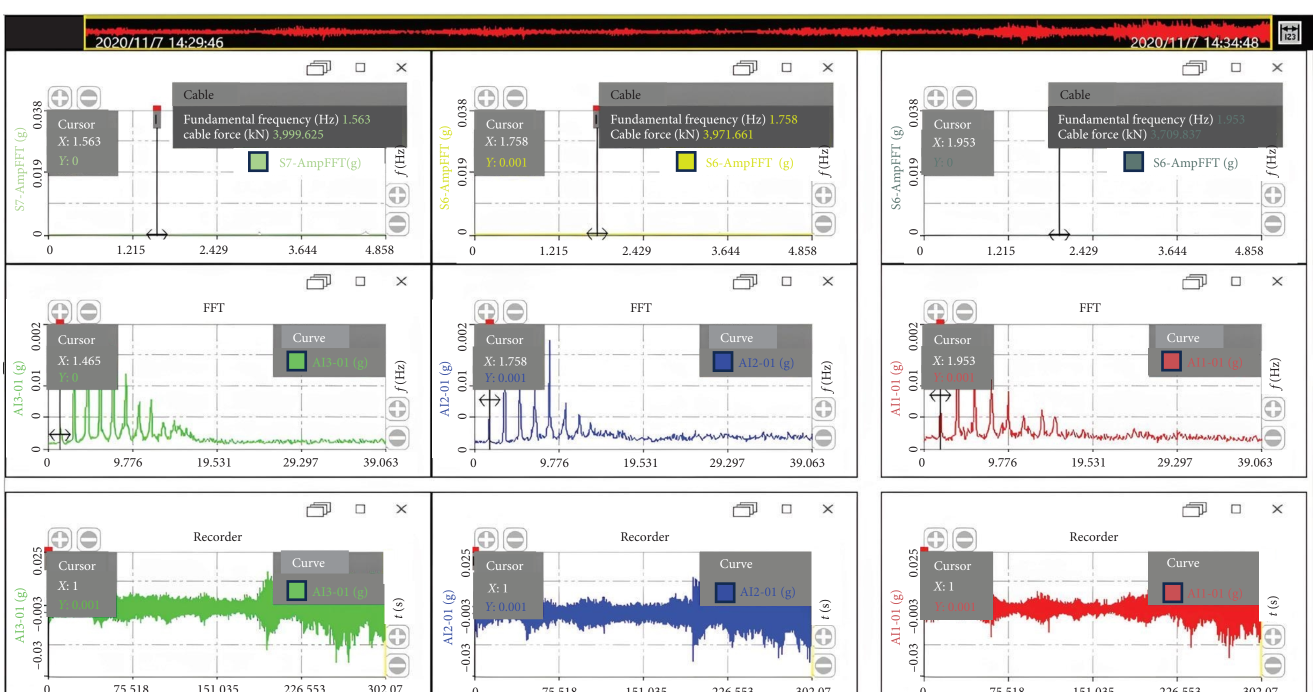

Figure 6: Cable frequency measurement results.

of various calculation parameters used here were obtained according to the specifications and related literature [16–19], and the results and deviations of the cable force calculations are shown in Table 2 and Figure 7.

According to the data results in Figure 7, the calculated results of the tensile string formula for short cables, ignoring boundary conditions, bending stiffness, and other factors, show a large deviation with a maximum deviation of 45.08%. For long cables, although the calculated results have relatively small deviations, reaching around 9.88%, there is still room for further optimization. The beam vibration formula takes into account the influence of bending stiffness but shows similar overall calculation deviations as the string formula, with a maximum deviation of 44.97%. Yi-Fan and Shuan-Hai [5] calculate cable force using corrected cable length and achieve a maximum deviation of 35.31%, but for long cables S5, S6, and S7, the deviations are relatively small within 7.2%. The calculation formula proposed by Weixin and Gang [6], considering the sagging degree, is not applicable to bridge calculations as it still yields a maximum deviation of about 44% even when considering bending stiffness effects with an additional maximum deviation of approximately 9.88%. Zui et al. [7] consider flexural stiffness, drape effects, and boundary conditions; using fundamental frequency yields a maximum deviation result of 39.44%, while using second-order frequency calculation gives a result with a maximum deviation of 34.14%. Shao-Ping et al. [8] eliminate bending stiffness in their calculation formula, resulting in a maximum deviation of calculated results at 49.54%.

As can be seen from Figure 7, the deviation of the formula for the long cable is less than that for the short cable, and the deviation of the cable force calculation gradually decreases with the increase of the cable length, which indicates that the boundary conditions and bending stiffness and other influencing factors have a greater impact on the short cable. It can be seen that, in the actual calculation, if the actual situation is not considered on the impact of the parameters of the cable, the design value of the parameters of the cable as the actual value of the formula for calculation, the calculation deviation will not meet the requirements of engineering accuracy, especially for the short cable, the calculation deviation will be difficult to accept.

3. Establishment of Initial Finite Element Model of Cable

For the uniform cable structure under the action of self-weight, the self-weight is uniformly distributed along the length direction of the cable curve, so its exact line should be catenary. In this paper, the horizontal and vertical components of the cable force T and the stress-free length of the cable are obtained by solving the cable catenary equations and iteratively calculating them, respectively, and the corresponding cable shapes are applied to ANSYS software to establish the cable catenary model to simulate the response of the cable.

A 3D finite element model of the stay cable is established using a general finite element program, in which the stay cable is simulated using a beam element, and a total of 2,000 elements are divided along the length of the cable, and the cable force is considered by applying a temperature load to the beam element. Boundary conditions of the stay cable are very complex, not completely solidified or articulated, but rather a composite state between the two. Currently, there is no unified conclusion on the study of boundary conditions. Considering the presence of anchor devices at both ends of the cable, the boundary conditions lean towards solidification. This paper establishes an analysis of the solidification end boundary under a finite element model of the cable. In actual projects measuring cable frequency, a cable force dynamometer is attached to the upper surface of the cable; therefore, in finite element modeling analysis, only vibrations in the vertical plane are considered.

In this paper, the finite element model of the cable under the end fixed boundary is established for analysis, and the natural frequency of the cable under specific cable force can be obtained by eigenvalue analysis of the finite element model of cable. The natural frequency of the cable under specific cable force is different with different model parameters, so it is necessary to determine the cable parameters as reasonably as possible according to the actual situation. The catenary finite element model of stay cable S7 is shown in Figure 8, which is divided into 2,000 units and 2,001 nodes.

4. Cable Finite Element Model Updating

Due to the difference between the ideal assumptions and boundary simplifications in the modeling process, the finite element model established based on the initial design parameters of the cables has a certain deviation from the actual structural response, and the finite element model correction can significantly reduce this deviation. Factor design can determine the significance of parameters and parameter interaction, and the response surface method is used to determine the explicit functional relationship between the parameters to be corrected and the objective function. Then, the optimal values of the parameters to be corrected are solved iteratively through the explicit functional relationship according to the measured data. The bridge has seven pairs of stay cables. This paper only takes cable S7 as an example to illustrate the process and key aspects of the parameter correction of the cable finite element model.

4.1. Parameter Screening Test. The CCD test was used for the experimental design, and the high-level value and low-level value of each parameter were determined based on the coefficient of variation of each parameter. The objective function f_{sn} $(n = 1, 2, 3\ldots 7)$ was determined by combining the measured data during the construction monitoring process, and the f_{sn} is measured fundamental frequency of the cable Sn. Table 3 shows the value ranges of the three parameters to be modified, which are determined by referring to the existing specifications and literatures and according to the coefficient of variation of the response.

4.2. CCD Test Fit Response Surface Equation. Combining the actual measured values of the objective function and the

Table 2: Calculation results of different cable force formulas.

Cable number	Measured frequency in this paper (Hz)		Calculation results of cable force (kN)			Calculation results of Weixin and Gang [6] (kN)	
	Fundamental frequency	2nd order	String model	Beam model	Yi-Fan and Shuan-Hai [5]	Sag	Bending stiffness
S1	1.563	3.027	6,121.10	6,116.42	/	1,530.27	6,113.05
S2	1.758	3.516	5,518.45	5,515.73	5,677.61	1,379.61	5,512.63
S3	2.051	4.004	5,336.29	5,334.51	5,070.48	1,334.07	5,331.66
S4	2.441	4.785	4,929.83	4,928.58	4,656.24	1,232.46	4,926.10
S5	3.027	5.957	4,691.70	4,690.77	4,399.04	1,127.93	4,688.56
S6	3.809	7.813	4,469.77	4,469.05	4,399.48	1,117.44	4,468.08
S7	5.260	10.024	4,446.90	4,446.33	4,102.98	1,111.72	4,444.51
Cable number	Theoretical cable force (kN)	Calculation results of Zui et al. [7] (kN)		Calculation results of Shao-Ping et al. [8] (kN)	Calculation results of Xu-Dong et al. [9] (kN)	Calculation results of Jianfei [10] (kN)	
		Fundamental frequency	2nd order			Fundamental frequency	2nd order
S1	4,031	5,883.14	/	6,308.96	5,912.20	6,121.07	/
S2	4,068	5,346.28	5,628.48	5,423.08	5,515.73	5,518.44	5,854.71
S3	4,105	5,199.55	5,032.4	5,392.83	5,334.51	5,336.28	5,212.28
S4	4,143	4,819.61	4,628.05	4,994.48	4,928.58	4,929.83	4,778.39
S5	4,178	4,599.11	4,379.98	4,765.53	4,690.77	4,691.7	4,510.85
S6	4,196	4,390.42	4,390.54	4,469.77	4,469.05	4,469.76	4,510.9
S7	4,219	4,376.37	4,101.49	4,539.3	4,446.33	4,446.9	4,208.32

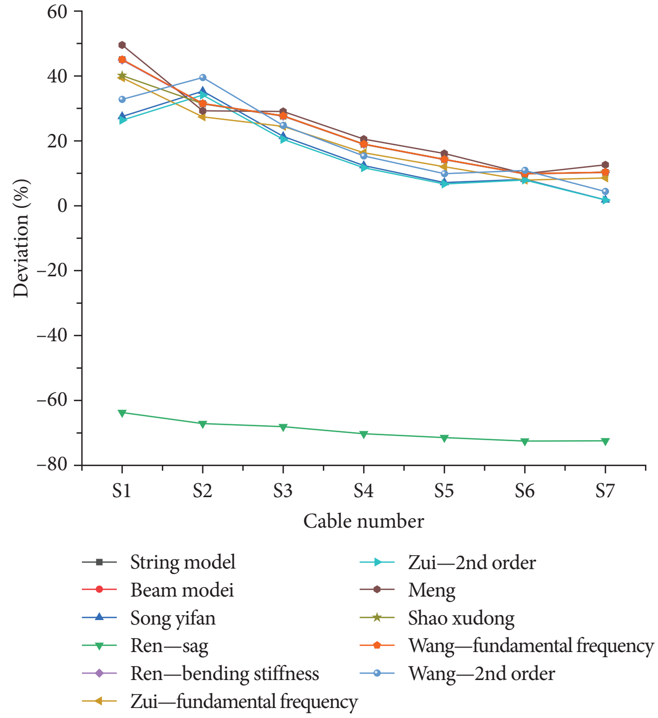

Figure 7: Deviation of cable force calculation results of formula.

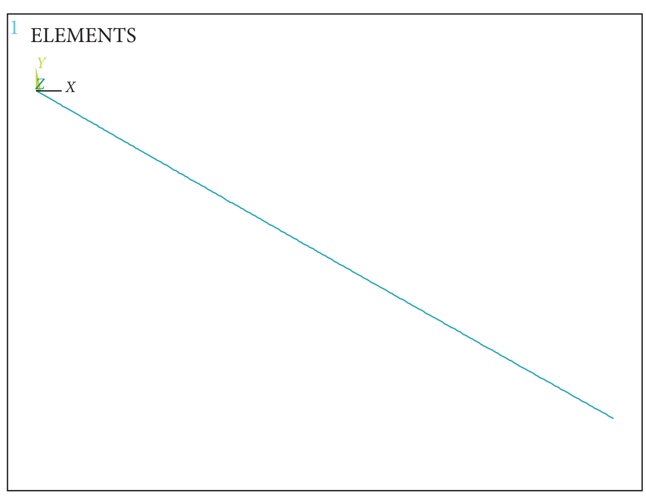

Figure 8: Catenary finite element model of cable S7.

Table 3: Parameters to be modified.

CCD test code (unit)	Parameter	Design value	Low level	High level	Coefficient of variation
X ($kN \cdot m^2$)	Cable bending stiffness	$0.4EI_{max}$	$0.1\ EI_{max}$	$0.7\ EI_{max}$	0.10
Y (m)	Calculated length of cable	$L–L_1$	$L–2L_1$	L	0.05
Z (kg)	Unit weight of stay cable	$m + 0.5m_1$	m	$m + m_1$	0.20

Note. EI_{max} is the maximum bending stiffness of the cable. L is the length between anchor positions at both ends of the stay cable, and L_1 is the length from the anchor end to the shock absorber. m is the sum of the unit weight of 43 parallel steel strands, and m_1 is the unit weight of the HDPE casing.

parameters to be corrected selected in Table 3, a 5-level CCD test with three parameters and one objective function was conducted with S7 cable as an example, and a total of 20 test scenarios were designed and obtained, as shown in Table 4. In Table 4, −1, 0, and 1 represent the low-level, design value, and high-level values of the parameters, respectively, and ±1.68, respectively, represent the maximum and minimum values of the parameters. Sample 1 in Table 4 indicates that

Table 4: CCD test design scheme of S7 cable.

Sample number	Code of parameters in CCD test		
	X (bending stiffness)	Y (calculated length)	Z (unit weight)
1	0	0	−1.68
2	0	0	0
3	−1.68	0	0
4	1	−1	−1
5	0	0	0
6	0	1.68	0
7	1	−1	1
8	0	0	0
9	0	0	0
10	−1	1	−1
11	0	0	0
12	1	1	−1
13	−1	−1	−1
14	1.68	0	0
15	1	1	1
16	−1	1	1
17	0	−1.68	0
18	0	0	1.68
19	−1	−1	1
20	0	0	0

Table 5: Calculation results of the objective function.

Sample number	Objective function results R_{f7}	Sample number	Objective function results R_{f7}	Sample number	Objective function results R_{f7}
1	1.537	8	1.409	15	1.156
2	1.409	9	1.409	16	1.145
3	1.393	10	1.260	17	1.618
4	1.613	11	1.409	18	1.308
5	1.409	12	1.272	19	1.454
6	1.235	13	1.600	20	1.409
7	1.466	14	1.417		

when each parameter to be corrected is taken at each level, the results of the combination of the parameter levels are used as a set of test scenarios for calculation and analysis of the finite element model as a sample, and the meaning of other samples 2–20 is the same as that of sample 1.

By substituting each test sample into the initial finite element model in turn to calculate the analysis, the corresponding 20 groups of objective function calculation results can be obtained, as shown in Table 5.

According to the calculation results in Table 5 and the results of the significance analysis of the objective function, the significance analysis was performed for the parameters single term, higher term, and cross term, considering that the fitted model is a second-order model, so only the squared term was considered for the higher term. According to the significance analysis, this test parameter $s = 3$, test sample $n = 20$, take the significance level $\alpha = 0.05$, and can be calculated $F_{0.05}(2, 17) = 3.59$. The ANOVA significant results are shown in Figure 9.

It can be seen from the significant results of variance analysis in Figure 9 that, for the stay cable S7, only the cable calculation length X, cable unit weight Y, and square term X^2Y have significant influence on the objective function, and the square terms of other parameters have no significant influence on the objective function. The cable bending stiffness X is not significant for S7 cable, which shows that the influence of cable bending stiffness on the calculation of long cable is very small.

According to the parameter significance results, the test design is conducted for each parameter. The response surface model of each parameter to the objective function f_{s7} can be obtained by the CCD test, as shown in Figures 10–12.

Based on the results of the parametric significance analysis, some terms that have no significant effect on the target response

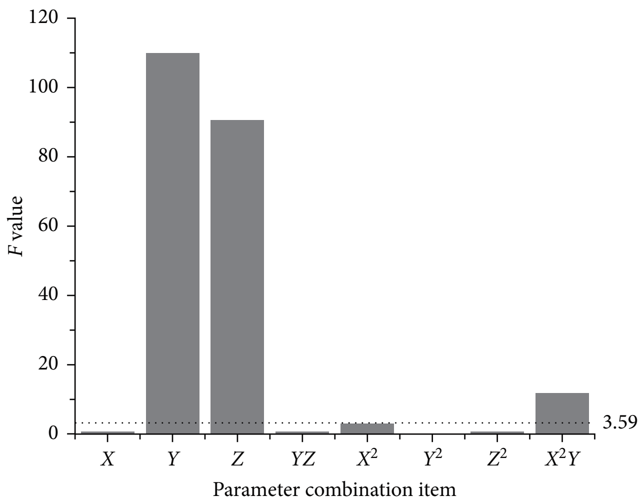

FIGURE 9: Significant results of variance analysis.

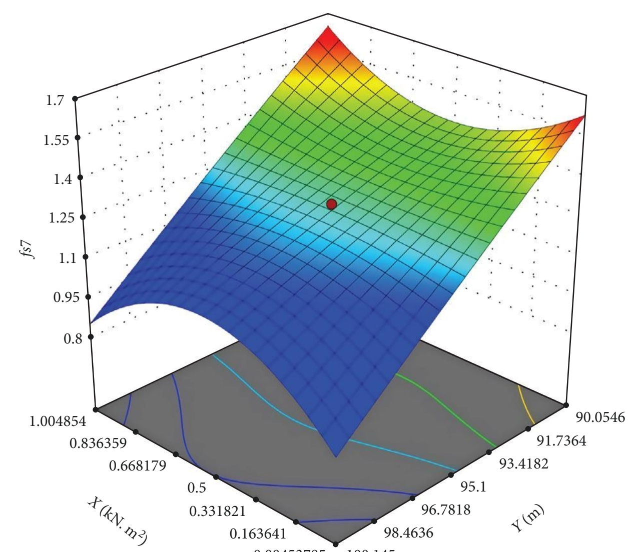

FIGURE 10: Response surface model of parameters X and Y.

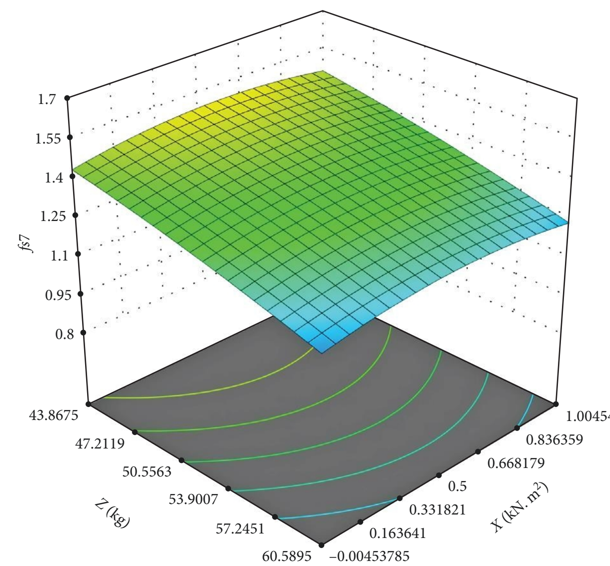

FIGURE 11: Response surface model of parameters X and Z.

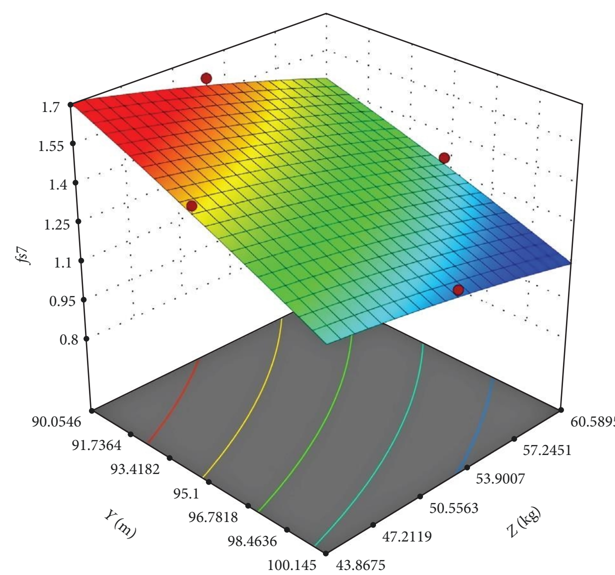

FIGURE 12: Response surface model of parameters Y and Z.

TABLE 6: Fitting accuracy test of the response surface.

Objective function	R^2	R^2_{adj}	RMSE
R_{f7}	0.9793	0.9643	0.0259

TABLE 7: The range of parameters to be modified and the result.

Parameter to be corrected	Range of initial values	Initial value	Corrected value
X	$(0.1\ EI_{max}, 0.7EI_{max})$	$0.4\ EI_{max}$	$0.352\ EI_{max}$
Y	$(L–2L_1,\ L)$	$L–L_1$	$L–0.979L_1$
Z	$(m,\ m+m_1)$	$m+0.5m_1$	$m+0.198m_1$

TABLE 8: The range of parameters to be modified and the result of S7 cable.

Objective function	Measured value	Uncorrected calculated value/deviation	Corrected calculated value/deviation
R_{f7}	1.563	1.409/9.8%	1.566/0.19%

Table 9: Calculation results of different cable force formulas.

Cable number	Measured frequency in this paper (Hz)		Calculation results of cable force (Hz)			Calculation results of Weixin and Gang [6] (Hz)	
	Fundamental frequency	2nd order	String model	Beam model	Yi-Fan and Shuan-Hai [5]	Sag	Bending stiffness
S1	1.563	3.027	4,373.54	4,371.14	/	1,093.38	4,368.67
S2	1.758	3.516	4,340.62	4,339.35	4,487.64	1,085.15	4,337.09
S3	2.051	4.004	4,443.85	4,443.07	4,234.94	1,110.96	4,441.04
S4	2.441	4.785	4,263.26	4,262.73	4,029.39	1,065.82	4,261.00
S5	3.027	5.957	4,167.83	4,167.45	3,901.13	1,041.96	4,165.93
S6	3.809	7.813	4,051.25	4,050.96	3,969.59	1,012.81	4,049.62
S7	5.260	10.024	4,093.87	4,093.64	3,752.85	1,023.47	4,092.42
Cable number	Theoretical cable force (Hz)	Calculation results of Zui et al. [7] (Hz)		Calculation results of Shao-Ping et al. [8] (Hz)	Calculation results of Xu-Dong et al. [9] (Hz)	Calculation results of Jianfei [10] (Hz)	
		Fundamental frequency	2nd order			Fundamental frequency	2nd order
S1	4,031	4,229.54	/	4,507.77	4,338.79	4,373.53	/
S2	4,068	4,236.45	4,459.06	4,265.60	4,339.35	4,340.61	4,606.54
S3	4,105	4,361.12	4,221.31	4,490.93	4,443.07	4,443.84	4,341.95
S4	4,143	4,196.57	4,030.25	4,319.17	4,262.73	4,263.26	4,133.55
S5	4,178	4,111.81	3,916.44	4,233.42	4,167.45	4,167.83	4,008.32
S6	4,196	4,003.24	4,003.29	4,051.25	4,050.96	4,051.25	4,089.61
S7	4,219	4,051.19	3,797.38	4,178.94	4,093.64	4,093.87	3,875.20

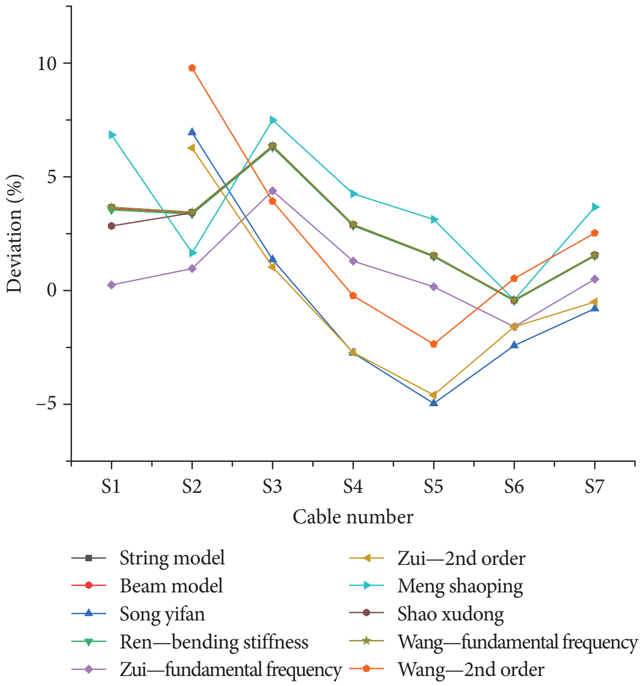

Figure 13: Deviation of cable force calculation results of formula.

are ignored, and a quadratic polynomial is fitted. After solving the undetermined coefficient, the quadratic response surface equation is obtained, as shown in Equation (1):

$$\begin{aligned} R_{f7} &= 1.41 + 0.0063X - 0.114Y - 0.0665Z + 0.0078YZ \\ &\quad -0.0115X^2 - 0.004Y^2 - 0.0052Z^2 - 0.0485X^2Y \end{aligned} \quad (1)$$

After obtaining the response surface equation, the fitting accuracy test is required, and the specific calculation results are shown in Table 6.

As can be seen from Table 6, both R^2 and R^2_{adj} of the response surface model are close to 1, and the RMSE is close to 0, indicating that the calculated value of the fitted response surface model is highly consistent with the calculated value of the real finite element model. Therefore, the response surface model can accurately reflect the corresponding relationship between the parameters and the objective function within the reasonable range of the parameters and can be used to replace the finite element model for model updating.

4.3. Finite Element Model Updating of S7 Cable. According to the obtained quadratic response surface model and in combination with the measured results of the objective function, the parameters to be corrected are optimized and solved within the parameter value range, and a group of optimal values of the parameters to be corrected are obtained. The results are shown in Table 7.

As can be seen from Table 7, the corrected bending stiffness of S7 cable is 0.352 EI_{max}, which is 29.6% less than the design value because the long cable is less affected by the bending stiffness, and with the increase of the cable length, the degree of impact will become smaller and smaller, and the results obtained are consistent with the existing literature cognition; The calculated cable length of the modified S7 cable is L–0.979L_1, which is close to the length before the dampers at both ends of the S7 cable. In combination with the installation of the dampers on site and considering that the stiffness of the S7 cable damper is large, the existence of the damper has changed the vibration mode and frequency of the S7 cable, and the dampers at both ends can be approximately considered as the cable boundary condition is fixed; The unit weight of S7 cable after considering HDPE casing is $m + 0.198$ ml, and the HDPE casing is not in full contact with the stay cable, so it is unreasonable to directly add the weight of HDPE casing. The corrected parameters are consistent with the actual situation, and the results of parameter correction are within the range of parameter variability.

The corrected parameters were substituted into the initial S7 cable finite element model for analysis and calculation, and the comparison of the corrected fundamental frequency of S7 cable and the initial fundamental frequency was obtained, as shown in Table 8.

From Table 8, it can be seen that the deviation between the calculated and measured values of S7 cable fundamental frequency is reduced from 9.8% to 0.19% before the correction, and the correction effect is obvious.

The results of cable force calculation and the deviation from the theoretical cable force are shown in Table 9 and Figure 13, after the analogy of the corrected values of each parameter of S1–S6 cables with reference to S7 cables.

From Table 9 and Table 2, it can be seen that the deviation of cable force calculation after correction is significantly reduced compared with that before correction. The deviation of S4–S7 cable using classical string theory and beam theory formulas is within 3%, which meets the engineering requirements, while the deviation of S1–S3 cables is more than 3%, in which the deviation of S3 cable reaches 6.36%; The deviation of S4–S7 cables calculated by the rest of formulas is within 5%, and most of the deviations are within 3%, and the deviations of the calculated force of S1–S3 cables are relatively large within 10%, and most of them are within 7%.

Referring to Figure 13, it can be seen that the deviation of the calculation result using the fundamental frequency is smaller than that using the second-order frequency, so the deviation of the calculation result using the fundamental frequency is smaller.

5. Conclusions

The following conclusions can be obtained from the analysis and study of the modification of the parameters of the stay cable model.

(1) Most of the existing cable force calculation formulas only consider the influence of one factor alone. When these formulas are substituted into the initial parameters of the cable to calculate the cable force,

the deviation is large, and the deviation is up to 30%–50%, which does not meet the engineering requirements.

(2) The response surface model based on the response surface method has high fitting accuracy. In the reasonable range of each parameter, the response surface model can effectively reflect the corresponding relationship between each parameter and the objective function and can be used to replace the finite element model for model updating.

(3) According to the obtained optimal solution of parameter correction, the parameters are resubstituted into each formula for calculation, and the calculation deviation is significantly reduced compared with that before the correction. The calculation deviation of each cable is below 5% in most of the formulas after the correction, and the correction effect is significant and meets the engineering requirements.

Data Availability

All data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] L. Ma, "A highly precise frequency-based method for estimating the tension of an inclined cable with unknown boundary conditions," *Journal of Sound and Vibration*, vol. 409, pp. 65–80, 2017.

[2] 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 Engineering*, vol. 2, no. 1, Article ID 15, 2021.

[3] W. Y. Liao, Y. Q. Ni, and G. Zheng, "Tension force and structural parameter identification of bridge cables," *Advances in Structural Engineering*, vol. 15, no. 6, pp. 983–995, 2012.

[4] Y.-H. Huang, J.-Y. Fu, R.-H. Wang, Q. Gan, and A.-R. Liu, "Unified practical formulas for vibration-based method of cable tension estimation," *Advances in Structural Engineering*, vol. 18, no. 3, pp. 405–422, 2015.

[5] S. Yi-Fan and H. E. Shuan-Hai, "Research on dynamic calculating length of cable in cable stayed bridges," *China Journal of Highway and Transport*, vol. 14, no. 3, pp. 73–75, (In Chinese), 2001.

[6] R. Weixin and C. Gang, "Practical formulas to determine cable tension by using cable fundamental frequency," *China Civil Engineering Journal*, vol. 38, no. 11, pp. 26–31, (In Chinese), 2005.

[7] H. Zui, T. Shinke, and Y. Namita, "Practical formulas for estimation of cable tension by vibration method," *Journal of Structural Engineering*, vol. 122, no. 6, pp. 651–656, 1996.

[8] M. Shao-Ping, Y. Rui, and W. Jing-Quan, "Novel formula of tension measurement for tied arch bridges in precise consideration of flexural rigidity," *Journal of Highway and Transportation Research and Development*, vol. 25, no. 6, pp. 87–91, (In Chinese), 2008.

[9] S. Xu-Dong, L. I. Guo-Feng, and L. I. Li-Feng, "Vibration analysis and force measurement of hanger," *Journal of China & Foreign Highway*, vol. 24, no. 6, pp. 29–31, (In Chinese), 2004.

[10] W. Jianfei, *Vibration Method Measurement for Cable Tension of Arch Bridge*, Harbin Institute of Technology, China, 2012.

[11] L. Wang, B. Wu, J. Gao et al., "A new cable force identification method considering cable flexural rigidity," *Structural Engineering and Mechanics*, vol. 68, no. 2, pp. 227–235, 2018.

[12] B. Yan, W. Chen, J. Yu, and X. Jiang, "Mode shape-aided tension force estimation of cable with arbitrary boundary conditions," *Journal of Sound and Vibration*, vol. 440, pp. 315–331, 2019.

[13] Z. Yuan, P. Liang, T. Silva, K. Yu, and J. E. Mottershead, "Parameter selection for model updating with global sensitivity analysis," *Mechanical Systems and Signal Processing*, vol. 115, pp. 483–496, 2019.

[14] L. Yanqiang, L. Xiaohui, C. Zelin, and Z. Hao, "Updating of cable-stayed bridge model based on cable force response surface method," *Journal of the China Railway Society*, vol. 43, no. 2, pp. 168–174, (In Chinese), 2021.

[15] M. A. Yinping, L. I. U. Yongjian, and L. I. U. Jiang, "Multi-scale finite element model updating of CFSE compostite truss bridge based on response surface method," *China Journal of Highway and Transport*, vol. 32, no. 11, pp. 51–61, (In Chinese), 2019.

[16] R. Geier, G. De Roeck, and J. Petz, "Cable force determination for the Danube Channel Bridge in Vienna," *Structural Engineering International*, vol. 15, no. 3, pp. 181–185, 2005.

[17] D.-H. Choi and W.-S. Park, "Tension force estimation of extradosed bridge cables oscillating nonlinearly under gravity effects," *International Journal of Steel Structures*, vol. 11, no. 3, pp. 383–394, 2011.

[18] B. H. Kim, T. Park, H. Shin, and T.-Y. Yoon, "A comparative study of the tension estimation methods for cable supported bridges," *International Journal of Steel Structures*, vol. 7, no. 1, pp. 77–84, 2007.

[19] Z. Huang, X. Hua, Z. Chen, and H. Niu, "Performance evaluation of inerter-based damping devices for structural vibration control of stay cables," *Smart Structures and Systems*, vol. 23, no. 6, pp. 615–626, 2019.