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Stability analysis of synchronous construction of towers and beams of cable-stayed bridge

Zeying Yang [1,a,*], Minghao Sun[1,b], Yangyudong Liu[1,c], Yongye Qu[1,d], Yalei Zhang[1,e] and Xinnan Xie[1,f]

1. School of Civil Engineering, Shandong University. Jinan Shandong, 250000, China
Email:[a,*]13864197135@163.com, [b]1830008584@qq.com, [c]liuyangyudong@163.com, [d]253277272@qq.com, [e]1197598624@qq.com, [f]995895461@qq.com

Abstract. The synchronous construction method of tower and beam can greatly shorten the construction period of cable-stayed bridge, but the force condition is complicated. The overall stability of the bridge which use synchronous construction method should be studied further. Based on the Dingzihekou Bridge project, a finite element analysis model was established and three typical construction conditions were selected by using Midas Civil software. Linear stability analysis and geometric non-linear stability analysis about the construction period of the Dingzihekou Bridge were conducted. The stability factors of the two construction schemes and the modes of the linear instability failure in the construction periods of the cable-stayed bridgeare inferred. It is found that the geometrically non-linear stability safety factor is significantly less than the linear. There is no big difference in linear stability factor between synchronous construction and asynchronous construction of tower and beam. As for the geometric nonlinear stability analysis, the synchronous construction of tower and beam has a larger stable safety factor than asynchronous construction.

1. Introduction

At present, most of studies on the stability of cable-stayed bridges have been carried out during the bridging stage [1,2], and there is less analysis of stability during the construction phase. However, in the construction process of cable-stayed bridges, due to its incomplete structure, low overall stiffness, and uneven load, and the system transformation during the construction process changes the overall stiffness of the structure [3]. The stability analysis during the construction phase is indispensable. This paper uses the buckling analysis and geometric nonlinear analysis function of finite element software Midas Civil to find out the comparison on linear and nonlinear stability analysis of synchronous and non-synchronous construction schemes for the Dingzihekou Bridge. By comparing the stability safety factor and the instability mode of the bridge under various typical conditions, the overall stability of the structure under the coupled effect of the beam, tower and cable is evaluated[4].

2. Brief Introduction of Project

The Dingzihekou Bridge is located at the junction of Haiyang and Jimo of Shandong Province. Height of the main tower is 88.7m and the main beam is 1.836 to 2.5m. The main bridge is the 88m+200m+88m double-tower and double cable side concrete bridge. After the top of the main tower is closed, the construction of the tower top is completed in 5 stages. To shorten the construction period and make full use of the best construction season, the 5 stages of the main tower and the 5th section of the main beam are used simultaneously. In order to ensure the smooth construction of the bridge, the synchronous construction section was analysed and calculated.

3. Establishment of Finite Element Model Of Cable-Stayed Bridge

According to the structural characteristics of the bridge, a large-scale general-purpose finite element program was established by Midas Civil 2015 based on the spatial dimensions of the structure. The most unfavorable conditions that may occur were taken into consideration to calculate the deformation, stress and vibration characteristics of each component under different conditions, and analysis of structural strength and stability accordingly was gone ahead.

3.1. Related Loads and Material Parameters

3.1.1. Dead loads.
(1) The first stage of dead load: The weight of the structure is automatically calculated by the software program, and the weight of the cross beam is calculated by the node load.

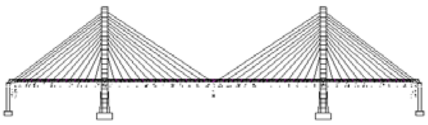

Figure 1. The Schematic elevation of the bridge

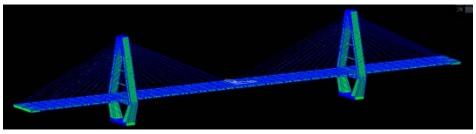

Figure 2. Three-dimensional finite element model

(2) The second stage of static load: The deck pavement is a 9cm double layer asphalt concrete, and the beam elements load is used for the paving and guardrails.

3.1.2. Temporary Loads. Hanging basket weight is 1800kN. Bridge deck mobile cranes are considered at 230kN, and considering the influence of10m partial load.Temporary pressure: Main beam 2# block is 1000kN; Main beam 3# and 4# block is 800kN; closure counterweight is 2000kN.Three pairs of temporary supports on towers is 1200kN horizontal top thrust.

3.1.3. Temperature. The concrete beam should be considered to have a temperature difference of ±20°C. The bridge tower should be considered to have a sunshine temperature difference of ±5°C, and the main beam local temperature difference should be determined according to the “General Specifications for Design of Highway Bridges and Culverts” (JTG D60-2015).

3.1.4. Wind Loads. The wind load is considered in the non-operating state, adopts the designed wind speed of once in a hundred years at the bridge location of 31.4m/s. The other wind parameters are based on the “Windbreak Design Code for Highway Bridges” (JTG/T 006-2004). After calculation, the average wind pressure on the tower is 2.35kN/m^2.

3.1.5. Uneven Settlement of Foundation. Uneven settlement of foundation at the bridge tower is considered in 2cm, and the two common piers is 1cm.

3.1.6. Materials. Temporary support materials are all Q235 steel. According to the relevant specifications and referenced relevant data, the material properties of the steel plates in the model are all taken as the elastic modulus MPa, and the poisson ratio is taken as 0.333. C50 concrete is adopted for the main girder, tower and cross beam. C40 concrete is used for the bridge piers and caps. The characteristics of in the model adopt the elastic modulus MPa. Poisson's ratio is 0.2 and the average relative humidity of environment is 68%. Prestressed steel strands are strand1860 steel strands with stretch at both ends and the control stress is 1395MPa. Parallel wires with elastic modulus of 1.95×105MPa is adopted for stay cables and the shock-absorbing spherical steel support is suitable for the structure.

3.2. Establishment of the Model

According to the model calculationof spatial structure, the main beam shares 638 beam element simulations, the main tower and cross beam are simulated with 628 beam elements and plate elements, and the temporary support of main tower shares 6 truss elements. The stay cables share 96 cable elements. The three-dimensional model of finite element is shown in Fig. 2.

3.3 Boundary Conditions
The main structure of the DingzihekouBridge is a semi-floating system. Towers and piers are consolidated, the main beams are erected at the bridge towers and common piers. Boundary conditions are shown in Table 1.

Table 1. Boundary conditions of the structure

Constraint direction	Common piers	Connection of tower and beam
Longitudinal	Slide	Slide; Limit
Transverse	Support restraint	Support restraints;Limit
Vertical	Restraint	Restraint

4. Calculation Conditions and Load Combinations of Stability

According to the construction schedule of the main bridge of the Dingzihekou, the construction period of the main tower is considered as 10 days, and the main beam is considered as 15 days. Theasynchronous construction process of tower beam is analysed according to the construction phase and construction steps, the structural loads and temporary loads are imposed in chronological order, and the concrete shrinkage and creep are considered for 5 years. The total period of the asynchronous construction process is 585 days, of which the tower beam asynchronous construction stage was 200 days. Synchronous construction are considered that the first five sections of the post-five-section main girder construction and the tension of the first five inclined stays are to be carried out at the same time, the tower beam asynchronous construction phase takes 110 days.

Table 2. Construction conditions of stability calculations

Serial numbers	Calculation conditions	Condition descriptions
1	After completing the pouring of the 1# block of the main beam, install the cable B1, Z1 Pouring first shut section of tower Installing main beam 2# block hanging basket (Synchronous construction just started. condition 5)	The dead weight of first section of tower, concrete wet weight of the the second shut section of tower, initial tension of cable B1, Z1is 275T, the right span of 1# main girder is hanging by a 23T crane(offset load) hanging basket for installing 2# block of main grider is180T
2	The 5th shut section of tower (synchronous construction has been completed. Condition 11)	The dead weight of 5th shut section of tower
3	Pouring 12# block of main girder, Installing cable B12, Z12, shut hanging basket (Maximum single cantilever condition 23)	The dead weight of12# block of main girder initial tension of cableB12 is 400T, initial tension of cable Z12 is 375T the right span of 1# main girder is hanging by a 23T crane(offset load) The pressure weight of temporary closure is 200T the weight of mobile hanging basket is 180T

In the overall stabilitycalculation and analysis of the structure, this paper selects several typical construction conditions shown in Table 2. The calculation load combinations for each typical working condition during the cantilever construction process are as follows:

LS1=weight + prestress + cable tension force + temporary construction load + longitudinal wind load

LS2=weight + prestress + cable tension force + temporary construction load + lateral wind load

LS3 = dead weight + prestress + cable tension force + construction temporary load

5. Linear Stability Analysis

The featuresof balance equation of eigenvalue buckling analysisare considering the geometric stiffness generated by the axial force under small deflection theory, including the P-Delta effect, but has not considered the effects of sag, large displacement, and material nonlinearity[5]. In the linear stability analysis, taking into account the effects of the stress during the construction process, displacement combination effect and the cumulative internal force of the construction phase on the geometric stiffness of the construction phase. The minimum buckling eigenvalue is the linear stable safety coefficient of the structure, and the destabilized modality represents the structural instability and the weak position where the instability has occurred. For the DingzihekouBridge under the typical conditions of the construction phase, the linear stability safety coefficient is shown in Table 3, and the destabilizing mode is shown in Fig. 3 to 4 (using the LS1 load combination under condition 3 as an example): Combining the calculation results of the linear stability safety factor and the instability modality diagram for the above DingzihekouBridge, the following conclusions can be drawn:

(1) According to the requirements of the “Design Guidelines for Cable-stayed Bridges” [6], the linear stability safety coefficient of bridges should be greater than 4. As can be seen from Table 3, under thetypical conditions of the construction phase of the Dingzihekou Bridge, the linear stability safetycoefficient meets the specification requirements, and the linear stability of the two construction schemesis very good.

Table 3. Stable safety factors of construction conditions in buckling analysis

Conditions		Linear stability safety factors			Major instability modes
		Synchroni-zation	Asynchro-nization	difference percentage	
1	LS1	91.838	93.420	1.693%	main tower lateral instability
	LS2	91.920	93.523	1.714%	main tower lateral instability
	LS3	91.861	93.438	1.688%	main tower lateral instability
	average value	91.873	93.460	1.698%	main tower lateral instability
2	LS1	118.654	118.131	0.441%	overall combination vertical instability
	LS2	118.671	118.226	0.375%	overall combination vertical instability
	LS3	118.670	118.218	0.381%	overall combination vertical instability
	average value	118.665	118.575	0.076%	overall combination vertical instability
3	LS1	29.562	29.550	0.041%	main tower vertical instability
	LS2	29.563	29.551	0.041%	main tower vertical instability
	LS3	29.563	29.551	0.041%	main tower vertical instability
	average value	29.563	29.551	0.041%	main tower vertical instability

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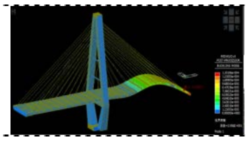

Figure 3. Deformation modality diagram under construction condition 3 in synchronous construction of tower and beam

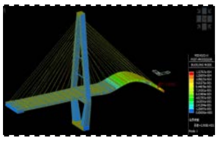

Figure 4. Deformation modality diagram under construction condition 3 in asynchronous construction of tower and beam

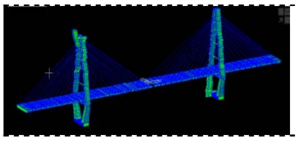

Figure 5. Deformation modality diagram under construction condition 3 innon-liner analysis (synchronous construction of tower and beam)

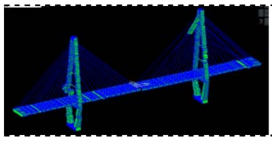

Figure 6. Deformation modality diagram under construction condition 3 innon-liner analyis (asynchronous construction of tower and beam)

(2) At the stage of cantilever construction, the stability and safety coefficient of the structure gradually increases. At this time, the instability mode shows the lateral instability of the main tower, and the linear stability safety coefficient reaches the maximum when the tower beam synchronization is completed (condition 2).The instability mode is the main beam with vertical instability. The reasons for the analysis may be that the length of the cantilever is short at the beginning and the stiffness of the main tower is relatively small. The instability of the main tower mainly occurs. As the cantilever of the main beam increases, the stiffness of the main beam gradually decreases, while the stiffness of the main tower increases as the cable's increasing gradually. The stability safety coefficient of the main girder is greater than that of the main tower, and the overall linear stability safety coefficient gradually increases. Therefore, the instability mode of main beam and the main girder combination are unstable; when the cantilever is long, the stiffness of the main tower continues to increase, the stiffness of the main beam continues to decrease, the safety coefficient of the main beam is gradually less than the instability safety coefficient of the main tower, the linear safety coefficient of the bridge gradually decreases, and the overall linear stability safety coefficient of the structure is minimum. The instability mode is mainly due to the longitudinal instability of the main beam.

(3) The change law of the linear stability and instability mode during the construction phase of cable-stayed bridge is generally as follows: the instability of the main tower and beam, and the instability of overall combination of the main tower and the main beam. The maximum value of the linear stability safety coefficient occurs in the stage of instability of the main tower and beam combination.

(4) For several different working conditions and load combinations, the difference between the two is very small, indicating that the synchronous construction of tower and beam impact little on the linear stability of the Dingzihekoubridge. Second, the effect of wind load on overall stability is also small.

(5) The linear stability safety coefficient of the structure cannot be regarded as the final criterion for structural stability, especially for large-span bridge structures with large nonlinear influence. However, the results of the linear stability analysis can roughly represent the upper limit of the geometrically nonlinear stability analysis of the actual structure.

6. Nonlinear Stability Analysis

Based on the linear stability analysis, the linear stability safety factor is used as the upper limit value of the nonlinear analysis, and the geometric nonlinear stability analysis of the typical working conditions during the corresponding construction phase is performed. In the process of geometrical nonlinear analysis, we should consider the displacement, stress superposition effect and internal force of the previous construction phase on the geometric stiffness of the stage during construction. At the same time, in addition to the P-Delta effect, large displacement effects and the sag effect of stay cables are also considered. Specifically, the following methods are used in the software: a cable element is used instead of a truss element to simulate a cable stay. And a large displacement effect and a P-Delta effect are automatically considered when the software program performs a geometric nonlinear calculation.

The curve of the structural instability is shown as follows: the load-displacement curve does not converge, and the displacement also increases rapidly when the load is constant. The load coefficient corresponding to a point that begins to diverge is the critical load safety factor of the structure[7]. When drawing the load-displacement curve, according to the displacement results calculated in the post-processing stage, the maximum deformation point of the main tower and the main beam was selected as the control point. Comparing the load-displacement curves in the transverse direction of the bridge, longitudinal direction of the bridge and vertical direction. The unsteady deformation diagram of the geometrical nonlinear analysis under typical conditions (using condition 3 under the LS1 load combination as an example) and the load-displacement curve are shown in the figure below.

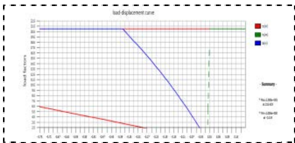

Figure 7. The load-displacement curve of control point in the tower under construction condition 3 **(sy**nchronous construction of tower and beam**)**

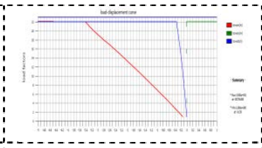

Figure 8. The load-displacement curve of control point in the tower under construction condition 3 (asynchronous construction of tower and beam)

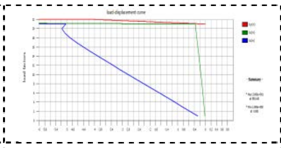

Figure 9. The load-displacement curve of control point in the beam under construction condition 3 (synchronous construction of tower and beam**)**

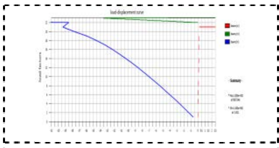

Figure 10. The load-displacement curve of control point in the tower under construction condition 3 (asynchronous construction of tower and beam)

Based on the above calculation results, the following conclusions can be drawn:

(1) The geometric nonlinear stability of the Dingzihekou Bridge gradually increases with the increase of the cantilever during construction stage. When the cantilever reaches a certain length, the geometric nonlinear stability decreases rapidly with the increase of the load. The instability shape is mainly the overall bending instability of the tower-beam combination.

(2) The trend of the curves of the two programs is basically consistent: the displacement of the initial phase increases linearly with the increase of the load, and then the acceleration of the displacement continues to increase, and the curvature of the curve becomes smaller and smaller with a nonlinear rise. Finally, it paralleling to the displacement axis. After reaching this stage, even if the load no longer increases, the displacement will rapidly increase and the structure will become unstable failure.

Table 4. Geometric nonlinear stability safety factors in different construction conditions

Working conditions	Geometrically nonlinear stability safety factor	
	Synchronous	Asynchronous
1	80.750	70.333
2	109.133	71.200
3	21.125	20.667

The load-displacement curve of the main tower and the main beam is integrated, and the starting point of the curve parallel to the displacement axis is taken as the geometrically nonlinear stability safety factor under this working condition, and the minimum value is taken in different directions under the same working condition. The geometric nonlinear stability safety coefficient of the two construction schemes is shown in Table 4. The linear stability safety factor and the geometrically nonlinear stability safety factor of the bridge under typical conditions during the construction phase are compared, as shown in Table 5.

Table 5. Comparison of linear and geometrical non-linear stability safety factors of two construction schemes

Working conditions	1		2		3	
	Synchronous	Asynchronous	Synchronous	Asynchronous	Synchronous	Asynchronous
Linear stability safety factor	91.873	93.460	118.665	118.575	29.563	29.551
Geometrically nonlinear stability safety factor	80.750	70.333	109.133	71.200	21.125	20.667
Nonlinear weakening percentage	12.11%	24.75%	8.03%	39.95%	28.54%	30.06%

By comparing the linear and geometric nonlinear stability safety factors of the above two programs, the following conclusions can be drawn:

(1) The geometrically nonlinear stability safety factor is generally smaller than the linear, and the decreasing amplitude is large. The stability factor is weakened by up to about 40%, and the instability shape also changes. It can be seen that considering the geometric nonlinearity has a significant impact on the overall stability of long-span cable-stayed bridges. When considering the stability of long-span cable-stayed bridges, only considering the linear stability is not enough, there is a large error with the actual project. The stability analysis after considering the influence of geometric nonlinearity can more accurately describe the actual geometrical characteristics of the structure. It is necessary to perform nonlinear stability analysis of long-span cable-stayed bridges.

(2) The synchronous construction of tower and beam and asynchronous construction are both stable, and the safety factors of the two are relatively close in the linear stability analysis.

7. Conclusion

(1) Synchronous construction of tower and beam has little effect on the linear stability of the Dingzihekou Bridge.

(2) The geometrically nonlinear stability safety factor is generally smaller than the linear. Considering the geometric nonlinearity has significant influence on the overall stability of the long-span cable-stayed bridge.

(3) Synchronous and asynchronous construction of towers and beams is basically consistent in terms of linear stability. For the geometric nonlinear stability analysis, the synchronous construction of towers and beams has larger and more stable safety factors than the asynchronous construction.

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