Study on the mechanical characteristics of steel truss cable-stayed bridge with water pipeline

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Abstract. Based on the engineering background of a water pipeline cable-stayed bridge, the static characteristics, dynamic behavior and stability of the bridge were studied through the finite element numerical simulation. In terms of static characteristics, the mechanical characteristics of each member of the main truss were analyzed. In the aspect of dynamic characteristics and stability, the influence of different connection modes of pipes and main beam on the dynamic characteristics and stability of the structure was compared. The results show that compared with the bridge used for traffic, the special pipeline bridge bears much more load, and its safety should be paid more attention to. Due to the direct action of the pipeline, the cross beam of the steel truss is the weakest member, which should be paid attention to in the design. When the rigid connection is adopted between the pipeline and the main beam, the lateral rigidity of the structure is larger and the stability is better. It is suggested that the rigid connection should be adopted between the pipeline and the main beam in the design of this kind of bridge to ensure that they can bear the load together.

1. Introduction

In water resources transportation engineering, water pipelines often need to cross rivers. With the development of cable-stayed bridges, pipeline cable-stayed bridge structure is a new form developed in the design of medium and large-scale pipeline projects. Pipeline cable-stayed bridge has been widely used in long-span pipeline crossing project for its advantages of large span, low cost and beautiful shape. However, the pipeline cable-stayed bridge belongs to flexible system, and the structural stress is complex, and with the increase of pipeline diameter, the influence of water pipeline on the bridge structure becomes more and more significant.

Xiaoping Wu⁴,⁵ et al. analyzed the dynamic characteristics and seismic response of this new structure and found that the initial internal force of the dead load has a great influence on the dynamic characteristics and the seismic response of the pipeline cable-stayed bridge, which should not be ignored in the analysis. Although the new structure is similar to the cable-stayed bridge, its dynamic characteristics are quite different. Jianyuan Sun⁶ et al. studied the dynamic action of the water pipeline on the bridge structure based on a single tower cable-stayed bridge. The results show that the natural frequency of the bridge structure and the water pipeline is quite different, and there is no resonance between them. Qingang Ma⁰ and Xiaojiang Zhuang⁵ pointed out that the large-diameter water pipes have a limited impact on the bridge structure and will not affect safety and driving comfort. Most of the above research background is to lay water pipelines on the bridges that were originally subjected to vehicle loads, so the water loads on the bridges are relatively small. However, different from the traditional highway and railway cable-stayed bridges, the special cable-stayed bridge for
water transporting not only bears large water load, but also has small width span ratio due to the need of transportation, so the transverse rigidity of the main beam is weak. Therefore, the mechanical characteristics of this kind of special bridge need special attention. At present, the pipeline cable-stayed bridge is developing towards the direction of large diameter and long span, but there is a lack of research on the static and dynamic characteristics of this special bridge structure, so the research on the pipeline cable-stayed bridge has important theoretical and practical significance.

Taking a steel truss pipeline cable-stayed bridge as the research object, the finite element model of the whole bridge was established by using the finite element program, and the static and dynamic characteristics and stability of the bridge were analyzed in order to provide reference for the design of this kind of special bridge.

2. Project overview
This project is a design scheme of a pipeline bridge which is built to transport water. The main bridge is 490m long, the span is (65 + 3x120 + 65) m, and the total width of the bridge is 18.5m. The structure of the cable-stayed bridge is a semi floating system with four towers and multiple spans, That is to say, the tower and pier are consolidated, and the tower and beam are separated. The main tower is of water drop concrete structure with a total height of 72m, which is 44.2m above the bridge deck and 27.8m below the bridge deck. The main beam is a steel truss girder with a net width of 16.5m; The members of the main beam are the upper chord, the lower chord, the main cross beam, the secondary cross beam, the longitudinal beam, the flat link and the diagonal member. The sections of the upper chord, the lower chords and the diagonal member are all box-shaped, and the other members are I-shaped sections. Pipes are laid on the left and right sides of the bridge deck at the bottom of the truss, that are made of Q345 steel and with a diameter of 3.45m, the water load in the pipe is 91kN/ m. The cables are arranged on both sides, directly anchored in the top chords, with a spacing of 8m on the beam and 2m on the tower. 12 pairs of cables are arranged on one tower and there are 48 pairs of cables in total. The overall layout of the bridge is shown in figure 1.

3. Finite element simulation
The finite element software Midas civil is used to build the bridge structure model for analysis. There are 1815 nodes and 2906 elements in the model, including 2810 beam elements and 96 truss elements. Steel girder, water pipes and towers are simulated by beam elements, and cables are simulated by truss elements. Eight supports and 264 elastic connections are used in the model, and there are four supports at the end of the beam, and eight supports at the position of the tower, which only restrict the vertical movement. There are rigid connections between the pipe and the main beam and there is no relative displacement between them. Cable and beam, cable and tower have common nodes, no other connection. The calculation model takes the longitudinal bridge direction as the overall coordinate X axis, the transverse bridge direction as the overall coordinate Y axis, and the vertical direction as the overall coordinate Z axis. The finite element model and calculated load of the whole bridge are shown in figure 2 and table 1.
Figure 2. Finite element model of the bridge.

Table 1. Calculated load.

| Load   | Number | Type of load                        | Value                      |
|--------|--------|-------------------------------------|----------------------------|
| Dead   | 1      | Self weight of structure            | Automatic calculation      |
|        | 2      | Second stage dead load              | 55.6 kN/m (one side)       |
|        | 3      | Weight of water                     | 91 kN/m (one side)         |
|        | 4      | Temperature rise of the main beam   | 15 to 49.3°C               |
|        | 5      | Temperature reduction of the main beam | -15 to -20.2°C             |
|        | 6      | Temperature rise of cable           | +10°C                      |
|        | 7      | Temperature reduction of cable      | -10°C                      |
|        | 8      | Positive temperature gradient of tower | +5°C                      |
|        | 9      | Negative temperature gradient of tower | -5°C                      |

4. Static characteristic analysis

This bridge is a special pipeline bridge. There is no sidewalk or driveway on the bridge, that is, there is no crowd load or vehicle load on the bridge deck. However, in order to observe the influence of water load on the static performance of the bridge, the water load is compared with the vehicle load. The value of one side is 91 kN/m, so the total weight of water is 182 kN/m. The bridge is a first-class highway with a net width of 17.5 m, and it is considered as a two-way four lane road. According to the General Code for Design of Highway Bridges and Culverts (JTGD60-2015), when the load is the first-class vehicle load of the highway, the uniform load is 10.5 kN/m, and the concentrated load is 360 kN/m. In order to compare the results clearly, if the concentrated load is equivalent to the uniformly distributed load, the calculated equivalent uniformly distributed load is 44.9 kN/m, then the water load is about 4 times of the vehicle load. Therefore, it can be concluded that this kind of special water pipeline bridge bears more load than ordinary bridge, and its safety should be paid more attention to.

Table 2 and table 3 show the maximum stress and displacement of the main components of the structure under the action of load combination: self weight + second stage dead load + water load + temperature rise of the main beam + Temperature reduction of cable components.

Table 2. Maximum stress of the main components.

| Component   | Maximum stress/MPa | Position          |
|-------------|--------------------|-------------------|
| Main truss  | 189.0              | The cross beam    |
| The tower   | -10.7              | Middle of tower   |
| The cable   | 675.1              | The third tower   |
| The pipe    | 9.2                | The end of main beam |

Table 3. Maximum displacement of the main components.

| Component | Maximum vertical displacement /mm | position |
|-----------|----------------------------------|----------|
Maximum vertical displacement of main truss
41
Mid span of beam that is between two towers

Maximum longitudinal displacement of tower
61
The top of the first tower

It can be seen from the above tables that under the load combination, the stress of each component meets the requirements, the maximum vertical displacements of the main beam are less than 1/400 of its span, the maximum longitudinal displacements of the tower are less than 1/200 of its height, and all deformations also meet the design requirements.

Figure 3. Maximum stress of different members.

Then the maximum stress of each member of the main truss are analyzed in detail. Since the system and load are completely symmetrical, half of the structure is taken for analysis. It can be seen from figure 3 that under the action of load combination, the maximum stress of the top chord, the bottom chord and the lower longitudinal beam along the length direction of the bridge presents a similar trend, and the stress values are also slightly different. These three types of members are basically under compression, and the maximum compressive stress appears on the bottom chord near the bridge tower, which is 117.7 MPa. The stress value at the middle span of the main beam between the two towers is small. In addition, the change trends of the stress of the diagonal bar and the transverse beam along the length direction of the bridge are similar. Generally speaking, the stress values are large but the fluctuation is not big, and the two components are in tension. Among the five components, the most dangerous component is the cross beam because of its large stress, and the maximum value can reach 189.2 MPa, which needs to be noted when designing.

5. Dynamic characteristic analysis
Compared with general bridges, the study of dynamic characteristics of pipeline bridges is more important. Because the boundary conditions have a great influence on the dynamic characteristics, this paper adopts three kinds of pipe-beam connection modes: compression only, vertical and horizontal constraint, and rigid connection of tube-beam to analyze and compare the influence of different tube-beam connection modes on the natural vibration characteristics of the structure. The method is to convert the dead load and water load into structural quality, and analyze the vibration characteristics of the bridge using Lanczos eigenvalue vector method. Due to space limitation, table 4 only lists the typical vibration modes and frequencies of the structure, but the analysis content is not limited to the table.

Table 4. Comparison of dynamic characteristics of the structure with different pipe-beam connections.

| Pipe-beam connection form | First transverse bending frequency/Hz | First longitudinal drift frequency/Hz | First vertical bending frequency/Hz |
|--------------------------|--------------------------------------|-------------------------------------|-----------------------------------|
| Compression only         | 0.339                                | 0.522                               | 0.796                             |
| Vertical and horizontal  | 0.339                                | 0.523                               | 0.850                             |
When the pipe-beam connection adopts compression only and restraint vertical and horizontal forms, the vibration response of the structure is very close. In the two cases, the first ten modes have the same shape, the difference of frequency value is less than 5% and the latter is slightly larger, because the latter is more constrained. Comparing the first two restraint forms with the third one, it is found that the longitudinal drift mode and the vertical bending mode of the main beam appear in advance, and the number of times of the transverse bending mode is reduced in the first ten modes under the rigid connection of the pipe-beam Due to the further strengthening of constraints, the first symmetrical transverse bending frequency decreased by about 28%, the first anti-symmetric transverse bending frequency increased by about 44%, and the first vertical bending frequency and longitudinal drift frequency has little difference. The results show that, when the pipeline and the main beam are rigidly connected, the lateral rigidity of the structure is relatively large because it can ensure that the two can bear the load together well. Table 5 details the first ten frequencies and vibration modes of the structure when the pipeline and the main beam are rigidly connected.

### Table 5. Maximum displacement of the main components.

| Number | Mode characteristic | Frequency |
|--------|---------------------|-----------|
| 1      | Symmetrical transverse bending of main beam | 0.433     |
| 2      | Anti-symmetric transverse bending of main beam | 0.494     |
| 3      | Longitudinal drift of main beam | 0.524     |
| 4      | Symmetrical transverse bending of main beam | 0.595     |
| 5      | Anti-symmetric transverse bending of main beam | 0.730     |
| 6      | Symmetrical vertical bending of main beam | 0.820     |
| 7      | Symmetrical transverse bending of and torsion of main beam | 0.828     |
| 8      | Anti-symmetric vertical bending of main beam | 1.081     |
| 9      | Anti-symmetric transverse bending and torsion of main beam | 1.227     |
| 10     | Symmetrical vertical bending of main beam | 1.375     |

On the whole, the low-order vibration modes of the bridge structure are mainly transverse bending vibration modes, one reason is that the width span ratio of the main beam is small, the other reason is that the structure is semi floating system, so the transverse rigidity of the bridge is weak. The symmetric transverse bending mode of the main beam is the earliest, and the corresponding first frequency is 0.433 Hz. The longitudinal drift mode appears later than the transverse flexural mode of the main beam, which appears at the third order with a frequency of 0.524 Hz. The vertical bending mode of the main beam first appears in the sixth order, and its frequency was 0.820 Hz. The latest appearance of torsional vibration mode indicates that the tower and cable have a strong restraining effect on the main beam, so the main beam has a large torsional rigidity. In addition, when the transverse bending mode occurs, it is usually accompanied by slight torsion. On the one hand, the stay cable is anchored at the upper end of the main beam. On the other hand, when the transverse bending occurs, the cable forces on the left and right sides will decrease on one side and increase on the other.

### 6. Buckling analysis

The small width span ratio of the bridge results in the weak transverse stiffness of the main beam, and the structure may lose its stability, so it is necessary to study the stability of the bridge. Because the criterion is based on the expression of the first kind of elastic stability problem of structure, this paper only studies the first kind of stability problem. The analysis method is as follows: the self weight as constant load, second stage dead load and water load as variable load are added to the main girder, and the Midas buckling analysis function is used to analyze the buckling of the steel truss Cable-stayed Pipeline Bridge at the completed stage. Three different connection modes of pipeline and main beam are analyzed respectively, and the first elastic buckling eigenvalues of the structure are calculated as shown in table 6.
Table 6. First stability coefficient of structure.

| Pipe-beam connection form       | First stability coefficient |
|---------------------------------|----------------------------|
| Compression only                | 24                         |
| Vertical and horizontal constraint | 8                      |
| Rigid connection                 | 111                        |

It can be seen from the above table that no matter which connection mode is adopted, the first type of stability safety factor of the structure is greater than 4, which meets the requirements of the “Design Details of Highway Cable-stayed Bridge” (JTG/T D65-01-2007). The overall stability of the structure is from strong to weak under three kinds of tube-beam connections: rigid connection > compression only > vertical and horizontal constraint.

7. Conclusions
Taking a steel truss pipeline cable-stayed bridge as the research object, the finite element software Midas civil was used to build a model to analyze the mechanical characteristics of the steel truss pipeline cable-stayed bridge at the completed stage. In the static analysis, the stress and displacement of each member of the bridge are studied. In the aspect of dynamic analysis and stability analysis, the influence of different tube-beam connection forms on the dynamic characteristics and stability of the structure is compared, and the following conclusions are drawn:

1) Compared with the ordinary bridge, the special water pipeline bridge bears much more load, so we should pay more attention to its safety.

2) Due to the direct action of water load, the cross beam of the steel truss is the weakest member, so attention should be paid to the design of such bridges.

3) The transverse bending mode of the main beam appears the earliest and the most times in the first ten frequencies, which indicates that the transverse stiffness of this kind of special bridge structure is weak.

4) Different types of pipe-beam connection have great influence on the dynamic characteristics and stability of the structure. It is suggested that rigid connection should be adopted between the pipe and the main beam in the design, so that they can bear the force together better, and the lateral rigidity of the structure is large and the stability is better.

References
[1] Wu, X.P., Hu, S.D., Feng, Q.M., Huang, W.C. (2001) Analysis of dynamic characteristics of long-span cable-stayed pipeline bridge. Structural Engineering, 01:7-11.
[2] Wu, X.P., Feng, Q.M., Jiao, S.J., Li, H.J. (2001) Seismic response analysis of Long-span Cable-stayed Pipeline Bridge. Earthquake engineering and Engineering Vibration., (03):49-54.
[3] Sun, J.Y., Wang, H. (2016) Study on the dynamic effect of water hammer effect on bridge structure of large water transmission pipeline. Chinese and Foreign Roads., 36(03):148-151.
[4] Ma, Q.G., Chen, F.D., Zhuang, X.J., Wang, F.P. (2009) Research on key problems of water pipe vibration of long-span cable-stayed bridge. World Bridge., 04:50-53.
[5] Zhuang, X.J., Ma, Q.G., Wang, F.P., Zhuang, Q.H., Zhou, H.W. (2011) Study on the effect of pipeline action in the approach bridge of Damen Bridge. Bridge Construction., 06:50-53.