Study on deformation monitoring of continuous through concrete-filled steel tube arch bridge

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Abstract. The great structural deformation and inner force will impact the normal use of the bridge, even endanger its safety. Based on it, the paper presents the theoretical analysis method of through concrete-filled steel tube arch bridge, and produce the monitoring methods of the structure deformation, takes a continuous through concrete-filled steel tube arch bridge in Guangzhou as an engineering example, the settlement, three-dimensional deformation of the pier top and the arch rib are monitored in detail. The results show that theoretical calculation are consistent with the measured value in general trend, the theoretical analysis methods and monitoring scheme of structural deformation adopted in this case can have some guiding significance to the similar bridges.

1. Introduction
As a lifeline engineering, bridge engineering plays an important role in the national economy. Due to the underground water variation, concrete shrinkage and creep, temperature variation and frequent load action, the foundation of bridge pier will cause settlement or displacement, resulting in the change of internal force and linear shape of bridge structure, which will have a serious impact on the bridge structure and even endanger its safety. So it is necessary to monitor the deformation of bridge and its causes. This paper analyses the causes of bridge deformation from a theoretical perspective, and take a three-span continuous through concrete-filled steel tube arch bridge in Guangzhou as an example to produce a comprehensive observation, which can have some guiding meanings to similar bridge evaluation.

2. Stress characteristics analysis of through tied arch bridge
Through tied arch bridge is frequently used in railway and highway because of its lower height. This kind of bridge is composed of live load distribution members, force transfer components and main bearing members. Among them, the live load distribution members are constituted by the joint action of bridge deck, beam and tie beam, the suspender plays its role as the force transfer member, while the steel tube arch rib and tie beam are the main bearing members. The overall bearing system of this type of bridge is composed of the above three main components.

At present, the FEM is used to analyze the stress state of the whole construction process and the completed bridge. In general case, the link elements are used to build the total model of the bridge. Due to its limitations, the results from the link elements model cannot reflect the actual stress conditions of the skewback accurately and comprehensively. It is necessary to build the local structure model in which the solid elements are adopted for the purpose of refinement analysis.
In order to reflect the actual stress state of the structure and easy to calculate, we adopt the following assumption: 1) there is no relative displacement between the steel tube and the concrete, 2) the area and shape of the components have no variation before and after deformations, 3) ignoring the impact of shear strain and shear force on the final results, 4) secondary dead load was treated as uniformly distributed load to apply to the tie beam. Otherwise, the transformed section method was adopted to treat the arch ribs. And the Plane truss elements are used to model the concrete-filled steel tube arch in that they bear axis force usually.

3. Bridge deformation monitoring methods

As the important components of bridge deformation monitoring, bridge deck deflection, pier displacement and bridge deck alignment measurement are also important indexes of bridge quality and safety evaluation. At present, there are many methods to measure the bridge deflection at home and abroad, including static leveling, deflection instrument observation method, dip Angle measurement method, photogrammetric, precise leveling, precise kinematic GPS, total station measurement method, etc., all of them have their own advantages and disadvantages. Combined with the actual of this project, the precision level and total station measurement method are selected for observations.

In order to improve the accuracy and weaken the influence of temperature change on the results of precise leveling, we must use a precise level and an invar leveling staff with small expansion coefficient. When the route is short (visual range≤60m), the instrument sight height method can be used. That is, positioning the precise level on the reference point away from the test bridge, and taking the grade rod at each monitoring point. Set $H_i$ and $H_j$, respectively, is the reading of the monitoring point on the bridge in two cases $i$ and $j$, then the relative deflection of the monitoring point is as follows:

$$H_{ij} = H_j - H_i$$  \hspace{1cm} (1)

The method has the advantages of fast speed, easy calculation and high precision, and it is mainly applied to the precise leveling which can provide the observation station near the monitoring point, and the deflection variation of the bridge is small and there are few monitoring points.

Multi-instrument fixed transmission method can be adopted when the bridge is long. This method assumes that the elevation of a monitoring point of the bridge is $H_i$ pre-loading and the elevation under the $i$ -grade loading is $H_i$, then the relative deflection under the $i$ -grade loading is:

$$h_i = H_i - H_i$$  \hspace{1cm} (2)

The basic principle of total station deflection measurement is trigonometric leveling. Pre and post loading, the variation of the relative height difference between occupied station and the monitoring point is as follows:

$$\Delta h = S \sin A - S_i \sin A_i$$  \hspace{1cm} (3)

In which, $S$ and $S_i$ represents the slant distances between occupied station and the monitoring point pre and post loading respectively; $A$ and $A_i$ represents vertical angle before and after loading respectively.

4. Engineering example

4.1 Engineering situation

The main bridge is 976.5 meters long. The span is 55m+83.6m+55m, the width is 25m, and the distance between the arch ribs is 18m. Among the arch ribs are the Two-lane Two-way Roads, and the 3.0m wide sidewalk lie in the two outer sides of them. The design load is auto-super 20, trailer-120.

The main bridge is three-span through concrete-filled steel tube arch bridge without wind bracing. The rise-span ratio of the side span and middle-span is 1:4.5, 1:5 respectively. The arch axis is
parabola. The main bridge deck are composed of 33 Paris of suspenders, 33 partially prestressed concrete cross-beam, ordinary concrete longitudinal stiffening beam, concrete trough plate, post-pouring concrete structure layer and steel fiber concrete paving layer.

The layout of the bridge is shown in figure 1.

Figure 1. General picture of bridge.

4.2 The observation items, methods and technical requirements

4.2.1 The observation items. According to the analysis result of FEM, Code for deformation measurement of building and structure (JGJ8-2016)、specifications for the first and second leveling (GB12897-2006) and some references, the observation items of the engineering including the settlement of the bridge deck, the deformations of the pier top and the arch ribs. The observation items are shown in table1.

| observation items                          | quantity |
|--------------------------------------------|----------|
| 3-D deformation monitoring points on pier top |          |
| Main pier of main bridge                   | 4        |
| Side pier of main bridge                   | 4        |
| settlement of the bridge deck              |          |
| Mid-span of main span                      | 4        |
| 1/4 of main span                           | 4        |
| Mid-span of side span                      | 4        |
| 1/4 of side span                           | 8        |
| 3-D deformations of the arch ribs          |          |
| Arch rib of main arch                      | 6        |
| Arch rib of side arch                      | 12       |

4.2.2 Layout of the reference points and the monitoring points. The settlement monitoring points should be laid in the position which are easily observed and can reflect the deformation characteristics. The mark should be stable, significant, easy observation and long-term preservation. The settlement monitoring points are laid uniformly around the object and are vertical and horizontal symmetric. 4 plane displacement reference points and 6 elevation reference points are laid on the bridge whose number is N1、N2、N3、N4 and BM1～BM6. 3-D deformation monitoring points on pier top、deformations monitoring points of the arch ribs and settlement of the bridge deck are shown in figure 2～figure 4.

Figure 2. 3D deformation monitoring points on bridge pier top.
4.2.3 The observation methods and technical requirements. The settlements of the bridge deck are monitored by electronic level. The closed net of elevation monitoring is shown in figure 5. The 3-D deformations of the arch ribs and pie top are measured by the total station, the plane monitoring-network is shown in figure 6.
4.3 Observation results

The closed net of elevation monitoring and plane monitoring-network are repetition measured, results showed that they are stable according to the former years. Due to the limited space, only the settlement of single side deck (Q1~Q13) are listed in table 2.

| points     | Node | Elevation(m) | deformation(m) | accumulative |
|------------|------|--------------|----------------|--------------|
|            |      | First time   | prior period   | This time    | This time    |
| bearing    | Q1   | 19.29134     | 19.28755       | 19.28835     | 0.00080      | -0.00299    |
| 1/4point   | Q2   | 19.45137     | 19.45372       | 19.45224     | -0.00148     | 0.00087     |
| Mid-span   | Q3   | 19.56013     | 19.55531       | 19.55393     | -0.00138     | -0.00620    |
| 1/4point   | Q4   | 19.64011     | 19.63360       | 19.63307     | -0.00053     | -0.00704    |
| bearing    | Q5   | 19.67721     | 19.68011       | 19.68036     | 0.00025      | 0.00315     |
| 1/4point   | Q6   | 19.77147     | 19.77421       | 19.77556     | 0.00135      | 0.00409     |
| Mid-span   | Q7   | 19.81124     | 19.80211       | 19.80117     | -0.00094     | -0.01007    |
| 1/4point   | Q8   | 19.77732     | 19.76877       | 19.76953     | 0.00076      | -0.00779    |
| bearing    | Q9   | 19.67833     | 19.67611       | 19.67660     | 0.00049      | -0.00173    |
| 1/4point   | Q10  | 19.63728     | 19.63835       | 19.63718     | -0.00117     | -0.00010    |
| Mid-span   | Q11  | 19.56221     | 19.56457       | 19.56333     | -0.00124     | 0.00112     |
| 1/4point   | Q12  | 19.46257     | 19.46955       | 19.46855     | -0.00100     | 0.00598     |
| bearing    | Q13  | 19.29629     | 19.29839       | 19.29942     | 0.00103      | 0.00313     |

The measured elevation curve of main bridge deck, settlement curve of this time and accumulative settlement curve of main bridge deck are shown in figure 7. ~ figure 9., respectively.

![Figure 7. Elevation curve of main bridge deck. (unit: m)](image)

![Figure 8. Settlement curve of main bridge deck. (unit: m)](image)
The observation results change a little between the elevation of this time and prior period, cumulative settlement is basically balanced, which are correspond with the theatrical results.

And, from the observation datum of 3-D deformation on pier top, it can be shown that there is no global displacement on the monitoring points of the pier top. The plane displacements of pier top deformation are shown in Figure 10.

The changes of the pie take on fluctuation tendency, minimal, which showed that the piers are stable.

It can be shown from the plane deformation datum that the displacement trend is not uniform along the X and Y-direction, and there are no global displacements on the monitoring points of the arch ribs. The plane displacements of arch ribs deformation are shown in Figure 11.

5. Conclusions
The following conclusions can be drawn from the monitoring of this bridge:

1) The observation results change a little between the elevation of this time and prior period. The settlement of this time lie between -1.48~1.43mm, and the maximum settlement occurs on Q2, the maximum raising point is Q20. The accumulative settlement lie between -10.07~6.00mm, and the maximum accumulative settlement occurs on Q7, the maximum raising point is Q25, which are correspond with the theatrical results.

2) From the observation datum of 3-D deformation on pier top, it can be shown that the maximum plane displacement occurs on point D2 in X direction, the value is 1.0mm. Otherwise, the maximum plane displacement occurs on point D8 in Y direction, the value is -1.0mm. All these show that there
are no global displacements on the monitoring points of the pier top. The displacement of the pier top lie between -0.15mm~0.30mm, the maximum settlement occurs on point D6, and the maximum raising occurs on point D7 in Y direction, the value is -1.0mm. The changes of the pie take on fluctuation tendency, minimal, which show that the piers are stable.

3) It can be shown from the plane deformation datum of arc ribs that the maximum plane displacement occurs on point G3 in X direction, the value is -2.0mm. Otherwise the maximum plane displacement occurs on point G1 in Y direction, the value is 1.9mm. All these show that there are no global displacements on the monitoring points of the arch ribs.

The theoretical analysis methods and deformation monitoring scheme can have some guiding significance for these kinds of bridge.

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