Research on long-term deformation monitoring of PC box girder bridge strengthened by a cable-stayed system

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Abstract. To study the down-warping improvement for main girder of Dongming Huanghe River Highway Bridge after the reinforcement of the cable-stayed system, the long-term data of the main girder deflection were collected from 2018 to 2020, and the effects of different years, quarters and span on main girder deflection were analyzed, the results showed that the main girder deflection tended to be stable within 9 months after the reinforcement, the down-deflection trend of main girder was effectively suppressed within 3 years, and the effect of the cable-stayed reinforcement was obvious. Compared with 2018, the mid-span of main girder was generally raised in the first quarter of 2020, but the mid-span down-deflection was increased in the second, third and fourth quarters. In the relatively high average atmospheric temperature of each year, the main girder had improved as a whole, and the temperature had a great influence on the deflection of main girder, especially in the third quarter of higher temperature, it can be seen that the deflection of each span fluctuated greatly.

1. Project context

Dongming Huanghe River Highway Bridge is located on the Huanghe River between Dongming, Shandong Province and Puyang, Henan Province, it is an important large bridge across the Huanghe River on the 106th National Road, The total length of the bridge is 4142.14m, the main bridge is transformed from the original prestressed concrete (PC) continuous rigid frame-continuous girder composite structure to the existing low tower cable-stayed structure [1-2], the main girder is a variable section box girder with nine holes and one joint, the span is (75+7×120+75) m, and the total length is 990m. The full width of the bridge is 18.34 m, the width of the carriageway is 15.44 m, and there is no separation zone in the middle.

The bridge began construction in October, 1991, completed in October, 1993, after four years of operation. Since 1997, found cracking and deflection, monitored the cracks in the box girder of the main bridge and the alignment of the bridge deck during this period. Cracking and deflection diseases were found to develop and worsen, and the main diseases included: oblique cracks at the 0.25 times of span ~ 0.75 times of span of the web; each span had different degrees of deflection, maximum mid-span deflection detected was 173 mm. For girder cracking and mid-span deflection, the main bridge was strengthened by increasing the cross section of the web, adding the outer tendons in the box and setting the transverse partition to enhance the integrity of the box girder in 2003. The bridge was tested in
December, 2009, and found the section normal stress and principal tensile stress of box girder to not meet the requirements the JTJ 023-85 code [3].

The Dongming Huanghe River Highway Bridge is the first long-span PC continuous box girder bridge strengthened by a cable-stayed system in China. Compared with other reinforcement methods [4-6], the construction procedures of cable-stayed system reinforcement were more complex, and the local stress concentration of main girder caused by tension construction is more prominent, which may lead to the sudden failure of cable-stayed reinforcement PC continuous box girder bridge structure in tensioning stage [8-10]. The Dongming Huanghe River Highway Bridge strengthened by a cable-stayed system was shown in figure 1.

Figure 1. Dongming Huanghe River Highway Bridge strengthened by a cable-stayed system.

2. Layout of main girder deformation measuring point
The main bridge alignment monitoring points were arranged on the main girder roof, two measuring points are symmetrically arranged along the central line of the main girder for each monitoring cross section, along the bridge longitudinal arrangement pier top section, 1/4 section, span middle section and 3/4 section, 36 points per line, a total of 72 measuring points were arranged. Figure 2 showed the layout of measuring points across 58# and 59#, the 60#, 61#, 62#, 63#, 64# and 65# cross layout methods were the same as 59# and 66# cross layout method and 58# cross the same.

Figure 2. Layout of alignment monitoring section of the Dongming Huanghe River Highway Bridge.

3. Analysis of long-term deformation of main girder
In this paper, the collected data were the deflection value of the main girder at the end of each quarter, and its values were the relative height difference of the main girder alignment when it was completed in June, 2017. Table 1 listed the average atmospheric temperature from 2018 to 2020. It can be seen from the table that the average atmospheric temperature of each quarter was not different when the data was collected.
Table 1. Collected average atmospheric temperature.

| Collected year / year | 2018 | 2019 | 2020 |
|-----------------------|------|------|------|
| Quarterly/season       | 1    | 2    | 3    |
|                       | 4    | 1    | 2    |
| Temperature/°C         | -6   | 24   | 32   |
|                       | 10   | -4   | 22   |
|                       | 10   | -2   | 20   |
|                       | 10   |      | 30   |

3.1. Results of the analysis of the data under the same quarter from 2018 to 2020

Figure 3. Deflection curves of main girder from 2018 to 2020: (a) First quarter; (b) Second quarter; (c) Third quarter; (d) Fourth quarter.
Figure 3(a)-(d) showed the next cross-flex data for the same quarter from 2018 to 2020. The deflection data was the difference between the lines completed in June, 2017. The maximum value of mid-span deformation occurred at 62# span, and down-deflection was 22.8 mm. We can see from the diagrams that the deflection is lower, the last two years of deflection basically accumulated in 2018 after reinforcement. Therefore, there was no obvious downward trend in the middle span after stabilization. Overall, compared to 2018, in the first quarter of 2020, the second, third, fourth quarter cross-middle deflection had an increasing trend. The mid-span deflection of 58# side span was up-deflection, and 66# was down-deflection. The mid-span deflection of both sides was anti-symmetric. The trend of 61# and 62# mid-span was basically the same, but the deflection of 62# and 65# span was the largest. Except for the 62# span, there was no obvious downward trend in the other spans from 2018 to 2020. Generally speaking, the effect of cable-stayed reinforcement was remarkable.

3.2. Results of Data Analysis of Cross and Down Scratch in Different Collection Years

![Figure 4. Relationship curves between deflection and span in different seasons: (a) 2018; (b) 2019; (c) 2020.](image-url)
Figure 4(a)-(c) showed the deflection data of main girder in different years. It can be seen from the figure that the deflection of each span in the first quarter was generally small, and the whole girder was improved in the quarter with higher temperature under the same collection period, and especially in the third quarter of higher temperature. After the completion of the main bridge reinforcement in June, 2017, the span deflection of 60# was raised within one year, so the effect of partial span lifting after reinforcement also had somewhat lagging.

4. Conclusion
To study the down-warping improvement for main girder of Dongming Huanghe River Highway Bridge after the reinforcement of the cable-stayed system, the long-term data of the main girder deflection were collected from 2018 to 2020, and the effects of different years, quarters and span on main girder deflection were analyzed. The main conclusions were as follows:

(1) Compared with the deformation data after completion in June, 2017, the maximum deformation of mid-span occurred at 62# span, and the deflection value was 22.8 mm. The amount of deflection in 2019-2020 was basically accumulated within 9 months after reinforcement, so there was no obvious down-deflection trend.

(2) Compared with 2018, the main girder generally was lifted in the first quarter of 2020, but mid-span deflection increased in the second, third and fourth quarter. The deflection of mid-span for the side span 58#, however, the opposite is true. The mid-span deflection of both sides was anti-symmetric.

(3) The deflection of each span in the first quarter was generally small, and the whole girder was improved in the quarter with higher temperature under the same collection period, and especially in the third quarter of higher temperature.

(4) After the completion of the main bridge reinforcement in June, 2017, the span deflection of 60# was raised within one year, so the effect of partial span lifting after reinforcement also had somewhat lagging.

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