Study on Calculation Method of Anti Overturning of Continuous Steel Box Girder

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Abstract. The self weight of steel box girder is light, and the stability effect is smaller than that of concrete bridge. In this paper, the anti overturning research of the main line bridge and ramp bridge is carried out. It is found that for the variable cross-section continuous beam bridge with wind barrier along the whole line, when the pressure reserve of the side pier is small under the action of self weight, the compression of the bearing under the action of basic combination can not ensure that the bearing will not be empty under the action of standard value combination; Centrifugal force, wind load and temperature load caused by vehicle load have great influence on bridge overturning, which can not be ignored; Temperature load and foundation displacement may lead to stability or instability according to the stiffness distribution of the main beam. In this paper, it is proposed that both the basic combination and the standard value combination should be considered when checking the bearing void. It is recommended to adopt the calculation method of "the stability effect is the standard value effect that makes the superstructure stable, and the instability effect is the standard value effect that makes the superstructure unstable" as the stability coefficient.

1. Introduction

With the advancement of urbanization, problems such as urban land shortage and heavy traffic are becoming more and more serious. Thus many cities have built viaducts over the roads with limited width to relieve traffic congestion. In order to speed up the construction, reduce the impact on the engineering on existing traffic, residents and pedestrians along the line during the construction period, and improve the construction environment for construction workers, prefabricated components are often used in viaduct construction. Prefabricated small boxes girder structures can be used for bridges with standard spans of 25 to 35m; continuous steel box girders can be used for the crossing junction of main line and ramp curve bridges for which small box girders are not convenient. According to the current urban express standards and the actual situation, one-way two-lane expressways, two-way four-lane expressways, and two-way six-lane expressways are most common. Correspondingly, the widths of the viaducts are 8.5m, 18m, and 25.5m, respectively. The viaducts are 25.5m wide on the main line and 8.5m wide on the ramp. The viaduct piers are generally set in the ground road's central separation zone,
the main line uses double-pillar piers, and the ramp uses double-pillar piers or single-pillar piers, so as to avoid affecting the traffic on the road or the city beautification project.

Due to the frequent bridge overturning accidents in recent years, the hidden safety hazards of bridges have attracted the attention of domestic bridge experts and scholars, and there have been a large number of studies on the calculation method of bridge overturning. Peng et al. [1][2] summarized several failure modes of single-pillar pier girder bridge overturning and proposed a practical calculation method and a simplified calculation method for the bearing capacity of single-pillar pier bridge against overturning damage. In terms of the lateral instability of single-pillar pier girder bridges, Wang et al. [3] proposed to use all torsion support failures (voids) as the criterion for judging overturning. Wang et al. [4] proposed to use the calculation formula for anti-overturning of highway girder bridge as the design basis and the calculation formula for anti-overturning of railway girder bridge as the verification basis by comparing the calculation methods for anti-overturning of highway girder bridges and railway girder bridges. Zhuang et al. [5] focused on the eccentric load of viaducts and put forward suggestions on the anti-overturning stability design of box girder bridges by comparing the existing codes at home and abroad. Xiong et al. [6] compared the code method, numerical simulation results, and actual results. They concluded that the code method based on an ideally supported rigid body rotation would significantly overestimate its anti-overturning performance. Since there is no unified standard for the viaduct anti-overturning checking calculation and there is no clear regulation on the selection of load checking calculation and the judgment of anti-overturning capability, Liu et al. [7] proposed a checking calculation method for viaduct anti-overturning and judgment standards for its anti-overturning capacity. They verified his proposal by comparing with actual projects. Niu et al. [8] used finite element software to simulate and analyze a single-pillar pier viaduct and put forward a calculation method for the anti-overturning stability of a single-pillar pier bridge. Song et al. [9] used the anti-overturning stability coefficient calculation formula provided by the code to carry out the anti-overturning checking: taking a ramp viaduct as an example and using MIDAS/Civil to establish a finite element model for analysis and calculation. Zhang et al. [10] compared the anti-overturning stability calculation formulas for U-shaped beams in domestic and foreign standards. They calculated U-shaped beams maximum lateral load while maintaining its anti-overturning stability. Liu [11] found a problem with the calculation method of viaduct anti-overturning capacity in the new JTG 3362-2018 Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts and proposed a calculation method for viaduct anti-overturning capacity by means of numerical simulation. However, all the above researches mainly focus on concrete single-pillar pier viaducts, and there is little analysis on continuous steel box girder with full-line wind barriers. Currently, in order to reduce noise in elevated urban buildings, more wind barriers are used. It is necessary to analyze this new situation because wind loads have a larger impact on viaducts. Combining JTG D64-2015 Code for Design of Highway Steel Structure Bridges and JTG 362-2018 Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts, we studied the anti-overturning performance of continuous steel boxes girder in this paper, emphasizing the importance of wind load in anti-overturning calculation and providing a reference for similar engineering.

2. Explanation about viaduct anti-overturning instructions

Article 4.2.2 of JTG D64-2015 Code for Design of Highway Steel Structure Bridges and Article 4.1.8 of JTG 362-2018 Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts pointed out that the beams must two requirements for anti-overturning: 1. under the action of the basic combination, the unidirectional compression bearing always maintains a compressed state; 2. the ratio of the design value of the effect of stabilizing the superstructure to the design value of the effect of destabilizing the superstructure is not less than 2.5. Therefore, the key to anti-overturning is that the unidirectional bearing always maintains the compression and contrasts the stability effect and the instability effect.
2.1 The one-way bearing keeps the state compression

Analyze the reaction forces of the bridge structure under basic combination and standard value combination, respectively. Take a steel box girder linear bridge with a span of 62+98+62m and a width of 8.5m as an example. The fulcrum is 2.6m away from the center line of the structure in the transverse direction, wind barriers are installed across the line, and the bridge is paved with 3cm of thick modified polyurethane concrete to reduce its dead weight. The bridge is shown in Figure 1.

![Figure 1. Layout of 62 + 98 + 62m steel box girder bridge(unit: m)](image)

Use finite element software to analyze the steel box girder bridge. Under the basic combination, the minimum reaction force of the side pier is 43.5kN. Under standard value combination, the minimum reaction force of the side pier is -56.9kN. As shown in Table 1.

![Figure 2. Calculation model of 62+98+62 steel box girder (unit: m)](image)

| Load category                                      | Load (kN) | Partial factor | Combined factor |
|---------------------------------------------------|-----------|----------------|-----------------|
| Structure weight                                  | 623.7     | 1.2            | -               |
| Minimum reaction force caused by basic displacement| -19.5     | 1              | -               |
| Minimum reaction force caused by vehicle load (including impact force) | -225.5 | 1.4 | - |
| Minimum reaction force caused by wind load        | -409.3    | 1.1            | 0.75            |
| Minimum reaction force caused by temperature      | -26.3     | 1.4            | 0.75            |

Minimum reaction force under basic combination: 43.5kN
Minimum reaction force under standard value combination: -56.9kN

Compare the basic combination and the standard value combination:
Basic combination value - standard combination value = 0.2 × Structural gravity + 0.4 × Vehicle load + 0.175 × Wind load + 0.05 × Temperature action

(1)

According to the above equation, when the negative reaction force of the pier caused by the wind load effect is large, and the pressure reserve generated by the structure weight is insufficient, the probability that the basic combination value is greater than the standard combination value higher. This situation generally occurs in the side piers of variable cross-section continuous beam bridges with wind barriers installed across the line, narrow bridge widths, or short side spans. The specification requires that the one-way compression bearing always keeps the state of compression under the basic
combination, but this requirement cannot guarantee that the bearing will always remain in the state of compression under the standard value combination. That is, it cannot guarantee that the one-way compression bearing will not get out of the normal state. It is suggested to supplement the requirement, "under the standard value combination, the one-way compression bearing of the box girder bridge should keep the state of compression".

2.2 Comparison of stability effect and destabilization effect

The Code for Design of Highway Steel Structure Bridges points out the stability effect and instability effect correspond to the design value of the basic combination (the partial factor is 1.0), but the specific load categories corresponding to the stability effect and the instability effect are not specified. According to the effect of force, structural gravity can stabilize the superstructure, automobile load (including impact force and centrifugal force), and wind load can destabilize the superstructure. The foundation displacement and temperature effects can stabilize or destabilize the structure, depending on its structural rigidity distribution. The combined value coefficient of wind loads and temperature effect is 0.75.

According to the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts, the stabilization effect is permanent. The instability effect is a variable effect, both of which are standard value combinations. The stabilization effect results from structure gravity and the displacement of the foundation, and the instability effect results from vehicle load (including impact force and centrifugal force), wind load and temperature. However, in the checking calculation for the anti-overturning of the steel box girder bridge, the instability effect is only included in the vehicle load.

In a continuous beam, the reaction force of the bearing caused by the foundation displacement may be positive or negative, and the effect may be beneficial to stability or may cause instability; the stratum structure is complex, the long-term deformation caused by foundation compaction is calculated using estimation. The potential hazards caused by estimation error can be offset by including foundation displacement into destabilizing effect. According to the Code for Design of Highway Steel Structure Bridges, the wind load and temperature is set to a standard value, with a combined value coefficient of 0.75. As the climate is changeable and the viaducts in densely built middle and high buildings adopt sound barriers, the proportion of wind load in the bridge load effect also increases. Therefore, use a standard value to determine the wind load and temperature effect, which is stipulated in the Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts, is more rational, but the temperature effect should be categorized according to actual effects. In this paper, a calculation method for stability coefficient is proposed. In this way, the stability effect is calculated by adopting the standard value effect that stabilizes the superstructure. The destabilizing effect is calculated by adopting the standard value effect that destabilizes the superstructure.

3. Study on the stability coefficient of the main line steel box girder

Variable cross-section continuous steel box girder has the advantages of light weight and good tensile and compression performance, and it can be processed in factories. It has been a preferred bridge type for urban crossing viaducts. In the existing and planned urban viaducts, the central separation zone of the main road is mainly 6m or 8m wide, limiting the distance between the supports in the transverse direction. According to CJJ 37-2012 Code for Design of Urban Road Engineering, for a road with a design speed of 60km/h and a central separation zone of 8m wide, the width of the curb belt of the motor vehicle lane is 0.5m, the width of the safety belt is 0.25m, and the actual distance of piers in the central separation zone is 6.5m. The variable cross-section continuous beam is generally twice as high as its side pier, there is no space for long cap beams in the substructure, but vane piers can be installed within the space of 8m wide. The support spacing is 6.5–8m.

To ensure the bearing of the beam and prevent support failure, two supports are set in the transverse direction at each fulcrum of the bridge. Meanwhile, to improve the girder's bearing capacity, the distance ratio of the supports is set to 1:1.5:1-1:2:1. Taking the bridge with a width of 25.5m as an example, the distance between the supports is preferably 10.93-12.75m. Considering the available space of the central
pier of the variable cross-section continuous steel box girder and the size and local bearing requirement of the support, the should be 1m away from the edge of the pier, and the distance between the centers of the two supports is only 4.5-6m.

For the variable cross-section steel box girder at the straight section of the main line viaduct with a combined span of 40+60+40m and a width of 25.5m, the checking computation of its anti-overturning is done by using the load effect method recommended in the Code for Design of Highway Steel Structure Bridges, Highway Reinforced Concrete and Prestressed Concrete and this paper. The steel box girder is equipped with wind barriers on the whole line, the road is paved with 10cm asphalt + 8cm reinforced concrete, the driveway load is two-way six-lane, and the city is A level. The girder height at the middle pier is 3m, the side pier and the mid-span girder are 1.8m high, the distance between the centers of the supports at the middle pier is 6m in the transverse direction, and the distance between centers of the supports at the side pier is 12m in the transverse direction, all the structures are symmetrical about the center of the structure line. The details are shown in Figure 3.

This is a straight girder bridge without centrifugal force. The loads used to calculate the anti-overturning are structural gravity (Phase 1 + Phase 2), foundation displacement, vehicle load (including impact force), wind load and temperature load. Except for the gravity of the structure, the other loads are taken as the most unfavorable arrangement relative to the failure support. The effect value is extracted from the finite element model analysis, and the calculation process of the stability coefficient is shown in Table 2-3.

| Failure support No. | 1-1 | 2-1 | 3-1 | 4-1 |
|---------------------|-----|-----|-----|-----|
| Foundation displacement effect/Structural gravity effect | 0.047% | 0.045% | 0.047% | 0.045% |
| Wind load effect/vehicle load effect | 81.9% | 57.7% | 57.7% | 81.9% |
| Temperature load effect/vehicle load effect | 3.3% | -6.9% | -6.9% | 3.3% |
Table 3. Summary table of the main line stability coefficient

| Failure support No. | 1-1 | 2-1 | 3-1 | 4-1 |
|---------------------|-----|-----|-----|-----|
| Steel structure specification | 4.5 | 3.7 | 3.7 | 4.5 |
| Interpretation of concrete specifications | 4.0 | 3.5 | 3.5 | 4.0 |
| Calculation example of concrete specification clauses | 7.4 | 5.3 | 5.3 | 7.4 |
| Recommended method | 4.0 | 3.3 | 3.3 | 4.0 |

The case used is a steel girder with small longitudinal bending stiffness, and the foundation displacement effect is small, which is less than 0.1% of the structure's gravity effect. The temperature load effect accounts for 3.3% to 6.9% of the vehicle effect, and the wind load effect accounts for 57.7% to 81.9% of the vehicle effect. According to the calculation method of the concrete code, the destabilization effect only considers the vehicle load. Thus the obtained stability coefficient increased by 51.4%-85% compared with the stability coefficient obtained from the interpretation of the concrete code. This proves that the girder is unsafe. Compared with the stability coefficient obtained from the steel structure specification calculation method, the stability coefficient increased by 5.7%-12.5%, proving that the girder is unsafe. Using the method recommended in this paper, the stability coefficient is the smallest. The coefficient at the middle pier is 5.7% smaller than the value calculated according to the interpretation of the concrete code, and the stability coefficients at the side piers are the same.

4. Research on the stability coefficient of ramp steel box girder

For a ramp with a width of 8.5m, the support spacing is preferably set to 3.64-4.25m. In this paper, the support spacing is 4m, the span combination is 30+40+45+35m, the curve radius is 75m, the design speed is 40km/h, the girder at the central pier is 2.2m high, and the girder at the side pier and the middle span is 1.8m high. The details are shown in Figure 5. The road is paved with 10cm asphalt + 8cm reinforced concrete, the driveway is one-way two-lane, and the city is A level. The checking computation of its anti-overturning is done using the load effect method recommended in the Code for Design of Highway Steel Structure Bridges, Highway Reinforced Concrete and Prestressed Concrete and this paper.

Figure 5. Schematic diagram of the layout of the ramp steel box girder bridge (unit: m)
The ramp is a curved bridge. Taking centrifugal force into consideration, the other loads are the same as the main line. The most unfavorable condition of vehicle load is that there is only one lane outside the curve. The calculation process of the stability coefficient is shown in Table 4-5.

Table 4. Load effect ratio of ramp steel box girder bridge

| Failure support No. | 1-1 | 2-1 | 3-1 | 4-1 | 5-1 |
|---------------------|-----|-----|-----|-----|-----|
| Foundation displacement effect/Structural gravity effect | 0.81% | -0.81% | 0.81% | -0.81% | 0.81% |
| Centrifugal force effect/vehicle load effect | 23.9% | 18.9% | 18.2% | 18.7% | 24.0% |
| Wind load effect/vehicle load effect | 126.0% | 129.4% | 122.3% | 135.4% | 122.6% |
| Temperature load effect/vehicle load effect | -112.4% | 338.9% | -109.1% | 356.3% | -111.0% |

Table 5. Summary table of ramp stability coefficient

| Failure support No. | 1-1 | 2-1 | 3-1 | 4-1 | 5-1 |
|---------------------|-----|-----|-----|-----|-----|
| Steel structure specification | 11.2 | 4.9 | 11.3 | 4.9 | 11.0 |
| Interpretation of concrete specifications | 17.1 | 4.1 | 17.4 | 4.1 | 16.9 |
| Calculation example of concrete specification clauses | 23.5 | 23.8 | 22.8 | 24.9 | 22.9 |
| Recommended method | 9.9 | 4.0 | 10.0 | 4.0 | 9.7 |

The foundation displacement effect is 0.81% of the structure gravity effect. The centrifugal force effect accounts for 18.2%-24.0% of the vehicle effect. The wind load effect accounts for 122.3%-135.4% of the vehicle effect, and the temperature load effect accounts for 109.1%-356.3% of the vehicle effect. According to the calculation example of the concrete code, the instability effect only considers the vehicle load. Compared with the stability coefficient obtained from the interpretation of the concrete code, the coefficient at piers 1, 3, and 5 has increased by 31% to 37.4%, and by about five times at piers 2 and 4. Compared with the stability coefficient calculated according to the steel structure specification, the coefficient at piers 1, 3, and 5 are lower, and the coefficient at piers 2 and 4 is higher. This proves that the girders are all unsafe. Using the method recommended in this paper, the stability coefficient is the smallest and the girder is safe.

5. Conclusion

This paper analyzed the overturning effect of the main line and ramp under permanent load and variable load, and drew the following conclusions:

(1) The centrifugal force, wind load and temperature load caused by the vehicle load have a large impact on the overturning and cannot be ignored.
(2) The temperature load and foundation displacement may lead to stability or instability, which depend on the stiffness distribution of the main girder. So the variable load effect cannot be defined generally as instability effect.

(3) This paper proposes to consider both the foundation combination and standard value combination when performing checking computation of support failure and recommended a calculation method, in which the "stability effect is calculated by using the standard value effect that stabilizes the superstructure, and the instability effect is calculated by using the standard value effect that destabilizes the superstructure instability". This method provides a reference for related departments.

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