

Research on Comprehensive Evaluation Method for Anti-overturning Safety of Bridges with Bent-straight Beam

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Abstract: Based on study of the critical state of overturning and the selection of overturning axis, a comprehensive evaluation method for anti-overturning safety is given for the continuous beam of bridge axis located on the bent-straight beam line. Based on the failure mechanism of the continuous box girder, the model of support separation is given for the overturning failure of bridge, and the specific calculation method for the safety factor of overturning is given. Taking a reinforced continuous box beam of the single-column pier on bent-straight- combined line as an example, a case study of a real bridge is carried out, and a full calculation of the support separation, the support angle and the overturning safety factor of the bridge is carried out. The application of a real bridge shows that the safety evaluation method for anti-overturning safety of bridges with bent-straight beam proposed in this paper is practical and reasonable.

1. Overview

When the bridge with continuous beam is located on a straight line or a line with a large radius of horizontal curve, there is a damage risk of entire overturning collapse. In recent years, there have been many bridge overturning accidents all over the world. For example, in August 2012, the separated ramp on Qunli Viaduct of the Third Ring Road in Harbin was overturned. Three people were dead and five people were injured. The accident was caused by 4 overloaded trucks densely driving on the right side of the same bridge deck and the beam offset stress was too large. In December 2014, an overturning accident occurred on an interchange under construction near Yuzui, Jiangbei District, Chongqing City. A 35-meter-span box beam was overturned. The cause of the accident was that the concrete tanker parked outside the bridge curve when pouring crash barrier. In July 2010, a newly-built national defense bridge on Basantpur-Kingal Highway in India collapsed a year after its completion, killing two people. The accident was caused by the intensive unbalance loading of four fully loaded heavy trucks. The overturning failure of bridges is an instantaneous mechanical behavior, with no obvious sign beforehand, yet its damage is extremely serious and thus should be highly regarded[1]. The above-mentioned accidents could have been avoided if the anti-overturning safety evaluation of the bridge had been carried out and overload had been strictly limited.

So far, scholars have carried out a series of studies on the overturning problem of bridges. In terms of the overturning mechanism, research on the anti-overturning stability of bridges with single-column pier and continuous beam can adopt a combination of theory and experiment. Finite element model is established to simulate the entire process of bridge overturning[2], the effects of bending, twisting, warping and distortion of the box beam are considered, and the space mechanical characteristics and overturning instability mechanism are analyzed [3-5]. Ales et al.[6] found in study that under the



effect of unbalance load, the inner and outer supports of the bridge are in the state of being pressed on one side and being separated the other side. When the unbalance load is withdrawn, the support is restored to its original stress state. Such cyclical action will cause fatigue failure to the support. In terms of research on anti-overturning safety evaluation methods, there are mainly the support reaction method [2,5] and the stability coefficient method [7,8]. It's insufficient to judge the overturning of bridge with single-column continuous beam only by support separation, and space calculation must be performed to determine the overall anti-overturning performance of the structure. At present, Chinese scholars gradually tend to use the idea of stability coefficient to judge the anti-overturning stability of bridges. This method is easy to operate in practical engineering. A reasonable stability factor can not only meet the economic requirements, but also ensure that the structure has a certain anti-overturning safety reserve. The core content of the stability coefficient method is the judgment of the critical state of overturning and the selection of the overturning axis position. In this paper, the comprehensive evaluation research on anti-overturning safety is carried out by using the combination of support reaction force, support rotation angle and anti-overturning safety factor. In the formulation of the anti-overturning norm: AASHTO Bridge Design Code of the United States [9] does not explicitly give the calculation method for the anti-overturning stability of bridges under unbalance load. The Japanese bridge engineering community has done a lot of researches on single-column viaducts and has revised the Specifications for Road and Bridges many times, but it basically focuses on the description of seismic response. Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts[7] (2012 Consultation Draft, hereinafter referred to as the Design Code) has specifically added anti-overturning calculation for continuous-beam bridges with integral sections. In 2015, Guangdong Provincial Communications Department issued the Guiding Opinion on the Checking Calculation and Evaluation of Transverse Anti-overturning Safety of Continuous Box Beam for Single-Column Piers on Highways of Guangdong Province(hereinafter referred to as the Guiding Opinion), which expanded the scope of checking calculation of anti-overturning, and pointed out that checking calculation of anti-overturning is not only necessary for single-column piers, but also for small-spacing double-column piers. Li Panzhi and other scholars [10] pointed out that the four types of standardized car load overturning effects of ramp bridges with single-column pier, from the smallest to the largest, are the USA's AASHTO Specification, Chinese 04 Highway Specification, 89 Highway Specification, and the UK's BS5400 Specification.

In summary, in recent years, the anti-overturning problem has been developed in terms of structural damage mechanisms, calculation methods, and revisions of specifications. However, its computational theory is not yet mature and the revision of relevant specifications is also controversial, moreover, most of the literature is directed at straight bridges or bent bridges, and there has not been study on the anti-overturning safety assessment of bridges with bent-straight axes. This paper presents a comprehensive evaluation method for anti-overturning safety of bridges with single-column pier and bent-straight beam and conducts a case study on real bridge.

2. Study on calculation method for anti-overturning

2.1. Determine the Critical State of Structure Overturning

There are three main indicators for judging the critical state of bridges with single-column pier and continuous beam: 1) There is negative reaction force of the side pier support because of support separation; the model of support separation is shown in Figure 1, which is an important basis for determining the overturning axis; we can see from Figure 1 (c) that there is also the risk of overturning in small-spacing double-column bridge pier. 2) The rotation angle of the mid-pier support reaches the limit; 3) The overturning moment is greater than the anti-overturning moment. Straight bridges are mainly controlled by indicators 1) and 3), while bent bridges are mainly controlled by indicators 1), 2), and 3).

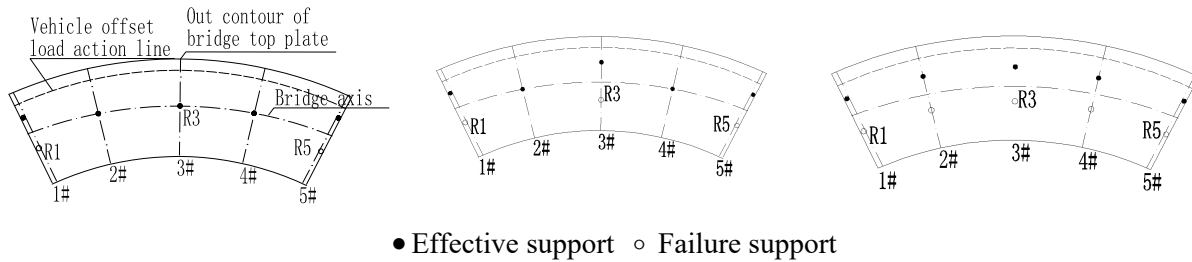


Figure 1. Effective support schematic diagram for Overturning critical state

2.2. Determine the position of the overturning axis

Reasonably determining the position of the overturning axis is crucial to accurately assess the anti-overturning safety performance of bridges[11]. Article 4.1.9 of the Design Code[7] stipulates that overturning axis is the connecting line of the support on the same side of two abutments straight-line bridges; for bent bridges, when all the supports of mid-span piers are located on the inner side of the support connecting line and outer side of the abutment, that is, when the bridge axis is on the large-radius curve, the overturning axis is the connecting line of the support on the outer side of the abutment; when all the supports of the mid-span piers are located on the outer side of the abutment and the outer side of the support connecting line, that is, when the bridge axis is on the small-radius curve, the overturning axis is taken from the connecting line between one of the abutment inner support and mid-bridge pier support. However, the Design Code does not provide a method for selecting the tilting overturning axis of bridges with continuous beam on bent-straight line. This paper proposes that anti-overturning axis shall be taken respectively for the straight segment and the bent segment for bridges with bent-straight beam according to the most unfavorable principle, and then checking calculation should be performed for the full-bridge anti-overturning stability on the anti-overturning axis of the straight segment and bent segment, respectively. Only when both the overturning axes pass the checking calculation of anti-overturning does it indicate that the bridge with bent-straight beam will not be overturned.

2.3. Calculate anti-overturn stability safety factor

The Design Code[7] proposed the overturning stability safety factor method based on the concept of degree of safety. The formula for calculating the overturning stability factor of the superstructure of bridges with small and medium-span beams and integral sections is as follows:

$$\frac{\sum S_{Rk,i}}{\sum R_{Sk,i}} > k_{qf} \quad (1)$$

In the formula: k_{qf} —anti-overturning stability coefficient, taking $k_{qf}=2.5$; when the bridge with single-column pier is in an overloaded section, k_{qf} should be properly increased. $\sum S_{Rk,i}$ —Effect design value that stabilizes the superstructure, $\sum S_{Rk,i} = \sum R_{Gki} l_i$; $\sum S_{Sk,i}$ —Effect design value that destabilizes the superstructure, $\sum S_{Sk,i} = \sum R_{Qki} l_i$; l_i —the vertical distance between the overturning axis and the i -th support, there is only one effective support in each pier under the critical state of overturning instability, as shown in Figure 1. R_{Gki} —the permanent reaction force of the ineffective support at the i -th pier, calculated according to the effective support system of all supports; R_{Qki} —the variable reaction force of the ineffective support at the i -th bridge pier, calculated according to the effective support system of all supports, and the vehicle load effect (considering the action of impact) is assessed based on the most unfavorable layout of each ineffective support.

3. Analysis of anti-overturning safety evaluation case

3.1. Project Overview

Foshan Nangang Interchange is located on the west side of Sanshanxi Bridge in Pingzhou Town, Nanhai District. It contains a total of nine ramps. Ramp F is analyzed in this case. Ramp F is 390.474 meters long. It was completed and opened to traffic in 1995. The superstructure of the main bridge adopts $(6 \times 20 + 26 + 2 \times 20)$ ordinary reinforced concrete beam. The box beam adopts C30 concrete. The bridge is 6.5m wide. The single-box single-chamber section is used. The top plate is 6.5m wide and the bottom plate is 3m wide. The flange plate on the two sides is 1.75m, the box beam is 1.2m high, and the top plate is 0.2m thick. The thickness of the bottom plate and webs varies along the span, and the anti-collision wall is 0.9m high.

The original structure is reinforced with carbon fiber in the first and fourth span. The remaining bridge spans are reinforced with steel plates with a thickness of 8mm. Each plate is 250mm wide, and there are a total of 10 plates; the diameter of the pier after reinforcement is 1.2m, and a layer of steel mesh is added. The sound barriers are arranged on the outside and the arrangement diagram is as Figure 2.

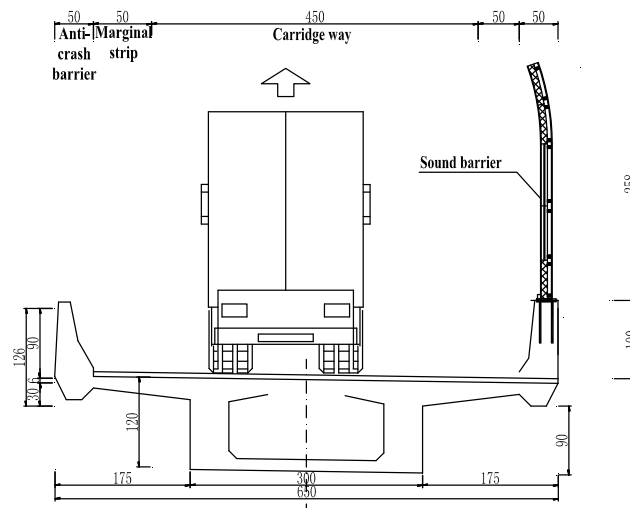


Figure 2. Cross-sectional schematic diagram of sound barrier arrangement

3.2. Finite Element Model

The checking calculation of the bridge uses a spatial analysis model. Specialized software Midas Civil is used to simulate finite element, and the structural unit is dispersed as shown in the figure below. There are a total of 223 units of the full bridge. The discrete principle of the structural units is that nodes shall be set at the change of section, bearing node, and loading position. Since this project is a straight-bent bridge, some of the structural lines are bent. In order to facilitate applying loads and constraining, the local coordinate system of nodes is defined. The finite element model is shown in Figure 3.

In the later stage of the structure, a sound barrier is added. The effect of wind load must be considered. When wind load is applied to the finite element model, the following issues need to be noted: 1) The position of the wind load will effect the checking calculation result of anti-overturning for the bridge, therefore, the wind load can not be directly added to the main beam, a virtual beam should be added in the position of sound barrier, and the wind load shall be applied to the virtual beam. 2) The wind direction at a certain time is the same. There is no wind coming from all directions. Therefore, wind load should not be applied to the entire straight-curved bridge at the same time. Corresponding wind load should be applied according to the position of the anti-overturning axis. The wind load should be applied on the virtual beam of the curve, and it should be equivalently loaded based on the projection of the wind load on the anti-overturning axis.

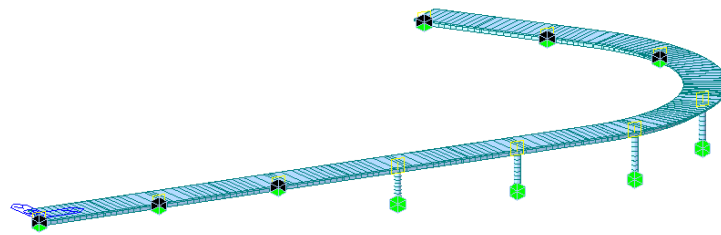


Figure 3. Finite element model of a bridge with straight-bent beam

3.3. Checking calculation of anti-overturning

3.3.1. Checking calculation of support reaction Figure 4 is the Comparison of minimum support reaction for the original structure without sound barrier and structure with sound barrier (load case 1 and load case 2, (load case 1 and load case 2, corresponded with overturning axis 1# and 2#, shown as Figure 6). Wind load is not considered in the original structure since there was no sound barrier, so only one group of minimum support reactions are worked out. However, for the structure with sound barrier, there are two wind directions, one is vertical to the overturning axis 1#, another one is vertical to the overturning axis 2#. Consequently, there are two load cases. According to Figure 4, support separation takes place in F1 and F10 for all of the three situations. After wind load is considered, the separation is rising. However, the whole structure is not reach critical state yet. The above result is consistent with that of the anti-overturning safety factor.

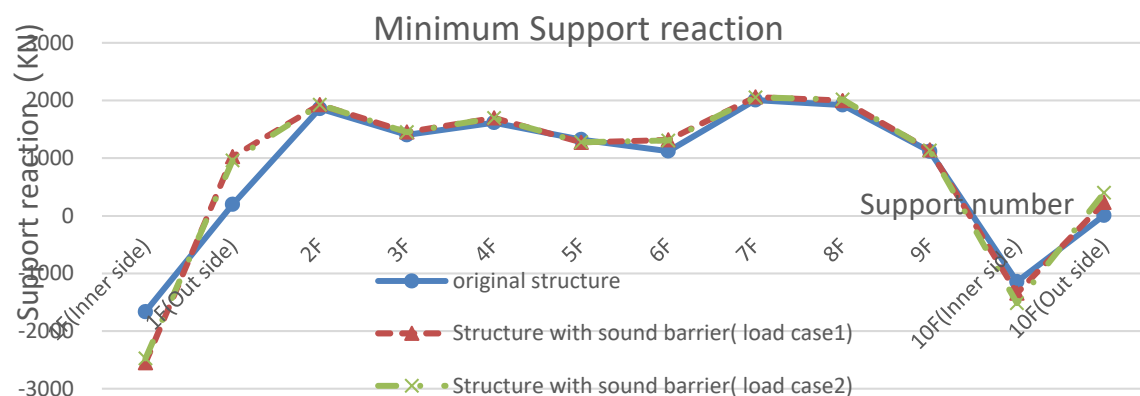


Figure 4. Comparison of minimum support reaction

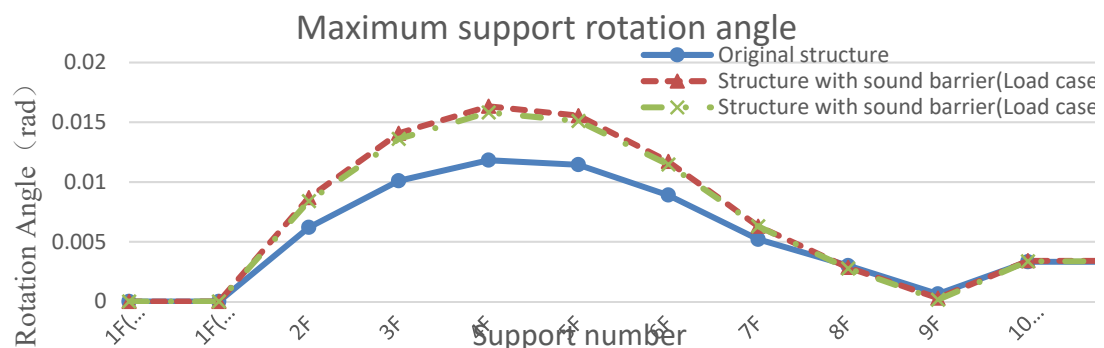


Figure 5. Comparison of maximum support rotation angle

3.3.2. Checking calculation of support rotation angle Figure 5 is the comparison of maximum support rotation angle for the original structure without sound barrier and structure with sound barrier. According to Figure 5, the rotation angles are all less than 0.02 rad. That means, the results are

satisfied with the requirement from the design codes[7]. However, after the sound barrier is added to the original structure, the support rotation angle increased. The rotation angle result is in the following order: Load case 1 > Load case 2 > Original. The above result is consistent with that of the anti-overturning safety factor.

3.3.3. Calculation of anti-overturning safety factor In this project, the anti-overturning axis is determined according to two working conditions. The stability safety factor for overturning is calculated for the two cases respectively, and the most unfavorable condition is taken as the overturning factor. The calculation is as follows:

In the first case, the connecting line between the support on the outer side of the beam end at the straight section and the support at straight-bent line transition point is taken as the anti-overturning axis. In the second case, the connecting line between F7 and F8 is taken as the anti-overturning axis. Showing as Figure 6.

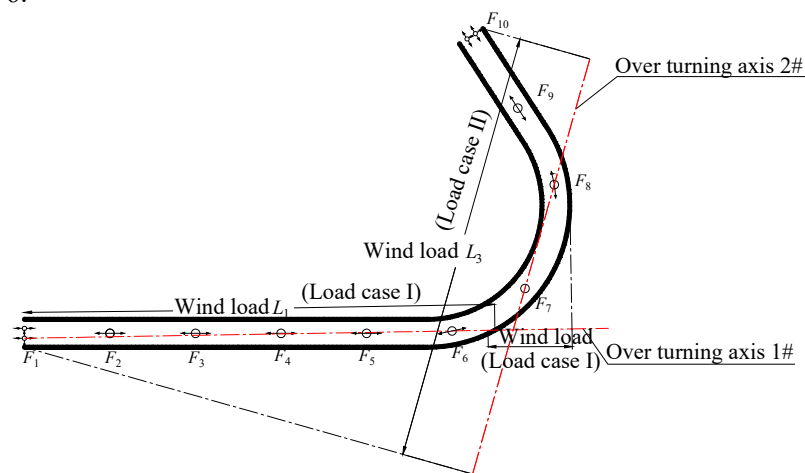


Figure 6. Anti-overturning axis

Table 1. Support reaction and arm of the force

Support number		Load case 1			Load case 2		
		R_{Gki}	R_{Qki}	$Xi(m)$	R_{Gki}	R_{Qki}	$Xi(m)$
1F	Inner side	175	-1356	2.3	175	-1242	110.07
	Out side	601	774	0	601	660	109.44
	2F	2412	-97	0.81	2412	-97	90.51
	3F	2050	-174	0.47	2050	-174	71.26
	4F	2144	-116	0.13	2144	-117	52.02
	5F	2147	-278	0.22	2147	-271	32.77
	6F	2006	-96	0	2006	-114	13.71
	7F	2606	-152	9.63	2606	-157	0
	8F	2555	-147	33.77	2555	-121	0
10F	9F	2189	-221	51.77	2189	-227	13.07
	Inner side	237	-375	68.12	237	-560	28.87
	Out side	598	31	69.34	598	213	27.35

Xi is the vertical distance from support to over turning axis.

Support reaction and arm of the force of load case 1 and load case 2 considering both dead load and live load is as Table 1. According to equation (1), the anti-overturning safety factor can be worked out with the finite element method calculation result in Table 1. The anti-overturning safety factor is 6.1 for load case 1 and 3.7 for load case 2. Both are satisfied with the requirement from the codes[7].

4. Conclusion and Prospect

Based on the study of the overturning failure mechanism, the evaluation of critical state of overturning and the selection of overturning axis, a concrete comprehensive anti-overturning safety evaluation method is proposed for continuous beams with bridge axis located on straight-bent line. The real bridge case shows that this method is reasonable and feasible. Based on the above study, the measures for continuous beam under unbalance load are given as follows: 1) Horizontal multi-support system (multi-column or single-column double-support structure) should be adopted, and the horizontal spacing of support should be maximized; when the structural forces meet the requirements, pier beams can be used for consolidation. 2) When the construction conditions are special, for example, when the piers that cross the separator in the middle of the road, or the single-column single-support structure must be adopted, continuous single-column structure should be avoided. 3) Reliable limit and anti-drop beam structures should be set at transition piers and bridge abutments.

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