WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.141882

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 3 2022

pp. 221 –240

Research paper

Anti-overturning safety performance investigation for single column pier bridge

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Abstract: Under eccentric load, a single column pier bridge often overturns. In order to study the anti overturning performance of a single column pier bridge, taking the accident bridge in Wuxi as an example, a finite element model is established based on ABAQUS. According to the model simulation results, the relationship between the ultimate rotational load and overturning load of the accident bridge is obtained, and the ratio of the latter to the former is 1.75. Based on the model, the stress state, displacement state, and support state of the accident bridge under dead load, highway class I vehicle load, and accident vehicle load are obtained. Whether the strength and stability of the accident bridge under each load meet the service requirements is analyzed. In order to explore the differences among China, United States, and Japan specifications, the lateral stability of accident bridges is checked. It is found that the safety of the United States and Japan specifications is conservative, but the utilization rate of bridge traffic capacity is low. The safety of China specifications is slightly lower, but it can maximize the bridge's traffic capacity and judge the ultimate overturning state of the bridge more accurately. The research results can provide technical references for the design and application of a single-column pier bridge.

Keywords: single column pier girder bridge, anti-overturning, finite element modeling, overturn ultimate load, rotation ultimate load

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1. Introduction

Single column pier bridges are widely used in bridge construction in China and abroad because of their convenient construction, simple structure, and small space occupation. However, the current bridge design principles pay more attention to whether the strength of the beam meets the requirements, ignoring the stability of the beam under eccentric load. At present, the research on the overturning mechanism of single-column pier bridges is not perfect. The overload events of trucks in China and abroad often occur, which leads to the potential risk factors of this kind of bridge. Under some extreme eccentric loads, the single-column pier bridge is likely to overturn. The following summarizes overturning accidents of single pier bridges in China in the recent ten years, as shown in Table 1.

Table 1. The single column pier bridge collapse accident

Time	Accident bridge	Cause of the accident
1995	Japan, Hanshin,shenhu, Single column pier bridge	Poor lateral stability
2007.10.23	China, Viaduct of Minzu East Road, Baotou City	Three trucks overloaded more than 100 tons respectively
2009.7.15	China, Ramp bridge of Jin Jin Expressway	5 trucks, 3 of which have a total overload of 265 tons
2011.2.21	China, Chunhui overpass in Shangyu, Zhejiang Province	4 trucks, 3 of which are overloaded with 196 tons
2012.8.24	China, Harbin yangmingtan Bridge	4 trucks, 3 of which are overloaded with 301 tons
2021.12.25	Vietnam, Jinou Province, Single column pier bridge under construction	Insufficient vertical bearing capacity

Liang [1] believes that the overturning accident of a single column pier bridge belongs to the problem of lateral stability. However, the designer pays more attention to the longitudinal strength of the bridge in the previous bridge design process. The "specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" put forward the checking calculation method of the anti-overturning of single column pier bridge and gives the corresponding safety factor [2]. In some studies, the overturning process of a single column pier bridge is regarded as the overturning of a rigid body around the axis, which has some shortcomings [3, 4]. (1) The beam is an elastic body. Suppose it is regarded as a rigid body, and the influence of its torsional deformation is ignored. In that case, it will overestimate the anti overturning capacity of a single column pier structure. (2) The interaction among beam, support, and pier is ignored. (3) The effect of beam length is ignored. (4) The rotation angle of the beam under eccentric load is ignored.

With the continuous occurrence of bridge overturning accidents, scholars began to pay attention to the lateral stability design of single-column pier bridges. Peng et al. [5] established the finite element model based on geometric and contact nonlinearity. They proposed the calculation method of anti overturning bearing capacity of single column pier bridge. Xu [6] established a finite element model based on a three-span single-column pier bridge and analyzed the anti overturning performance of the bridge under the design ultimate load. Lin [7] studied the influence of plane curve radius, bearing spacing, and other factors on single-column pier bridges. It was found that the larger the plane curve radius and the further the bearing spacing, the higher the anti overturning performance of single column pier bridge. Xue [8] analyzed the distribution of bearing reaction and overall stress when the single column pier bridge overturned on the centripetal and centrifugal sides, respectively. Related research based on the thin-walled theory of elastic straight bar, the thin-walled theory of elastic curved bar was proposed and deduced the Vlasov differential equation [9,10]. The equation explains the interaction between bending moment and torque and can accurately analyze the torsional deformation of the bridge. However, this method is complicated. The relevant research also proposed the curved bridge differential method to analyze the torsional deformation of the bridge, which includes closed solution and finite difference numerical solution [11, 12]. Song et al. [13] studied the influence of radius of curvature and bearing eccentricity on the anti overturning stability of curved bridges. The results show that the higher the bearing eccentricity is, the stronger the anti overturning performance is. With the increase of curvature radius, the overturning performance decreases first and then increases. A bridge collapse scene simulation method based on finite element analysis is proposed, which provides an important reference for the analysis of bridge collapse accidents [14]. Through the analysis of each failure case, the reasons for bridge collapse are evaluated, and the main reasons for the overall or partial collapse of bridge structures are found out and studied [15]. Against the background of a curved girder bridge in South Korea, its construction phase was carried out [16]. By establishing a finite element model, the dynamic parameters of the superstructure of the curved girder bridge an analysis was carried out and the effect of lateral bracing on the structure was explored [17]. The influence of different factors on the anti-overturning ability of the bridge is studied through different parameters in the structural design form [18]. The anti-overturning ability is studied according to the change of the size and position of the vehicle load [19].

Taking the accident bridge with a single column pier in Wuxi as an example, this paper calculates the ultimate rotational load and overturning ultimate load of the accident bridge through the finite element model and discusses the evaluation standard of the overturning of single column pier bridge. Firstly, the accuracy of the finite element model is verified by comparing it with the existing related research. Secondly, the finite element model is simulated the stress and deformation state of the accident bridge under the action of dead load, highway class I vehicle load, and accident vehicle load. Moreover, analyze whether its longitudinal strength and transverse stability meet the service requirements and discuss the cause of overturning. Finally, the support reaction of the accident bridge under three types of loads is obtained through the finite element model. Combined with the specifications of China, the United States, and Japan, the anti overturning calculation of the accident bridge is carried out, respectively. The rationality of different specifications is discussed to provide technical reference for the anti overturning design of single-column pier bridges in the future.

2. Numerical simulation analysis

2.1. Accident overview

A single-pillar pier bridge collapsed in Wuxi City, Jiangsu Province, and a truck carrying steel coils fell off the bridge on October 10, 2019. According to the investigation, when the overturning accident occurred, four trucks drove along one side of the viaduct, causing the bridge to bear the extreme eccentric load. Finally, the beam overturned and slipped. The accident vehicles are divided into vehicle 1, vehicle 2, vehicle 3, and vehicle 4 from north to south. The total weight of vehicle 1 is 18.625 tons, vehicle 2 is 153.29 tons, vehicle 3 is 163.59 tons, vehicle 4 is 149.68 tons and the total weight of four trucks is 485.185 tons. Vehicle 1 is overloaded, vehicles 2, 3, and 4 are seriously overloaded. According to the monitoring video of the accident site, when the bridge overturns, the beam has a noticeable trend of turning first and then sliding. It can be seen that under the eccentric load of four trucks, firstly, the support is separated from the compression state in turn, and the support system of the beam fails. Secondly, the beam is twisted, deformed, and inclined. Finally, the inclination angle of the beam is too large, the support is extruded, and the beam slides from the pier to the ground. The main beam has no strength failure in the whole process, indicating that the longitudinal strength safety reserve is greater than the lateral stability safety reserve. Although the cause of bridge overturning is ultimately attributed to vehicles' severe overload and eccentric load, it also causes people to dispute and question the structure of a single column pier.

2.2. Structural dimensions of accident bridge

The accident bridge is a three-span continuous beam bridge, with an end span of about 25 m and a mid-span of about 40 m. The width of the main beam is 11m, the width of the lane is about 10 m, the design lane is a one-way two-lane, and the design load grade is highway class I vehicle load. The site plan and elevation are shown in Fig. 1. The main beam is a steel box girder, the steel is Q345, and the yield strength is 345 MPa. The main

(a)

(b)

Fig. 1. Accident bridge: (a) elevation view, (b) cross section view

beam is supported by pier A, pier B, pier C, and pier D. Two plate rubber supports are placed on pier A and pier D, with a diameter of 0.35 m and a center distance of 2.5 m. In addition, a plate rubber support with a diameter of 0.68m is placed on pier B and pier C. The thickness of the support is 0.05m. The plane dimension of the Wuxi viaduct is shown in Fig. 2, and the cross-sectional dimension of support is shown in Fig. 3. Relevant research shows that the overturning axis of a straight bridge is the connecting line between two bearings on the same side, so the overturning axis of an accident bridge is the connecting line between the center points of bearings 1–2 and 4–2[20].

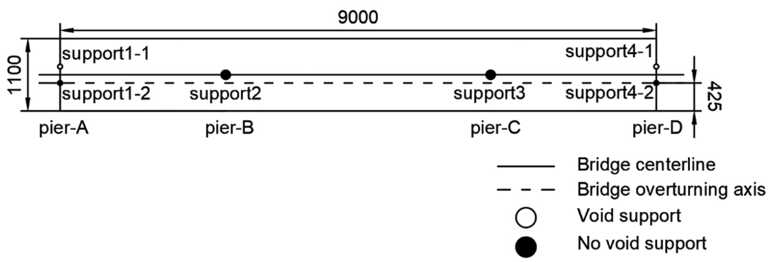


Fig. 2. Plan of accident bridge (mm)

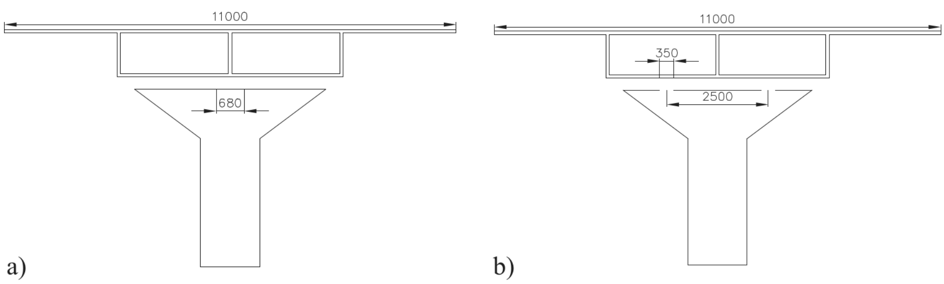


Fig. 3. Cross section of accident bridge: a) piers B and C, b) piers A and D (mm)

2.3. Finite element model

2.3.1. Unit element type and contact properties

The finite element model of accident single column pier bridge is established by using ABAQUS, and the model uses display dynamics and nonlinear geometric analysis. The linear weight of the beam body is about 120 kN/m, the bearing is plate rubber bearing, and the unit type of the beam body and bearing is C3D8R. The on-site pier has no strength failure and deformation, and the relevant research believes that the pier can be set as a rigid body [21]. Therefore, the pier is set as a rigid body in this study without considering its mechanical characteristics. The contact relationship among the main beam, the support, and the pier is general contact, and the friction coefficient is taken as 0.1 [22]. The mesh division of the model is shown in Fig. 4.

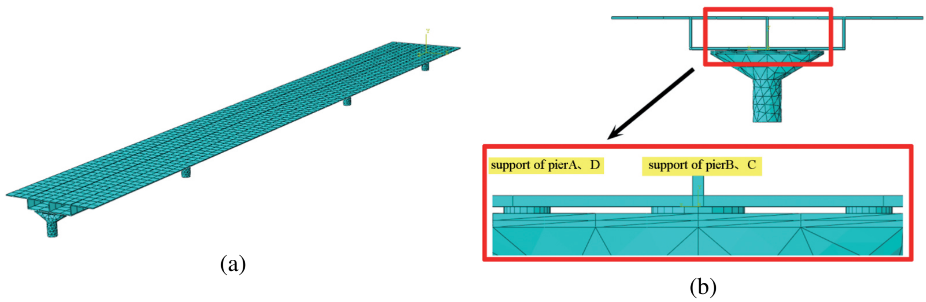


Fig. 4. Model meshing: a) elevation, b) cross section

Firstly, the dead load is applied to the model, and then the highway class I vehicle load is applied. If the bridge does not overturn, the highway class I vehicle load is linearly amplified to calculate the rotational ultimate load and overturning ultimate load of the bridge. Finally, the accident vehicle load is applied to the model, and the stress state, displacement state and support stress state of the bridge under four kinds of loads are compared and analyzed. Since the accident bridge is designed according to Chinese specifications, the proportion of axle load of any vehicle load applied to the model shall be transformed according to the highway class I vehicle load. The proportion of each axle load of the highway class I vehicle load is shown in Fig. 5.

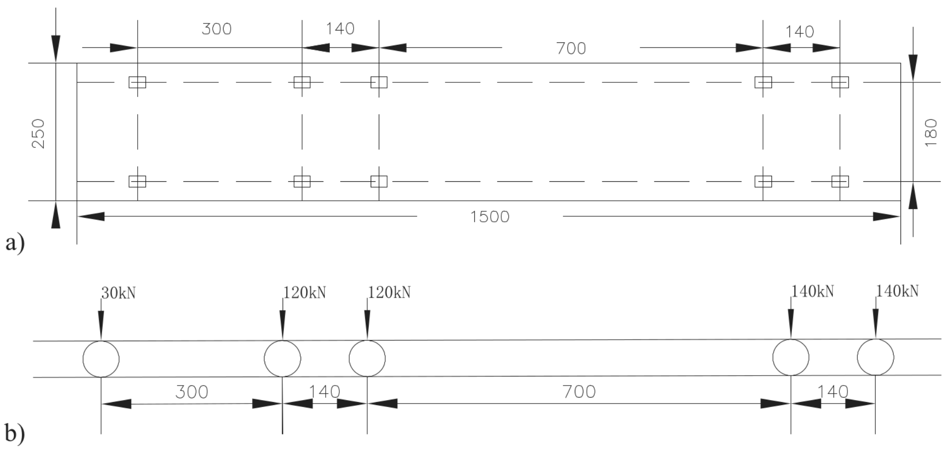
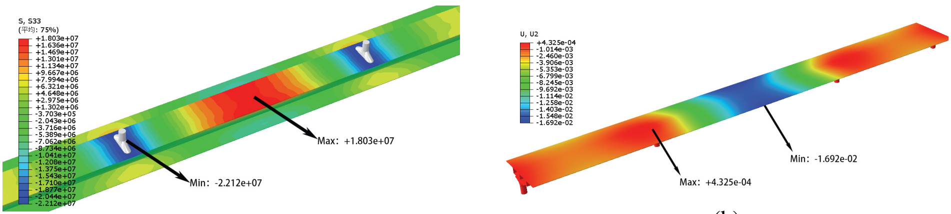


Fig. 5. Design load distribution: a) plane size, b) elevation size (cm)

2.3.2. Dead load

As shown in Fig. 6, the S33 is the longitudinal stress of the beam body, the compressive stress is negative and the tensile stress is positive, the U2 is the displacement value of the beam in the vertical direction, the vertical upward displacement is positive, and the vertical downward displacement is negative. No vehicle load is applied to the model, and the model only works under dead load. The bridge's stress state and deformation state are shown in Fig. 6, and the support state is shown in Fig. 7. According to Fig. 6a), the main beam's stress state and deformation state meet the stress characteristics of the continuous beam under a uniformly distributed load. The maximum tensile stress of the main beam is 18.03 MPa, which is located on the lower surface of the midspan, and the maximum compressive stress of the main beam is 22.12 MPa, which is located on the lower surface of the main beam in contact with support 2. The maximum stress is far less than the ultimate strength of steel, indicating that the bridge meets the strength requirements under the action of self-weight. According to Fig. 6b), the maximum vertical upward displacement of the beam is 4.325e-04 m, which is located on the upper surface of the main beam at pier B. The maximum vertical downward displacement of the beam is 1.692e-02 m, which is located on the lower surface of the midspan. As shown in Fig. 7, it can be seen that all supports are in compression. There is no vertical displacement difference between the two edge lines of the main beam, indicating that the main beam has no inclination angle.



(a) (b)

Fig. 6. Dead load: a) stress nephogram, b) displacement nephogram (MPa, m)

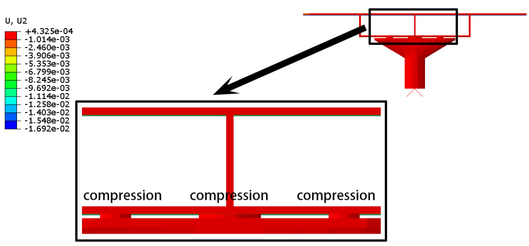
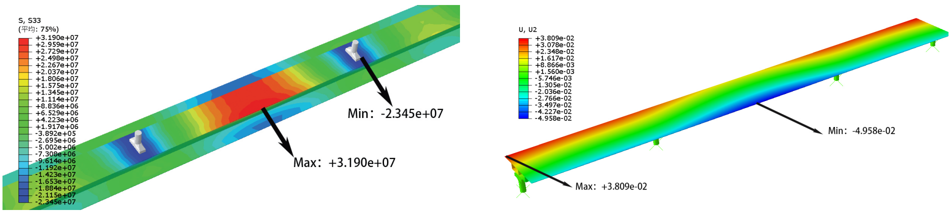


Fig. 7. Support state (m)

2.3.3. Highway class I vehicle load

Highway class I vehicle load is divided into vehicle load and lane load. Vehicle load is selected for simulation analysis because the overturning reason of the accident bridge is eccentric load and vehicle overload. The design vehicle load is 55 T per 15 m bridge length, and the plane and elevation dimensions of the vehicle load are shown in Fig. 5. The bridge must be full of 55 T vehicles when considering the highly unfavorable conditions. Six 15 m long loaded vehicles can exist simultaneously on one side of the bridge with a span of 90 m, and the vehicle load centerline is 1.9 m away from the edge of the deck. Apply dead load and highway class I vehicle load to the model. The bridge's stress state and deformation state are shown in Fig. 8, and the support state is shown in Fig. 9. The maximum tensile stress of the beam body is 31.9 MPa, and the maximum compressive stress of the beam body is 23.45 MPa, which is less than the ultimate rotation load and overturning ultimate load. According to Fig. 8, the maximum vertical upward displacement of the beam is 0.03809 m, the maximum vertical downward displacement of the beam is 0.04958 m, and the displacement difference on both sides of the main beam is 0.08767 m. According to Fig. 9, all supports are under slight eccentric compression.



(a) (b)

Fig. 8. Highway class I vehicle load: a) stress nephogram, b) displacement nephogram (MPa, m)

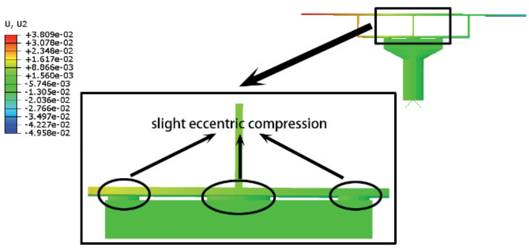
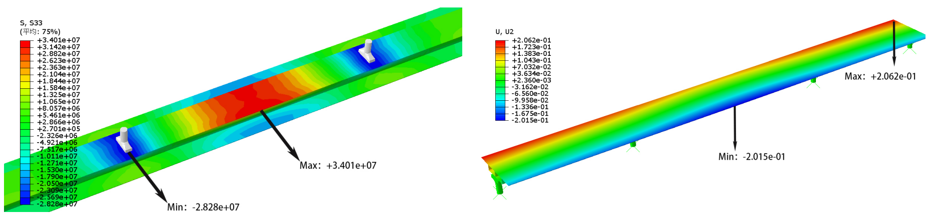


Fig. 9. Support state (m)

2.3.4. Rotational ultimate load and overturning ultimate load

The rotational ultimate load and overturning ultimate load of the bridge are calculated by linearly applying the highway class I vehicle load to the finite element model. When the bridge rotates, the beam body is separated from the support and emptied. At this time, the applied load is the ultimate rotational load. When the support is in the critical state of extrusion, the load at this time is the overturning ultimate load. According to Fig. 11, the moment when support 1–1 and support 4–1 are disengaged is the ultimate rotation state of the main beam. According to Fig. 13, the moment when support 1–2 and support 4–2 are extruded is the ultimate overturning state. According to Fig. 10a), the maximum tensile stress is 34.01 MPa, which is located on the lower surface of the midspan. Similarly, the maximum compressive stress of the beam is 28.28 MPa, which is located on the beam surface contacted by support 3. The maximum tensile stress and maximum compressive stress are far from reaching the ultimate strength of steel, indicating that the accident bridge will not have strength failure under the action of ultimate rotational load. According to Fig. 10b), the maximum vertical upward displacement of the beam is 0.2062 m, which is located at the end of the side. The maximum vertical downward displacement of the beam is 0.2015 m, which is located on the upper surface of the midspan. The displacement difference on both sides of the main beam is 0.4077 m, indicating that the main beam has an inclination angle. The maximum vertical upward displacement and the maximum vertical downward displacement are not in the same cross-section of the main beam, so it can be judged that the beam body has torsional deformation. Fig. 10a) is similar to Fig. 12a), which shows that the stress characteristics of a single column pier bridge under rotation limit load and overturning limit load are consistent. The maximum tensile stress is 39.86 MPa, and the maximum compressive stress of the beam is 34.08 MPa. Although it is greater than the rotational limit load, it has not reached the ultimate strength of steel. Therefore, the accident bridge will not have strength failure under the overturning limit load. The similarity between Fig. 10b) and Fig. 12b) shows that the deformation characteristics of a single column pier bridge under rotation limit load and overturning limit load are consistent. The maximum vertical upward displacement is 0.5947 m, and the maximum vertical downward displacement is 0.4438 m. The displacement difference on both sides of the main beam is 1.0385 m, which is greater than the rotation limit load, indicating that the torsional deformation and inclination angle of the accident bridge under the overturning



(a) (b)

Fig. 10. Rotational ultimate load: a) stress nephogram, b) displacement nephogram (MPa, m)

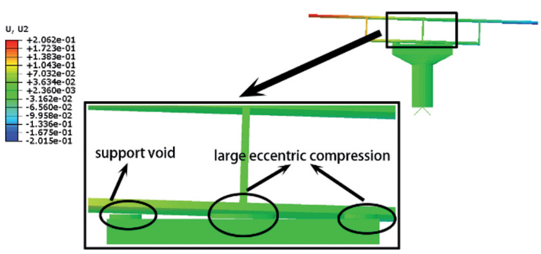
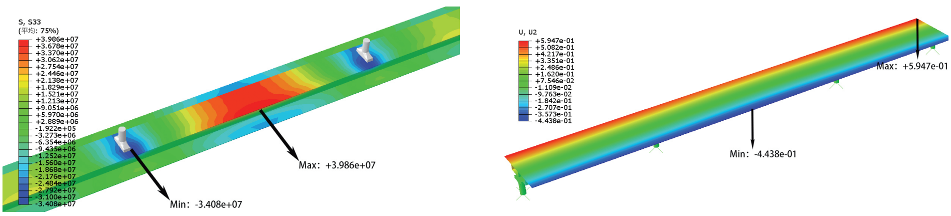


Fig. 11. Support state (m)

limit load is great. According to the applied load, the ultimate overturning load is about 1.75 times the ultimate rotational load. At the same time, some scholars found that the ultimate overturning load is about 1.65–1.8 times the rotational ultimate load, which is consistent with the calculation results of this model, which also verifies the correctness of the model [22].



(a) (b)

Fig. 12. Overturning ultimate load: a) stress nephogram, b) displacement nephogram (MPa, m)

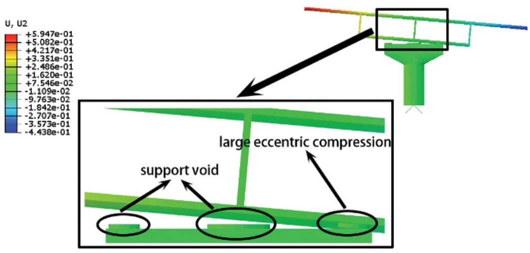


Fig. 13. Support state (m)

2.3.5. Accident vehicle load

The research shows that when the vehicle is driving in the middle span, the support reaction force of the end support will be reduced so that the anti overturning moment will be reduced [23]. Therefore, the structure is dangerous when the vehicle is driving in the middle span and safe when driving in the side span. Therefore, the load shall be distributed according to the most unfavorable position. According to the field investigation, the sequence of accident vehicles on the bridge is shown in Fig. 14. As the accident bridge is designed according to Chinese specifications, the accident vehicle load is transformed into the corresponding axle load based on the proportion of each axle load of highway class I vehicle load. According to the load ratio of the front axle, middle axle, and rear axle in Fig. 11, the load of each accident vehicle is converted into corresponding axle load in proportion. The axle load of vehicle 1, vehicle 2, vehicle 3, and vehicle 4 is shown in Fig. 15. The vehicle load centerline is 1.9 m away from the edge of the bridge deck. The bridge's stress state and deformation state are shown in Fig. 16, and the supports state is shown in Fig. 17.

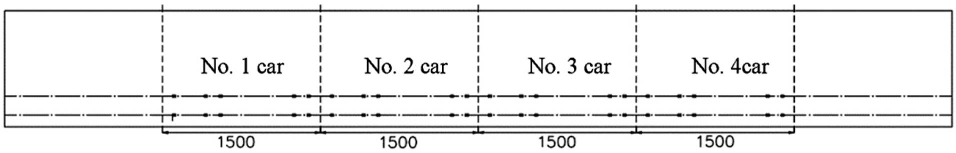


Fig. 14. Plane distribution of accident vehicles (cm)

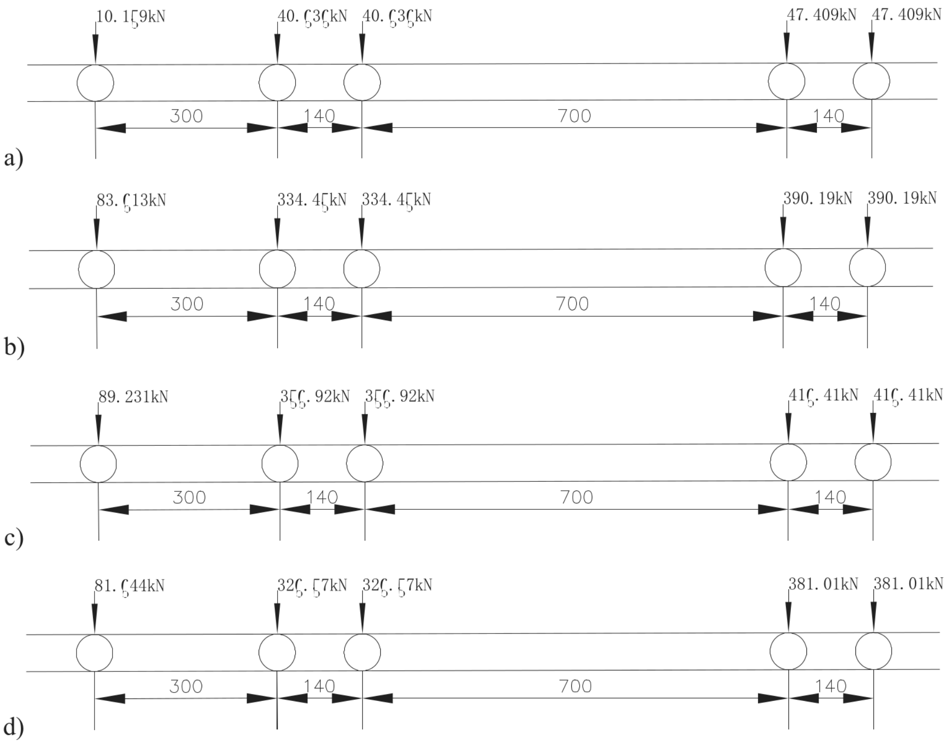
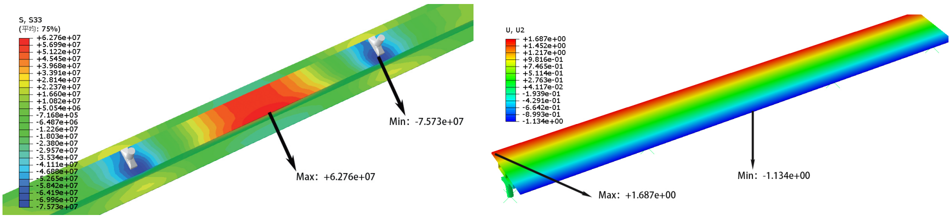


Fig. 15. Axle load diagram of the accident vehicles: a) vehicle 1, b) vehicle 2, c) vehicle 3, d) vehicle 4 (cm)

According to Fig. 16, the main beam's stress state and deformation state under the accident vehicle load are similar to the highway class I vehicle load. The maximum tensile stress of the main beam is 62.76 MPa. The maximum compressive stress of the beam body is 75.73 MPa, which is far from reaching the ultimate strength of steel, indicating that the bridge will not be damaged under the action of accident vehicle load. The maximum vertical upward displacement of the main beam is 1.687 m, the maximum vertical downward displacement of the main beam is 1.134 m, and the displacement difference on both sides of the main beam is 2.821 m. It shows that the beam's torsional deformation and inclination angle under the accident vehicle load are more significant than the overturning limit load.



(a) (b)

Fig. 16. Accident vehicle load: a) stress nephogram, b) displacement nephogram (MPa, m)

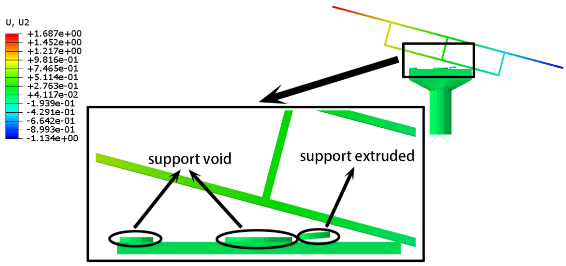


Fig. 17. Support state (m)

According to Fig. 17, support 1–1, support 2, support 3, and support 4–1 are in the void state, support 1–2 and support 4–2 are squeezed out by the main beam. The main beam finally slides off the pier column, which is consistent with the on-site accident.

Fig. 18 and Fig. 19 show the maximum tensile and compressive stress of the model under various loads. Fig. 20 shows the vertical relative displacement and turnover angle of both sides of the model under various loads. These parameters are dead load, highway class I vehicle load, ultimate rotation load, overturning ultimate load, and accident vehicle load from large to small. The results show no strength failure of the box girder, indicating that the strength design meets the using requirements, and even the safety reserve is too large – the greater the torsional deformation of the box girder, the more prone to overturning accidents. Therefore, the torsional deformation of the main girder under eccentric load must not be ignored. Furthermore, the overturning angle of the main beam under the ultimate overturning load is 5.41°, tan 5.41° = 0.094, which is close to the friction coefficient 0.1 set by the model, so the friction coefficient between the main beam and the support can not be ignored. In addition, it is also verified that it is inaccurate to use the bearing void state as the basis to judge the bridge overturning, and the anti overturning specification of the bridge still needs to be further optimized. The following is a preliminary introduction and comparison of Chinese specifications, American specifications, and Japanese specifications. Then, the anti overturning checking calculation of the accident bridge is carried out using the three countries' specifications. Finally, the advantages and disadvantages of the specifications of the three countries are further compared.

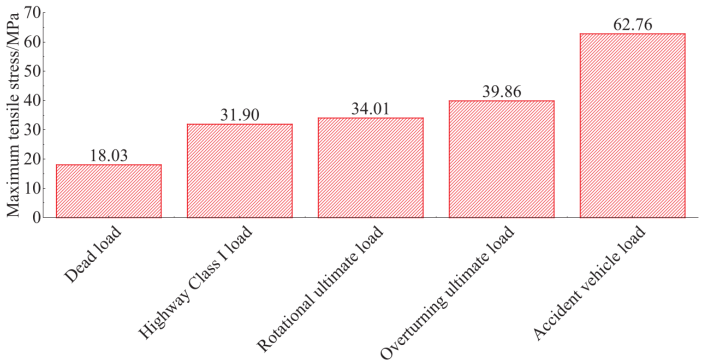


Fig. 18. The maximum tensile stress of the beam under various working conditions

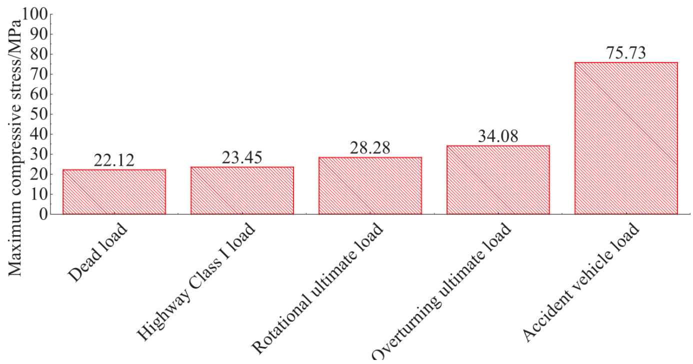


Fig. 19. The maximum compressive stress of the beam under various working conditions

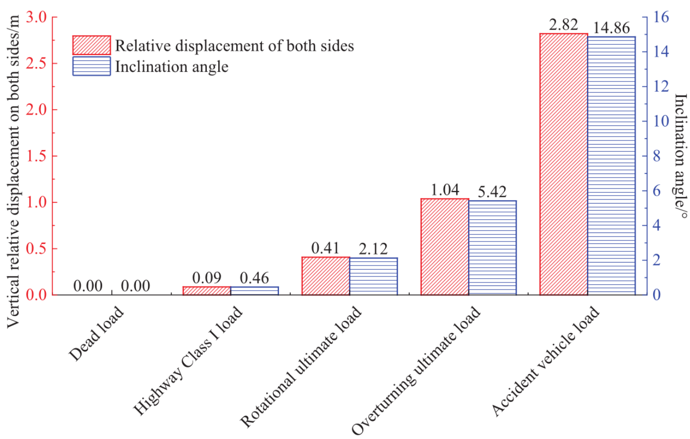


Fig. 20. The maximum relative displacement and rotation angle of the beam under various working conditions

3. Anti overturning checking calculation

3.1. Standard checking calculation in China and abroad

The anti overturning calculation of accident bridges is carried out by using the specifications of China, the United States, and Japan. China specification, American specification, and Japanese specification have explicit provisions on bridge overturning, but they are different, as shown in Table 2.

Table 2. Anti-overturning Specification of China, The United States, and Japan

Country	Specification	Normative provisions
China	Specifications for design of highway reinforced concrete and prestressed concrete bridges and culverts (JTG 3362-2018)	Under the permanent condition, the structural system of the bridge shall not change, and the following provisions shall be met at the same time: 1. Under the basic combination of action, the unidirectional compression bearing always maintains the compression state; 2. When combined according to the action standard value, the transverse anti overturning stability coefficient of integral section simply supported beam and continuous beam shall not be less than 2.5.
The United States	AASHTO LRFD 2007 [24]	1. Under any limit state, the bearing with void tendency shall be restrained by tie rod or anchor. 2. The minimum vertical force of multidirectional movable bearing shall not be less than 20% of its bearing capacity; 3. Special design is required for bearings with support reaction less than 20% of vertical bearing capacity.
Japan	Japanese Road and Bridge instructions [25]	The support reaction force cannot be negative, and the calculation formula of support reaction force is the algebraic sum between the support reaction force under the most unfavorable live load and the support reaction force under dead load.

The specifications of China, the United States, and Japan all restrict the value of support reaction force to prevent support void. However, China, the United States, and Japan have different requirements and calculation methods for support reactions. First of all, the United States has higher requirements for support reaction than China. Secondly, the Japanese pay more attention to vehicle load and gives a higher coefficient of vehicle load, which is higher than the requirements of China. Based on the calculation results, the specification reserves of the three countries are the United States, Japan, and China, from large to small. However, the advantages and disadvantages of the specification of the three countries still need to be further compared and analyzed through specific examples.

3.2. Calculate support reaction

Since the specification of the three countries has limited the support reaction force, the model should be used to output the reaction force value of each support. First, the constraint relationship among the main beam, the support, and the pier is changed to binding constraint. Then on the premise that each support system is effective, the support reaction force of the model under the action of dead load, highway class I vehicle load, and accident vehicle load is output. Under the action of dead load, the reaction force of each support is pressure, but under the action of highway class I vehicle load or accident vehicle load, support 1–1 and support 4–1 have great tension. The spacing between two supports per pier is 2.5 m. In order to explore the influence of support spacing on support reaction force, the support spacing is changed to 3.5 m, and the support reaction force is calculated again. The results are shown in Fig. 21. According to Fig. 21b) and Fig. 21c), increasing the support spacing can effectively reduce the tension of support 1–1 and support 4–1.

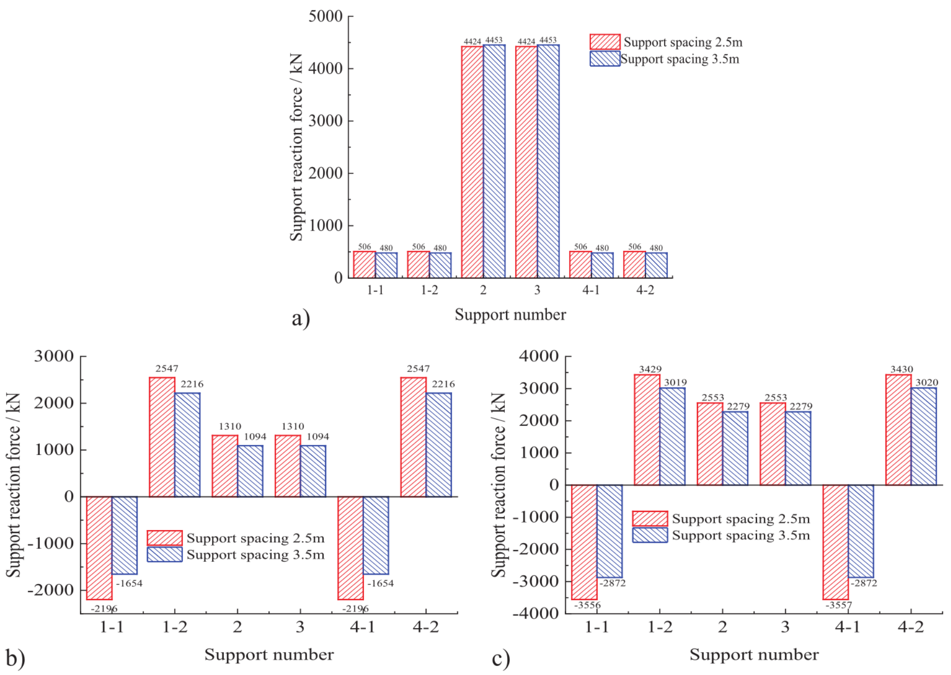


Fig. 21. Support reaction force under various load: a) dead load, b) highway class I vehicle load, c) accident vehicle load

Therefore, increasing the support spacing can be used to enhance the anti overturning capacity of a single-column pier bridge.

3.3. Chinese specification

The China specifications specify two characteristic states. On the one hand, under the essential combination of load action, the support remains in a compression state without tension. On the other hand, the ratio of stability parameters to instability parameters is more significant than 2.5.

$$\frac{\sum S_{bk,i}}{\sum S_{sk,i}} \geq k_{qf} \tag{3.1}$$

where: k_{qf} – Lateral anti overturning stability coefficient, $k_{qf} = 2.5$ in the specification, $\sum S_{bk,i}$ – design value of effect to stabilize superstructure, $\sum S_{sk,i}$ – design value of destabilizing effect of superstructure

The manual checking calculation is combined with the finite element model data, and the results are shown in Table 3 and Table 4.

Table 3. Checking calculation of characteristic state 1

Support number	1–1	1–2	2	3	4–1	4–2
$1.0R_{Gki} + 1.4R_{Q-1}$/kN	–2568	4071	6258	6258	–2568	4071
$1.0R_{Gki} + 1.4R_{Qki}$/kN	–4472	5307	7997	7997	–4473	5308

Table 4. Checking calculation of characteristic state 2

Support number	1–1	1–2	2	3	4–1	4–2
$S_{bk,i}$/kN · m	1265.9	0	0	0	1265.8	0
S_{Q-I}/kN · m	5490.8	0	0	0	5490.0	0
$S_{sk,i}$/kN · m	8890.7	0	0	0	8892.8	0
Stability factor	$\sum S_{bk,i}/\sum S_{sk,i} = 0.142$, $\sum S_{bk,i}/\sum S_{Q-1} = 0.617$					

According to the checking calculation results, in the characteristic state 1, the reaction forces of supports 1–1 and 4–1 are tensile forces, which do not meet the specification requirements. In characteristic state 2, the lateral anti overturning stability coefficient is less than 2.5 and does not meet the specification requirements. On the premise of not meeting the specification requirements, the model has not overturned, so the ultimate rotation state cannot be used as the basis for judging bridge overturning. It is suggested that the ultimate overturning state should be used as the basis for judging bridge overturning.

It is proposed that the ultimate overturning load is about 1.75 times the rotational ultimate load, and the China specification has sufficient safety reserves. However, the Wuxi viaduct was established in 2003. At that time, there was no specific anti overturning specification in China, so it is reasonable that it did not meet the requirements of the new specification.

3.4. American specification

The American specifications only stipulate that the support cannot be disengaged. That is, the support reaction force cannot be tensile. According to Table 4, the support produces considerable tension. Although the checking results do not meet the requirements of American specifications, the model does not overturn, so even if it does not meet the requirements of American specifications, the bridge does not necessarily overturn. Although the American specifications are safer than the China specifications, it can not make efficient use of the bridge's traffic capacity.

3.5. Japanese norms

Like the American code, the Japanese code also stipulates that the bearing reaction cannot be a tensile force, except that the vehicle load factor is high. The vehicle load can cause the bearing to produce tension. Thus the Japanese code is more conservative.

$$R_U = 2R_L + R_D \tag{3.2}$$

where: R_U – bearing reaction, R_L – bearing reaction under the most unfavorable live load, R_D – bearing reaction under dead load

According to the bearing reaction given in Table 4 and combined with the calculation formula of Japanese code, the bearing reaction conforming can be calculated, as shown in Table 5. The checking results do not meet the requirements of Japan specifications, but the model does not overturn. Even if it does not meet the requirements of Japan specifications, the bridge does not necessarily overturn. Japanese specifications are higher and safer than China and American specifications but waste the bridge's traffic capacity.

Table 5. Checking calculation of characteristic state 2

Support number	1–1	1–2	2	3	4–1	4–2
Highway–Class I/kN	–3886	5600	7044	7044	–3885	5599
Accident vehicle load/kN	–6606	7365	9529	9528	–6607	7367

Fig. 22 shows the specified load of the three countries' specifications and the ultimate overturning load of the model. The results show that the three countries' specifications are too conservative, and the anti overturning safety reserve is too large, far from reaching the ultimate overturning load of the bridge. The safety reserves from large to small are Japan, the United States, and China. Based on the calculation results, China's specification safety is slightly lower than Japan's and the United States' specifications. However, China's specifications are more accurate and can give full play to the traffic performance of this bridge.

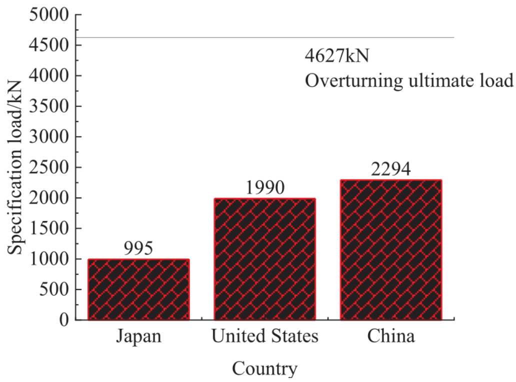


Fig. 22. Specification load

4. Conclusions

Under the action of accident vehicle load, the field situation is consistent with the model simulation results. Furthermore, the beam body has no strength failure and only overturning accident, which shows that the longitudinal strength design takes precedence over the transverse stability design of the bridge in the process of bridge design.

Single column pier is prone to torsional deformation under eccentric load, and excessive torsional deformation can easily lead to beam overturning. Therefore, this factor should be paid attention to when discussing the lateral stability of a single column pier.

The contact relationship between the main beam and the support and between the support and the pier is also an essential factor determining the anti overturning stability of the single column pier. According to the model results, the overturning angle of the main beam of the bridge under the ultimate overturning load is $5.41°$, $\tan 5.41° = 0.094$, which is close to the friction coefficient set by the model of 0.1. Therefore, when considering the anti overturning performance of the single column pier, The friction between the main beam and the support can not be ignored. It can be considered to increase the friction coefficient between the three to improve the anti overturning stability of single column pier.

The United States and Japan specifications regard the support void as the critical condition for bridge overturning and stipulate that the bearing reaction is no tensile force. Although the anti overturning performance of the bridge is guaranteed, the traffic volume of the bridge is limited. The China specification divides the bridge overturning process into two characteristic states. Each characteristic state has a corresponding calculation method, and the judgment basis is closer to the actual overturning conditions. Thus, although the safety reserve is slightly lower, the traffic utilization rate of the bridge is higher.

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Received: 14.11.2021, Revised: 12.04.2022