Research on Mechanism of Overturning Failure for Single-column Pier Bridge

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ABSTRACT

This paper presents the research on mechanism of overturning failure on box girder under overload and partial load for the single-column pier bridges. It includes (1) the definition of two key states before the box girder overturns(i.e., the disengaging state leading to the unbalanced load bearing and the ultimate state of overturning stability),(2) the depiction of three stages along overturning (stable stage, transitional stage, and overturning stage, (3) the development of an ABAQUS finite element model considering contact nonlinear and geometry nonlinear for analyzing Chunhui bridge collapse, and (4)the undertaking on identifying the relationships between overturning ultimate load and elastic modulus of box girder, load position, bridge length and friction coefficient of bearing and box girder. The results indicate that the overturning load calculated by finite element simulation conforms to the measurements collected at the collapse site of Chunhui bridge, reflecting the validity of the proposed study. The ultimate state of the overturning stability can be used to judge whether the bridge is overturning. It is more accurate than using the disengaging state of one side end bearing to judge, and the overturning ultimate load is 1.5-2 times than the rotating ultimate load.

INTRODUCTION

On Monday, February 21, 2011, the Chunhui bridge overpass in Shangyu, Zhejiang, China, collapsed. Four trucks fell into the road and three people injured. This bridge failed after about six years in service. Essentially whether overloading was cause was the concern for safety of other similar types of bridges. According to the statistics, there are another three bridge collapsed in China in recent six years (Table1).

Table 1. Single-Column Pier Bridge of collapse in last six years

Time	The bridge collapsed
2007/10	Baotou National Road Viaduct
2009/07	Jin-Jin Highwayapproachbridge inTianjin
2012/08	HarbinHongfuRoad Viaduct upstreamramp

Single-column pier bridges such as Chunhui Bridge are very common in concrete bridge design and construction in the United States and worldwide. Until the event occurred, single-column bridge had earned the reputation of being economic, reliable and aesthetic. Forensic evidence from Chunhui bridge after collapse suggested that the bridge failure was initiated by extremely eccentric overload. It becomes especially important to be able to accurately predict and understand the behavior of a structure when loading is the beyond service standard.

Several studies have been conducted on the failures of constructed facilities (Kumalasari 2003, Abba G.1993, Minmao 2011; H.M. Salem 2008).

The subject of ductility and strength capacity of single-column bridge piers has been largely investigated and is supported by seismic design criteria in many bridge codes. A number of damage studies on concrete columns under seismic and overloads (Priestley and Park 1987; Priestley and Benzoni 1996; JTirasit and Kawashima 2007; Konstantinidis 2009) were conducted, accompanied design procedures for the capacity assessment of bridge column with different cross sections and reinforcement details (Kowalsky and Priestley 2000; Satoko Hashimoto 2005)

The application of these studies is currently discarded estimate the overturn stability of single-column bridge because overturn is not the main factor of bridge collapse on service load. Actually, in China's current highway and bridge codes, there are no relevant provisions about transverse overturn stability. However, the maximum partial load on bridge should not more than 30 percent of vertical design load, which is defined in code of China's railway in order to avoid superstructure's overturning. On the other side, the minimum vertical load on a pot bearing should not be less than 20 percent of vertical design load, defined in the AASHTO specification.

In view of this, firstly, this study makes a detailed investigation of Chunhui bridge, and then defines two key states and three stages in the collapse process of the superstructure. Meanwhile, the collapse mechanism of single-column bridges is studied using ABAQUS finite element model considering the contact nonlinear and geometric nonlinear for numerical analysis.

COLLAPSE INVESTIGATION OF CHUNHBUI BRIDGE

Bridge description. The bridge consisted of six 20-m spans; the longitudinal gradient is 3.5%. The diameter of the pier is 1.1m, the height of piers are followed by 2.8m, 3.5m, 4.2m, 4.9m, 5.6m, 6.3m and 7m. This bridge adopts the one-way two lanes, and bridge deck width is 8m, using double column piers at either begin and end, using single column pier in the middle. The plan and pier number of Chunhui bridge as shown in Figure1.

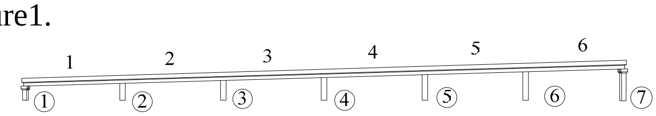

Figure 1. Elevation View of Chunhui Bridge

According to the investigation of collapse site investigation, the 4 overloaded trucks' loading weight were 28.52t, 124.44t, 125.6t and 110.73t. The light one is inside, and the three heavier vehicles pass outside with low velocity when the bridge collapsed.

Field Investigation. Through the analysis of collapsed wreckage, the pier failure suggests mainly compression and bending type dominated by bending type. From the pier 2 to pier 6, the top of piers all have 42-48° punching shear failure plane. As shown in Figure 2.

Figure2 Failure pattern of pier at collapse scene

Because it is unable to determine the top of pier failure results from the box girder sliding, or Local compression under the overload and eccentric loads, this study further compared contact traces of pier and the bottom of box girder, as shown in Figure 3. We can find that after failure contact traces of pier and the bottom of box girder are obvious, but scratches are very shallow, so it can be judged that after a short time the box girder overturning, the piers damaged. Therefore, it can be inferred that box girder rotates under partial loads, and when it rotates to a certain angle, the bottom of box girder and pier contact, which make the pier had high local pressure and finally destructed. In short, we can think of pier is not damaged, until the box girder critical collapse occurred.

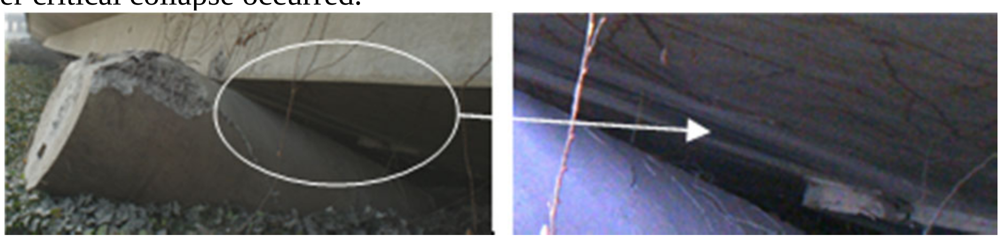

Figure 3.ure The contact traces of piers at collapse scene

At the scene of the Chunhui bridge collapsed, there is an obvious damage happened between pier 5 and pier 6, as shown in Figure4.

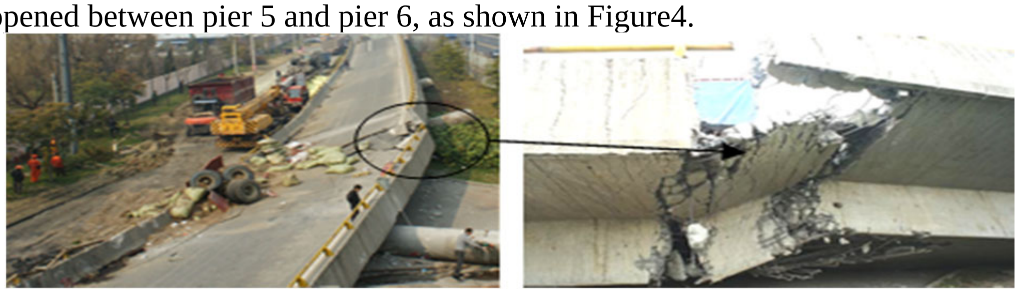

Figure 4. The failure pattern of box girder at collapse scene

There are two possible reasons of box girder destruction as follows: one is after the bridge pier collapsed, the box girder has curved destruction in place of overload vehicle, as shown in Figure5. Another is in the falling process of box girder, because the box girder on higher pier takes longer time to fall, and have larger horizontal displacement, after the box girder on lower pier is landed, the ground has constraints on box girder, but the box girder on higher pier is still falling, and the lateral movement of box girder results in central box girder destruction, as shown in Figure6.

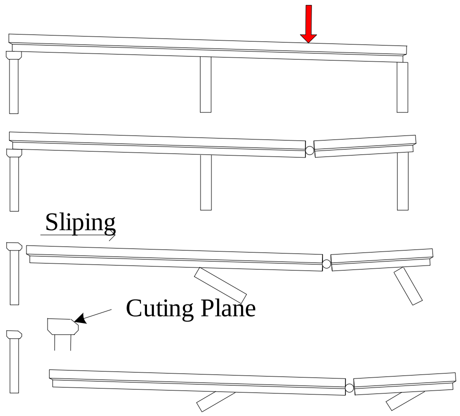

Figure 5. Curved destruction

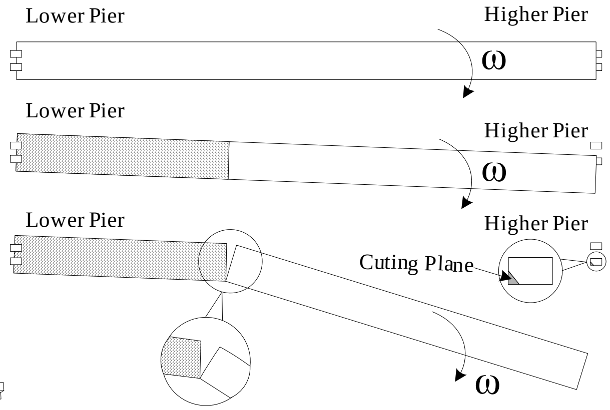

Figure 6. Movement destruction

To confirm reasons of box girder destruction, we made further comparison of collision traces of the box girder wreckage in this paper.

As can be seen from the Figure7, when box girder collapse occurs, box girder and pier contact. Through the analysis of the contact traces, we can find the mainly movement trend is that the box girder rotates along a horizontal axis, and moves along the longitudinal axis of the bridge if the ends have no curved destruction. Therefore, we can confirm that the upper structure has no huge curved destruction before the pier collapse, and keep intact before overturning. Subsequent paper will focus on the superstructure overturning firstly.

Figure 7. Wreckage collision traces of box girder at collapse scene

3D FINITE-ELEMENT ANALYSIS OF THE CHUNHUI BRIDGE

FEM modeling. According to the 3D laser scanning map from the collapse site, identified the specific size of box girder: diameter of the pier is 1.1m, longitudinal slope is 3.5%, bearing with diameter 600mm, thickness 150mm for each pier, from bearing to the edge of box beam bottom flange is 0.4m. Vehicle load is applied in accordance with（TGD60-2004 General Code for Design of Highway Bridges and Culverts, loading position is shown in Figure 8.

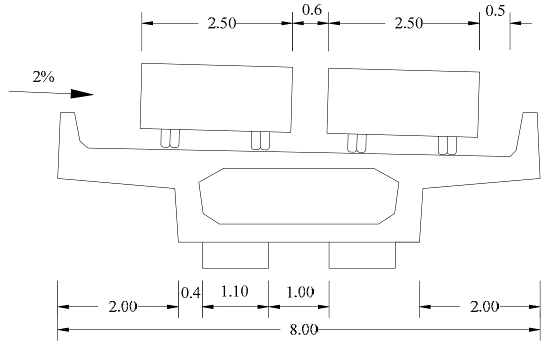

Figure 8. Schematic diagram of box girder section size and vehicle loading position

Due to the weight of the three heavy vehicles close to each other, it is simulated with three times the standard load in the calculation. That is three heavy vehicles with a capacity of165tper truck load linear stepwise applied from zero, as shown in Figure9. In addition, to study the factors affecting the overturning of the bridge, the following four conditions were designed.

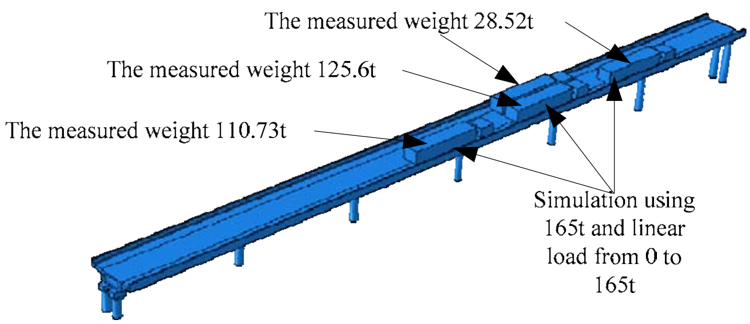

Figure 9. Vehicle-bridge contact finite element model

To simulate box girder's torsions and overturning under partial loads, bearing-pier's contact surfaces adopt the friction coefficient of 0.3, Vehicle – bridge's contact surfaces adopt the friction coefficient of 0.7. At the same time, the results of Collapse site traces indicate box girder remain intact before overturning, Therefore, the elastic model can be used on box girder to analyze the process of overturning.

Table 2. Load cases of finite element analysis

Number	Group	description
1	Normal group	Bearing-box beam's friction coefficient0.3, vehicles -box beam's friction coefficient0.7, E=3×10^{10}
2	Contact Conditions	Take bearing-box beam's friction coefficient difference with 0.2，0.25
3	Tensional stiffness	The elastic modulus of the supperstructure are3×10^{10}，5×10^{10}，7×10^{10}，9×10^{10}，1.5×10^{11}Pa
4	Loading position	The distance from car to the rightmost of bridge are0，0.15，0.3，0.45，0.6，0.75，0.9，1.05，1.2，1.35m

Evaluation at Limit States. Box girder deform under partial loads of the overloaded car, when the structure reached the rotation ultimate load, one side end bearing is disengaging; when the load is more bigger, reaching the ultimate overturning load, comes the biggest corner of box girder; when the load Increases continue, box girder slip occurs under unbalanced loads, eventually lead to overturn.

With the increasing process of partial load, rotation axis moves from the center of bearing to the edge, shown in Figure10(load shown in the Figure is the weight of per heavy vehicle when the partial load is applied, the same as follow); After reaching the ultimate overturning load, box girder overturn.

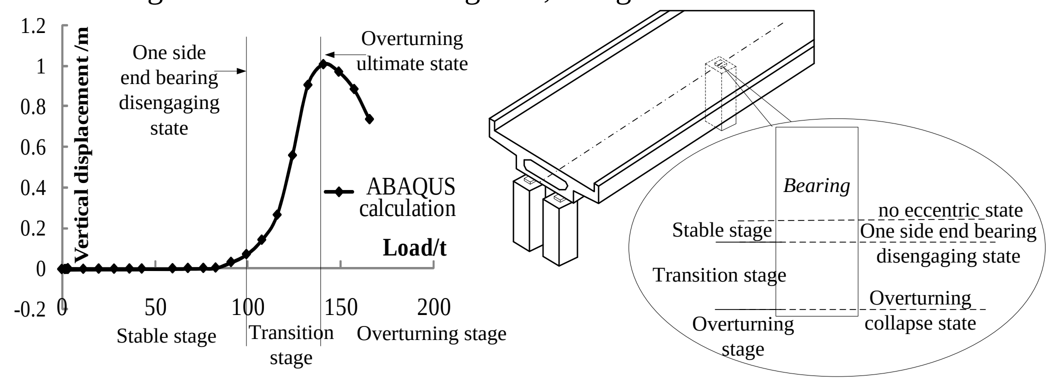

Figure10. Finite element simulation results

In view of this, this article defines two key states and two loads;

1）**One side end bearing disengaging state:** Partial loads on the other side and the two end bearing reaction force is zero, or one is zero and another is negative.

2）**Overturning stability limit state:** When the rotating line of the box girder near the bearing edges, the rotating line reaches the limit position, can no longer move outside, at this time the overturning of the box girder occurs; for the convenience of calculation, similar to rotating shaft to bearing edge line as the judgment standard of overturning limit state.

(a) **Rotation limit load**: the load when the **one side end bearing disengaging state** occurs. (b) **Overturning the ultimate load**: the load when the **overturning stability critical state** occurs.

Influence factors to bridge Overturning Capacity. This paper studies the influence of bearing-box beam's friction coefficient and elastic modulus on the rotational limit load and overturning limit load. The results show that (as shown in Figure 11), It have reached the rotational limit load near the 90t, reached overturning limit load near the 140t, the coefficient of friction between the bearing and box girder has no obvious influence on the rotational limit load and overturning limit load. As can be seen from Figure 12, overturning ultimate load increases with the elastic modulus, proving increasing structural reinforcement ratio can improve the performance of the anti-overturning.

When the vehicle load is gradually moving from the edge to the center, rotation ultimate load and overturning ultimate load are larger; under 165t car load, when the vehicle load near the end of bearing, rotation ultimate load greater than 165t, As shown in Figure13 and Figure14.

Based on these definitions above the box girder overturning process is further divided into three stages: stable stage, transition stage and overturning stage.

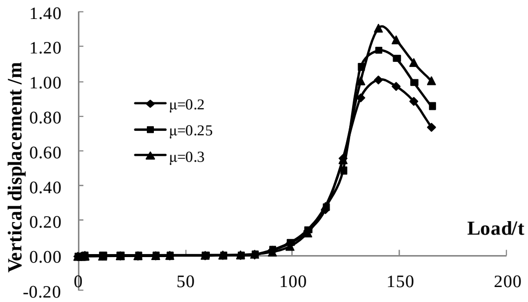

Figure11. Overturning load vary by friction coefficient between bearing and box girder

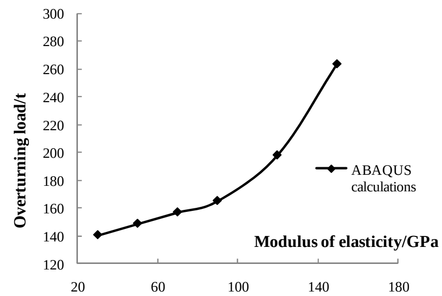

Figure12. Overturning ultimate load changes with the elastic modulus

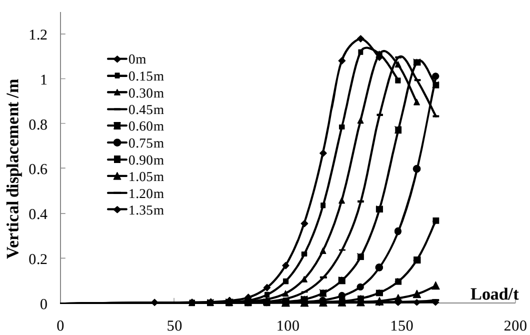

Figure13. The box girder vertical displacement changes with the loading position

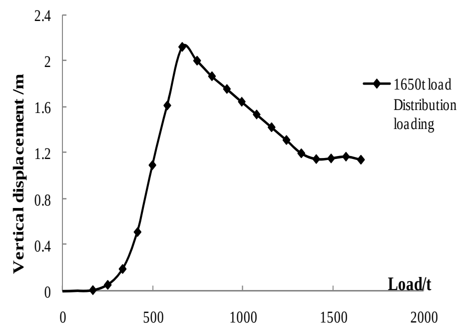

Figure14. The box girder vertical displacement changes under seriously overloaded

In order to further verify when the car load is in the end bearing connecting line, the bridge may also be overturned, it designed the finite element model of load center is in the outside bearing connecting line.

CONCLUSION

In this paper, on the background of Chunhui Bridge, it analyzed the finite element model, get the following conclusion:

(1)According to the single column pier bridge theory analysis and finite element calculation results, the overturning of the bridge is divided into three stages.

(2)According to the results obtained in finite element simulation are accurately simulate the overturning limit load of box girder, the results show that the Chunhui Bridge collapse initiated as the box girder's overturning first;

(3)Overturning stability limit state can be used to judge the basis for overturning; the corresponding overturning limit load is 1.5-2 times of bearing disengaging overturning loads, more accurately than using bearing void determines the overturning.

ACKNOWLEDGMENTS

This research is financially supported by the NSFC (Grant No. 50908211), by the Zhejiang Provincial Natural Science Foundation of China (Grant No. LY13E080014)

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