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Damage investigation of girder bridges under the Wenchuan earthquake and corresponding seismic design recommendations

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Abstract: An investigation of girder bridges on National Highway 213 and the Doujiangyan-Wenchuan expressway after the Wenchuan earthquake showed that typical types of damage included: span collapses due to unseating at expansion joints; shear key failure; and damage of the expansion joint due to the slide-induced large relative displacement between the bottom of the girder and the top of the laminated-rubber bearing. This slide, however, can actually act as a form of isolation for the substructure, and as a result, the piers and foundation of most of the bridges on state route 213 suffered minor damage. The exception was the Baihua Bridge, which suffered severe damage. Corresponding seismic design recommendations are presented based on this investigation.

Keywords: Wenchuan earthquake; bridge damage investigation; seismic design recommendation

1 Introduction

The economic losses caused by the Wenchuan earthquake, which occurred on May 12, 2008, are enormous. Roads and infrastructure in Wenchuan Town near the epicenter were heavily damaged, especially the bridges on National Highway 213 (see Fig. 1) and on the Doujiangyan-Wenchuan expressway. Most bridges on National Highway 213 are girder bridges, either simply supported (including those with continuous bridge deck) or continuous. Laminated-rubber bearings are usually placed directly under the main girder of these bridges. The investigation of the performance of girder bridges on National Highway 213 after the Wenchuan earthquake shows that typical damage includes: span collapse, bearing displacement, shear key failure, destruction of the expansion joint, pounding of adjacent girders, and cracking of abutments. These damage phenomena are similar to those observed in Chi-Chi earthquake in Taiwan (Liu and Chang, 2006).

These types of earthquake damage to bridges on National Highway 213 and the Dujiangyan – Wenchuan expressway are described and discussed in this paper, and corresponding seismic design recommendations are proposed.

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2 Span collapses

2.1 Miaoziping Bridge

The Miaoziping Bridge is a long span-high pier bridge (see Fig. 2) near the Dujiangyan Ziping Dam, located 29 km from Yingxiu town, the epicenter of the Wenchuan earthquake. The main span consists of a continuous rigid frame 1.436 km long, with the highest pier over 108 m. The approach span consists of 50 m×19 spans simply supported girder with a continuous bridge deck. Each span was assembled with 10 pieces of T-shaped girder, weighing 140 t each. When the earthquake occurred, this bridge was not yet ready for traffic, as only the main structure had been completed. Due to the arge relative displacement induced by the earthquake between the girder and the piers, the girder at the expansion joint of the fifth span of the approach bridge fell off, as shown in Fig. 3.

As shown in Figs. 3(b) and 3(c), laminated-rubber bearings were placed on the supporting concrete pads, the seating width between the girder and the pad is about 60 cm, and no longitudinal restrainers were used to prevent unseating. Since there was no connection between the bottom of the girder and the bearing, when the inertial force of the girder became larger than the friction force provided by contact between the girder and the bearing, relative sliding occurred. When the relative displacement became larger than the seating width, the

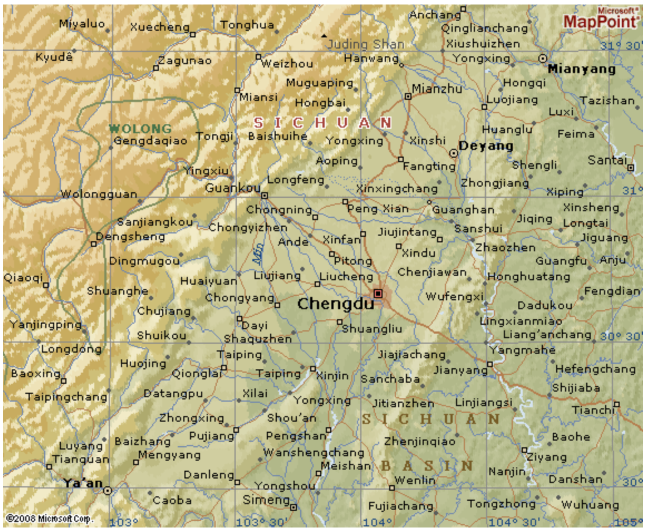


Fig.1 National Highway 213 in Wenchuan earthquake affected area

fifth span of the approach bridge fell off during the earthquake. Figure 3(c) also shows the damage at the supporting concrete pads and the edge of the pier caused by pounding due to collapse of the span.

Other parts of the Miaoziping Bridge also suffered damage due to this earthquake. The damaged shear keys and bearings at the link pier are shown in Fig. 4.

The span collapse of Miaoziping Bridge was mainly due to the large relative displacement between the girder and the pier induced by the earthquake. However, the structural configuration details of the supporting system may also have had some influence on the span collapse. Since the bearings were placed on the supporting concrete pads, the seating widths between the girder and the pad were much less than between the girder and the pier, causing the span to collapse once the displacement of the girder exceeded the seating width between the girder and the pad.

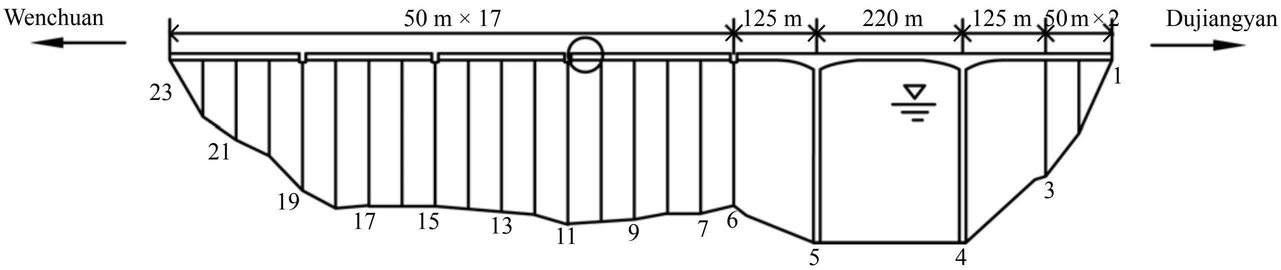
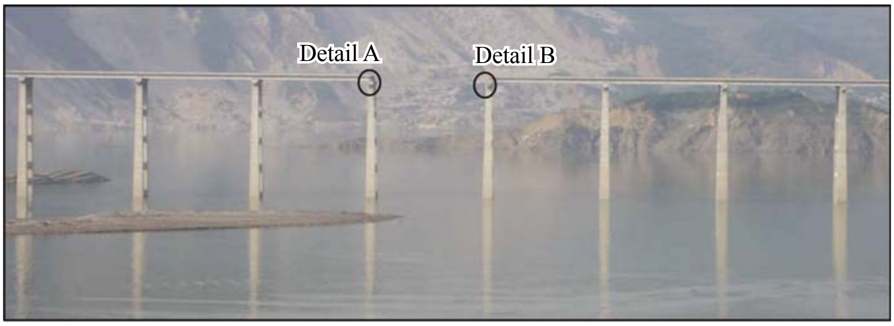


Fig. 2 Miaoziping Bridge



Detail A/detail B

(a) Collapse of the fifth span

(b) Detail A (at expansion joint)

(c) Detail B (at bridge deck)

Fig. 3 Span collapse of the Miaoziping Bridge

(a) Shear key damage

(b) Bearing damage

Fig. 4 Damaged shear keys and bearings at the link pier

2.2 Baihua Bridge

The Baihua Bridge is located at K1009 + 1009 + 691 km on the National Highway 213, at the upper wall of the main central fault (Beichuan-Yingxiu fault), only 2 km from Yingxiu Town. This bridge was constructed in December, 2004; the substructure was designed with the column pier connected by lateral braces. The bridge is 495.55 m long and its highest pier is 30.87 m. The superstructure is composed of 25 m × 4 Reinforced Concrete (RC) continuous spans, 25 m × 5 RC continuous spans, 50 m simply supported T beam, 25 m × 3 RC continuous spans, 20 m × 5 RC continuous spans, and 20 m × 2 RC continuous spans, as shown in Fig. 5. The horizontal line shape of the bridge consists of a 150 m radial curve (left) and a 66 m radial curve (right). The fifth segment, i.e., the 20 m × 5 RC continuous spans, completely collapsed (see Fig. 5). Other piers and joints where the lateral braces meet were also damaged, and large girder displacements and destruction of the expansion joints were observed. Typical damage is shown in Figs. 6 and 7.

The Baihua Bridge is located at N31.044°, E103.475°, 10.6 km from the epicenter, which was located at N31.021°, E103.367°. The direction of the Beichuan-Yingxiu fault is 229°. Obviously, the strong earthquake caused the collapse of the bridge; however, its design and geometrical configuration exacerbated the damage.

Figure 8 shows the plane configuration of the fifth and sixth segments of the Baihua Bridge. The sixth segment consists of 20 m × 2 RC beams, with bilateral sliding bearings on the abutment and a fixed bearing on the 19th pier. The fifth segment consists of 20 m × 5 RC beams with a fixed bearing on the 16th pier, located on a 66 m radial curve. The left end of the fifth segment is supported on the in- span hinge with seat type located 1.73 m from the 18th pier, and the right end is supported by bilateral sliding bearings on the top of the 13th pier. Table 1 shows the heights of each pier of the fifth and sixth girder segments.

As seen in Table 1, the pier placed on the fixed bearing of the fifth segment is nearly three times higher than the sixth segment, which can result in a large difference in stiffness and dynamic characteristics. The out of phase vibration between the fifth segment and the sixth segment caused the large relative displacement at the in-span hinge.

Once the displacement exceeded 60 cm, the end of the girder collapsed; meanwhile, due to a very low ratio of hoop reinforcement in the piers of this bridge (0.048%–0.067%, far less than required by

Fig. 5 Failure of the Baihua Bridge

the specification (1990) and larger than 0.3% at the bottom of the pier), the 17th pier could not handle the added axial force and bending moment caused by the imbalance created when the girder fell, so the entire fifth segment collapsed.

Although the strong earthquake is the main cause of this severe damage, the non-uniform distribution of mass and stiffness, the lack of longitudinal and transverse restrainers to prevent unseating at the in-span hinge, and the low hoop reinforcement ratio also significantly contributed to the damage. AASHTO (2007) has very clear requirements of less than 0.5 for the stiffness ratio of all piers in one segment and 0.7 for any two segments, and requires longitudinal and transverse restrainers to

Fig. 6 Column joint failure

(a) Confinement failure

(b) Shear failure

Fig. 7 Failure at the bottom of a column

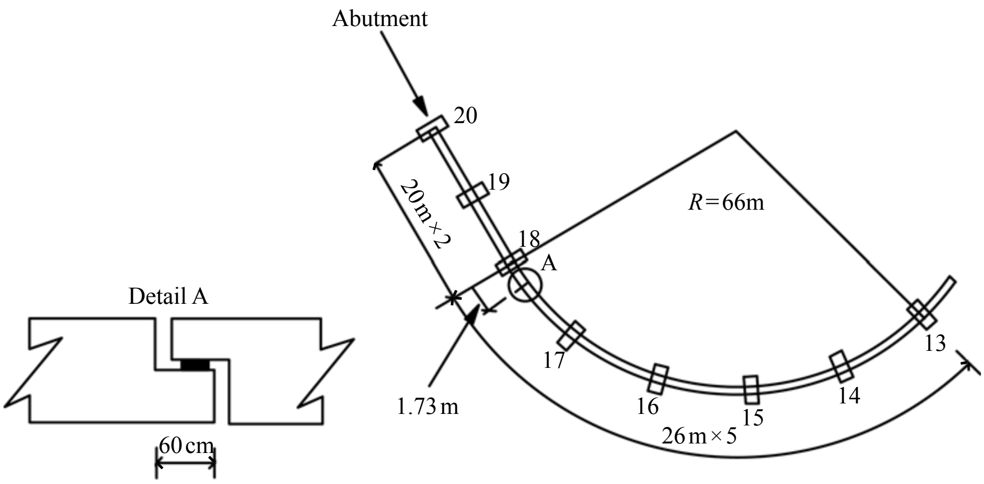


Fig. 8 Plan view of the fifth and sixth segments of the Baihua Bridge

Table 1 Height of piers for the fifth and sixth segments of the Baihua Bridge

Segment	5th						6th	
Pier order	13	14	15	16 (fixed)	17	18	19 (fixed)	20
Height (m)	30.3	29.9	29.7	26.9	22.2	18.1	7.1	abutment

prevent unseating at the in-span hinge. However, these requirements were not considered in the design of the Baihua Bridge.

3 Bearing displacement and girder movement

Laminated rubber bearings are normally used on short to medium bridges in the seismic areas of Wenchuan. The girder is placed directly on the bearings, and no additional connecting components are used. During the earthquake, sliding between the girder and bearings was very common, which caused large displacements of the girders. However, on the other hand, this sliding can actually isolate the seismic response of the superstructure, therefore providing some protection to the piers and the foundation.

3.1 Minjiang Bridge, Yingxiu

The Minjiang Bridge is a skewed prestressed

Fig. 9 Mingjiang Bridge in Yingxiu

(a) Upstream at Wenchuan side

(b) Downstream at Wenchuan side

(c) Exposed bearings (at location A)

(d) Exposed bearings (at location B)

Fig. 10 Girder rotation of the Minjiang Bridge in Yingxiu

continuous RC slab bridge as shown in Fig 9. The skew angle is 80°, which refers to the angle between the longitudinal continuous main slab and the lateral pier cap. During the earthquake, the slab on the Yingxiu side (left side of the figure) moved 0.8 m in the upstream direction, and the slab on the Wenchuan side moved about 2.0 m in the downstream direction. The slab moved totally off the bearings, and the shear key was also damaged (see Fig. 10).

3.2 Shoujiang Bridge

The Shoujiang Bridge, shown in Fig. 11, is a six span prestressed hollow slab bridge, with a span arrangement of 30 m × 3 + 50 m × 3 + 13 m, and is 263.3 m long.

After the earthquake, the left abutment moved laterally, causing lateral and longitudinal displacements of the 30 m span, causing it to be in danger of collapse.

The left and right ends of the T-shaped girder of this span moved 50 cm and 60 cm, respectively, toward the abutment. The T-shaped girder fell off the bearings on the top of pier No. 1 and did not have any support on the right side, and was supported by a length of less than 10 cm in the middle by the pier cap, as shown in Fig. 12.

3.3 Other bridges

The most common damage to bridges caused by the Wenchuan earthquake was sliding between the girder and the bearing and large displacement of the girder, as shown in Fig. 13.

4 Damage to shear keys and expansion joints

Due to the large displacement induced by sliding between the girder and the bearing, most lateral shear keys and expansion joints of the bridges described in this paper suffered some damage. Typical damage is shown in Figs. 14 and 15.

However, damage to the shear key can be beneficial to the pier and foundation. If the shear key was designed to be very strong, the inertial force of the superstructure will be transferred directly to the pier and foundation, causing more damage to the substructure. Of course,

Fig. 11 Shoujiang Bridge

(a) Lateral displacement of girder at abutment

(b) Collapse of the bearing of girder at pier 1

Fig. 12 Girder displacement of the Shoujiang Bridge

(a)

(b)

(c)

(d)

Fig. 13 Sliding between the top of the laminated-rubber bearing and the bottom of the girder

Fig. 14 Typical shear key damage

Fig. 15 Typical expansion joint damage

if the shear key was not strong enough to prevent the girder from falling of the span, the design would not be appropriate. Therefore, finding a method to determine the appropriate stiffness and strength of the shear key in seismically active areas needs further research.

5 Damage to abutments

Typical damage to abutments included cracking of the abutment itself and damage to the back fill and retaining wall, as shown in Fig. 16.

Fig. 16 Abutment damage

6 Conclusions and recommendations

Based on the observations detailed in this paper, typical damage to girder bridges on National Highway 213 from the Wenchuan earthquake are span collapses, sliding between a bearing and girder, shear key failure, destruction of the expansion joint, pounding of adjacent girders, and cracking of abutments. All this damage was caused by sliding between the girder and bearing, which induced large girder displacement, and caused span collapse and damage to the shear key and expansion joints. However, as discussed above, this sliding can actually act as a type of isolation for the substructure. Not much damage was observed to the piers and foundations of the bridges on National Highway 213, except for the Baihua Bridge. In this case, severe damage was not only related to high seismic intensity levels, but also to a highly irregular structural configuration and inappropriate design details, such as a lack of restrainers at the in-span hinge and very low hoop reinforcement ratio in the piers. Based on this investigation, the following recommendations are offered for seismic design of bridges in areas susceptible to strong earthquakes:

(1) Adopt symmetric, regular structural geometrical configurations to have uniform mass and stiffness distribution.

(2) Select appropriate connection types between the superstructure and the substructure. For bridges with high piers, rigid connections at suitable locations are suggested; for bridges with short piers, bearings are suggested to connect the superstructure and substructure using carefully designed seating widths.

(3) For bridges with laminated rubber bearings without connections between the bearing and the girder, the shear key should be designed as a fuse to mitigate the seismic response of the substructure. However for these bridges, it is difficult to design the restrainers and provide adequate seating widths to prevent span collapse, while at the same time mitigating the seismic response of the piers.

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