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Bridge Lessons Learned from the Wenchuan, China, Earthquake

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A strong earthquake of M7.9 occurred in Wenchuan County in Sichuan Province, China, on May 12, 2008. This paper presents the field observations on various types of bridge damages, including unseating of girders, longitudinal and transverse offset of decks, pounding at expansion joints, shear key failure, bearing displacement, column shear, and flexible cracks. Plausible causes of damages and collapses are discussed and the lessons learned from this event are briefly summarized. Some of the postearthquake temporary constructions are also reported.

The M7.9 Wenchuan earthquake occurred at 06:28:01 (UTC) on May 12, 2008, in the Longmen-Shan thrust zone. Its epicenter was located at 30.989° N/103.329° E near a town called Yingxiu in Wenchuan County, Sichuan Province, China. The focal depth of the earthquake was approximately 10 km. The highest recorded peak ground acceleration was 0.65*g* (F. R. Xie, Z. M. Wang, Y. Du, and X. L. Zhang, "Preliminary Observations of the Faulting and Damage Pattern of M8.0 Wenchuan, China, Earthquake," unpublished manuscript). At least 35 aftershocks with magnitudes equal to or greater than M5.0 were recorded within the first 3 months after the main shock with the strongest aftershock of M6.4.

The M7.9 Wenchuan earthquake and several strong aftershocks resulted in massive landslides and rockfalls. These events caused approximately 70,000 fatalities and economic loss of over $110 billion. They damaged more than 1,000 bridges, approximately 20 of which had to be replaced. The severity of bridge damage greatly increased with proximity to the fault, with the worst damage occurring in mountainous terrains. This made the recovery more difficult. Most mountain roads are switchbacks with steep grades over narrow passes with little room for detour. Massive landslides covered or undermined the roads, making it difficult to bring in equipment and supplies.

SURFACE RUPTURE NEAR EPICENTER

The Longmen-Shan thrust zone was formed by the Eastern Tibetan Plateau pushing against the Sichuan Basin (*1*). The thrust zone has three faults: the front fault (Guanxian–Jiangyu–Guangyuan), the center fault (Yingxiu–Beichuan–Chaba–Linjueshi), and the back fault (Wenchuan–Maoxian–Qingchuan). On the basis of the distribution of aftershocks, approximately 300 km of the faults were estimated to have ruptured, breaking the ground surface along the Yingxiu–Beichuan segment of the center fault (210 km) and the Guanxia–Jiangyu segment of the front fault (70 km). According to Xie et al. (F. R. Xie, Z. M. Wang, Y. Du, and X. L. Zhang, "Preliminary Observations of the Faulting and Damage Pattern of M8.0 Wenchuan, China, Earthquake," unpublished manuscript), the vertical fault displacements measured were more than 5 m.

The surface rupture of the center fault in the Longmen–Shan thrust zone was observed in Yingxiu as illustrated in Figure 1. The thrust fault appeared to cross the Ming River at a right angle. As shown in Figure 1, the earthquake left behind a distinct dislocation on the river bed. The northwest (NW) side of the fault on the upstream of the river moves upward against the southeast (SE) side of the fault. The fact that one deck panel along the new expressway elevated bridge was still supported by one pier in Figure 1 indicated a sudden push by a near-field pulsing effect. On the other side of the Ming River was the old Dujiangyan–Wenchuan highway. Because of surface rupture, the vertical dislocation of the old highway was approximately 1.5 m, as illustrated in Figure 1.

Figure 1 also shows that the bridge in parallel with the fault line suffered damage in one side span only due to landslides. The significant difference in damage pattern between the two elevated structures at right angle suggests a strong directivity effect. The bridge perpendicular to the fault line experienced substantial motion in a longitudinal direction due to the thrust fault movement, dropping off all spans.

OBSERVED DAMAGE TO BRIDGES

Although the performance of many bridges was evaluated in the field, only the three most severely damaged and collapsed bridges are discussed.

Bridges in Nanba Town

Three bridges crossed a river (the river's name was not known) near Nanba Town as shown in Figure 2. The west structure was a

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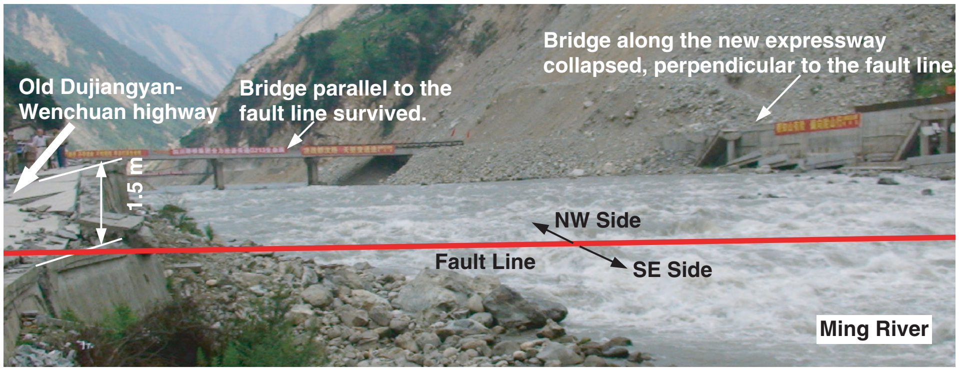


FIGURE 1 Surface rupture near Yingxiu Town.

concrete and masonry three-span arch bridge built in the 1970s. The old arch bridge collapsed during the earthquake as shown in Figure 3. Immediately downstream of the arch bridge was a 10-span river crossing (on a 10° skew) that was under construction during the earthquake, as shown in Figure 3. Each 6-m-long span was simply supported on two-column bents and seat-type abutments with 560 mm seats. As shown in Figure 4, each span consisted of eight precast box girders with a cross section of 1,067 mm by 1,520 mm. Each girder was supported on two 200-mm round elastomeric bearings at each end. At the time of the earthquake, the girders were in place but the concrete deck had not yet been poured, as seen from Figure 4.

As shown in Figures 3 and 4, most of the box girders of the new bridge dropped into the river and the two-column bents were distorted. The end box girders were transversely displaced by approximately 760 mm. Most of the shear keys were cracked or knocked off. Many of the bents were leaning or distorted, but with no damage visible above the waterline. At the time of the earthquake, the bridge deck had not been poured, and the slightly skewed girders were loose and not tied together into a bridge superstructure as a system. In addition to strong shaking at the site, these factors contributed to the collapse of the 10-span bridge.

There was no indication that the 10-span bridge suffered any damage due to a fault crossing. As such, the three-span arch bridge must have been damaged by ground shaking, perhaps exacerbated by soil movement. Liquefaction, lateral spreading, or other soil movement may also have been responsible for the distortion of the two-column bents. The reconnaissance team was not able to discern what type of foundation system supported the bents, but apparently they were not sufficiently embedded into good material.

On the east side of the old and new bridges is a temporary structure that was being constructed by launching Bailey bridges onto new reinforced concrete (RC) pier walls at the time of field reconnaissance. As shown in Figure 5, vehicles were driving across the river on fill materials laid over culverts in the meantime.

Miaozhiping Bridge

Miaozhiping Highway from Dujiangyan to Wenchuan was under construction during the earthquake. It consists of a tunnel at Zhipingpu and a bridge over the Ming River as schematically shown in Figure 6. The tunnel, shown in Figure 7, experienced little damage during the earthquake. The highway was scheduled to open in October 2008. Near the highway is the well-known Dujiangyan Dam. The bridge of approximately 1.4 km consists of three parts: a main span and two approach spans as shown in Figures 6 and 8.

As shown in Figure 6, the approach spans near the tunnel consist of a two-span, RC girder structure with 50-m span length each. The bridge deck is supported on five RC girders and two-column bents with several cross-struts. The bridge deck is continuous but its supporting girders are simply supported on the bents. As shown in Figure 6, the main bridge is a continuous, nonprismatic, three-span structure supported on two intermediate wall piers with a length of

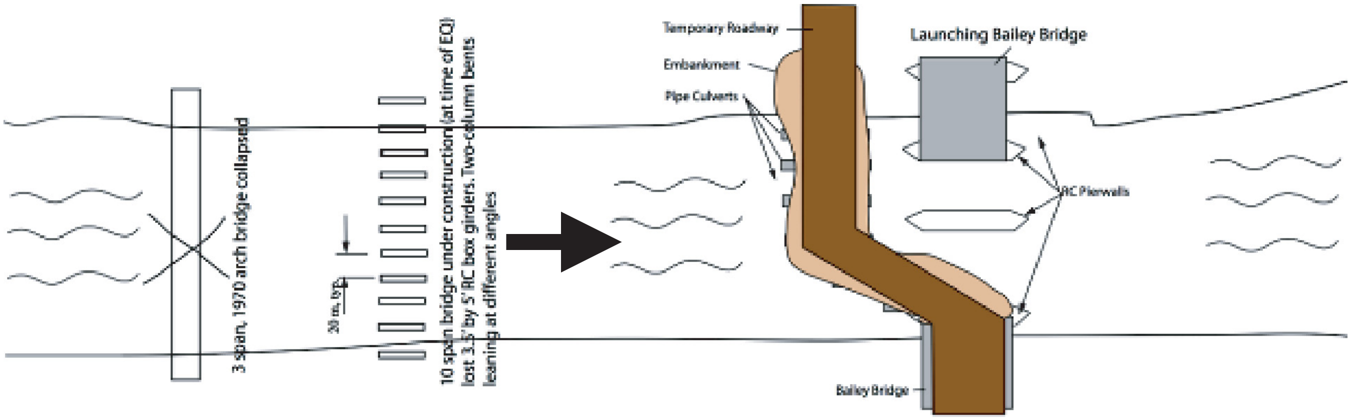


FIGURE 2 Three bridges at Nanba Town.

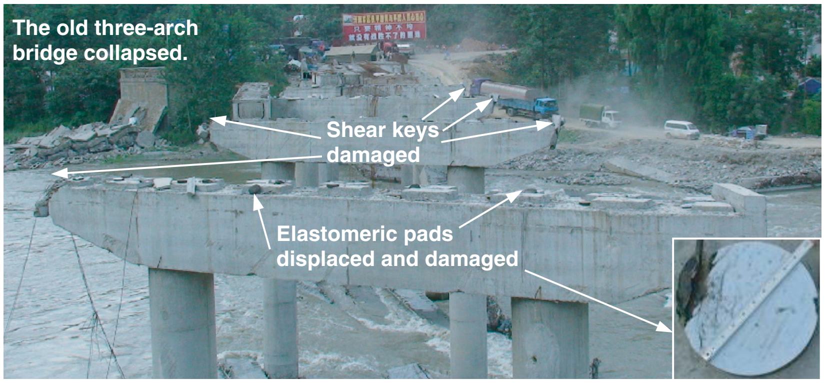


FIGURE 3 Collapse of old arch bridge and 10-span bridge.

FIGURE 4 Damage to 10-span bridge under construction.

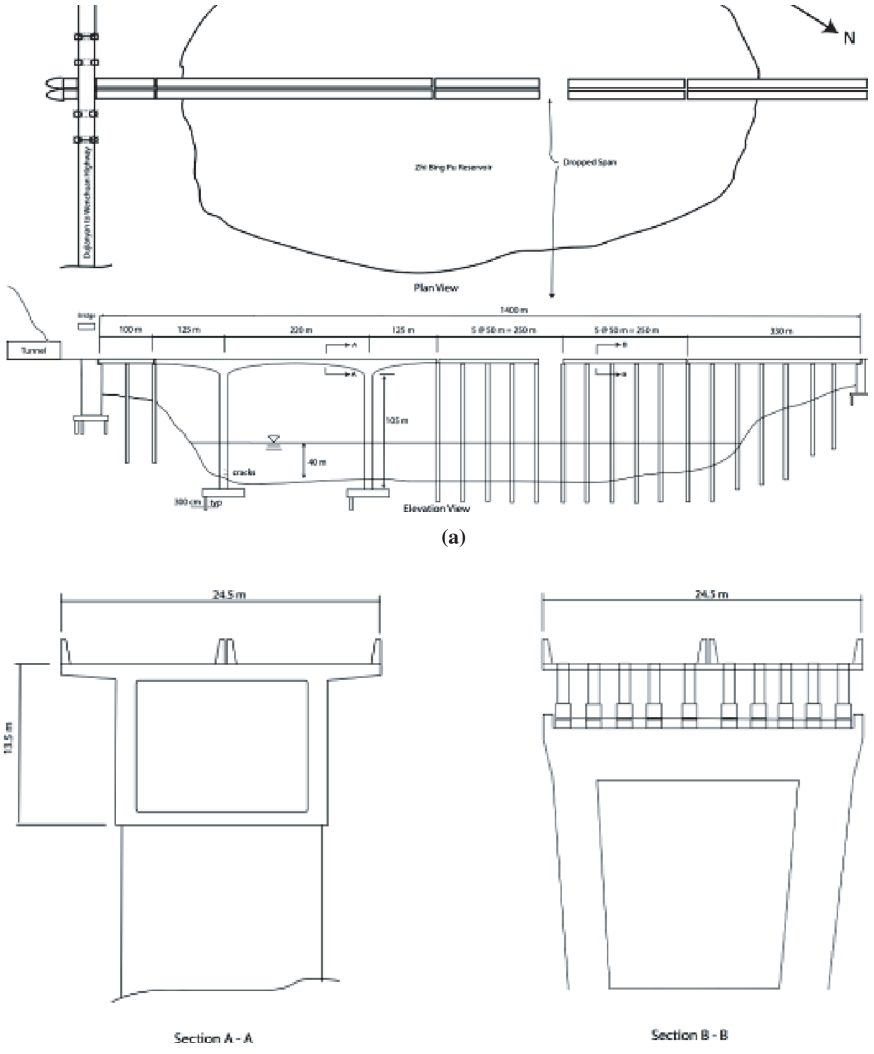
125 m, 220 m, and 125 m, respectively. The superstructure is a single-cell box girder structure. The depth of girders varies to a maximum depth of 4.0 to 4.5 m.

The approach bridge on the other side of the main span has three parts of 250 m, 250 m, and 100 m, respectively. The first part has five spans of 50 m long, supporting 10 RC girders. All girders are simply supported on the bents for dead load but the bridge deck is continuous for live load. The bents are as tall as 105 m. In some locations, they are 40 m deep into water in the Zidingdu reservoir of the Dujiangyan Dam in the main span of the bridge. Expansion joints are present between the parts and between the approach and main bridge.

FIGURE 5 Construction of a temporary bridge.

The construction of the bridge was near completion except for the installation of expansion joints at the time of the earthquake. The most severe damage was to the end span of a five-span T-girder segment that became unseated at the expansion joint end as illustrated in Figure 9, fractured in the continuous deck at the other end due to gravity load, and fell off the supporting bent caps during the earthquake. The bent seats were approximately 300 mm in length but the bridge experienced at least 500 mm of longitudinal movement due to earthquake shaking. Since the columns of each bent are approximately 105 m tall, the accumulated displacement at the bent cap was likely significant during the earthquake. There were other indications of large longitudinal movement. As shown in Figure 10, the barrier rails were overlapped by about 300 mm at the southeast expansion joint. The barrier also moved transversely for approximately 250 mm. Divers found cracks at the bottom of the main span columns due to earthquake shaking. Shear key failure was also observed as shown in Figure 8. After the earthquake, the bridge deck was jacked back into place with hydraulic jacks.

The end of the Miaozhiping Bridge near the tunnel is divided into two parallel elevated structures to guide traffic in both directions in



(a)

(b)

FIGURE 6 **Schematic view of the Miaozhiping Bridge: (*a*) plan and elevation and (*b*) cross section of main span and approach bridge.**

alignment with the twin tunnels as indicated in Figure 7. Over the southeast approach is a four-span RC girder overpass built in 2004. The overpass supports the old highway from Dujiangyan to Wenchuan and Juzhaigou. The old highway was built along the mountain terrain, perpendicular to the Zhipingpu Highway at Zhipingpu Town. The bridge showed shear key failures and embankment cracking, as seen in Figure 11. In the vicinity of Miaozhiping Bridge there are several RC girder bridges, as shown in Figure 12. These bridges appeared to suffer little damage. No weight limits were posted on these bridges.

FIGURE 7 **Miaozhiping Tunnel.**

Baihua Bridge

Baihua Bridge is part of a Class 2 highway from Dujiangyan to Wenchuan. It was built in 2004 by the owner of a nearby hydroelectric plant to bring in workers. As schematically shown in Figure 13, the bridge is an 18-span, RC structure with a total length of 450 m. The bridge superstructure was supported on two-column bents of varying heights as it climbs over the hilly terrain. The tallest bents have one or two struts to provide transverse restraint between the columns. The bridge has both straight and curved spans. For convenience, the bridge structure can be divided into six sections as summarized in Table 1. The superstructure was a prestressed box girder with a drop-in T-girder span between Bent 9 and Bent 10. There were expansion joints at Bents 2, 6, 9, 10, 14, 18, and at the two seat-type

FIGURE 8 Overview of Miaozhiping Bridge.

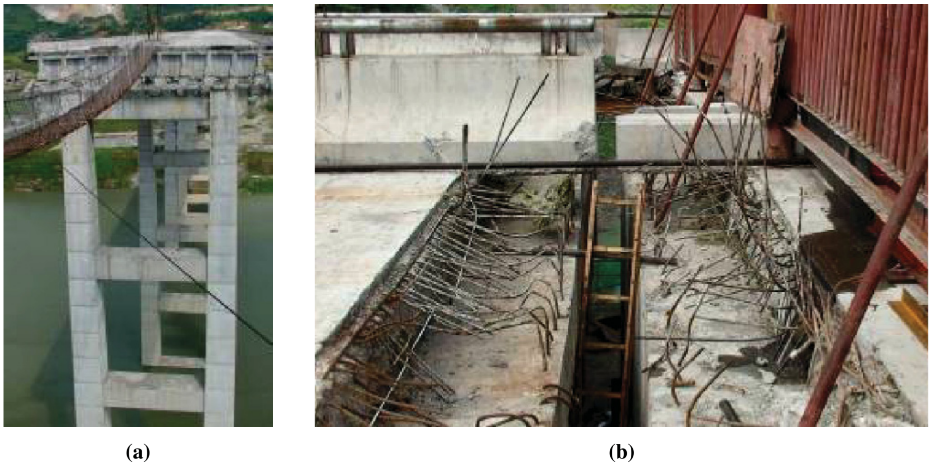

(a) (b)

FIGURE 9 Dropped-off span and construction details between two spans.

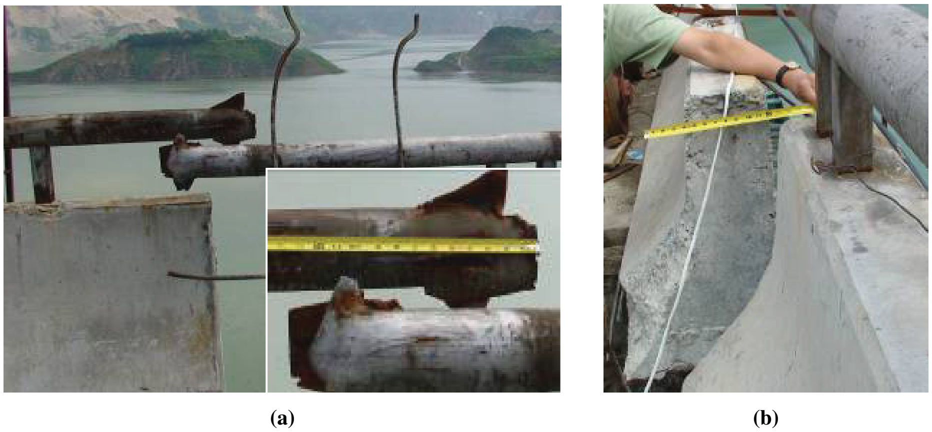

(a) (b)

FIGURE 10 Longitudinal and transverse offset of bridge deck.


(a) (b)

FIGURE 11 Damage to shear key and embankment of the overpass.


(a)

(b)

FIGURE 12 Bridges in the vicinity of Miaozhiping Bridge.

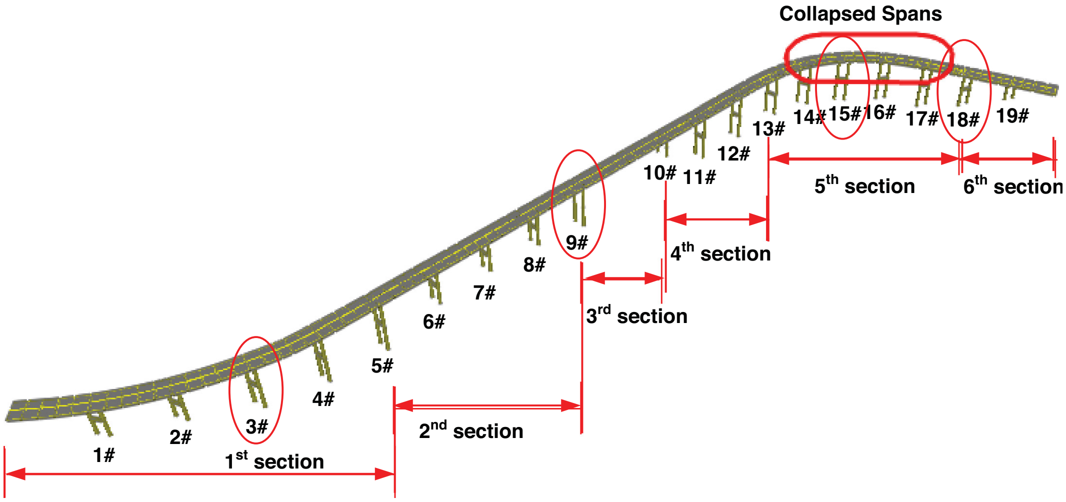


FIGURE 13 Schematic view of the Baihua Bridge before earthquake.

abutments. For the drop-in span, the bridge deck just rested on the bent cap at both ends.

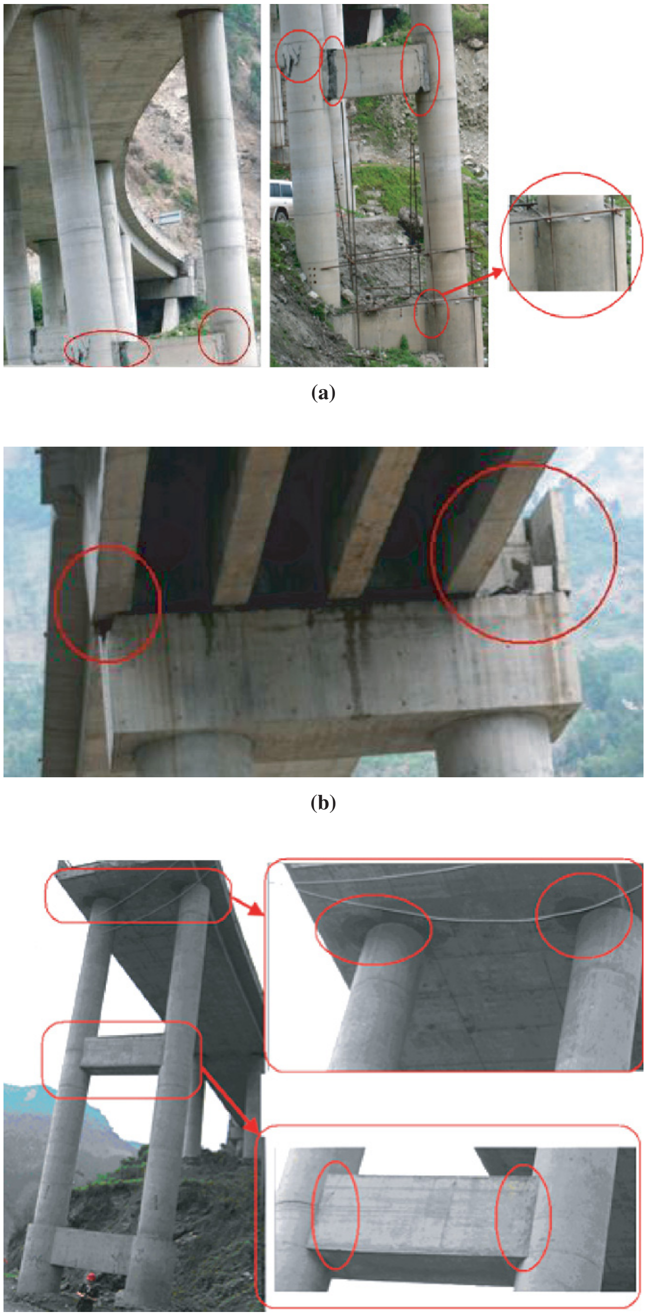
During the earthquake, the more highly curved section of the bridge collapsed, as illustrated in Figure 14. The rest of the bridge suffered varying degrees of damage, including shear cracks and failure at columns and struts and shear and key failure, as shown in Figures 15*a* to 15*c* for Bents 3, 9, and 18, respectively. At Bent 3, typical damage occurred between the strut and columns in the form of spalling and cracks. At Bent 9 with expansion joints, the superstructure had significant transverse displacement, knocking off the shear key. At Bent 15, the bridge section was collapsed, likely resulting from a combined effect of large deformation in tall columns and the presence of the expansion joint at Bent 14 and the in-span hinge near Bent 18. As illustrated in Figure 14, the full-width cracks in the superstructure at Bents 15 and 17 support the suggested collapse mechanism. At Bent 18, in addition to cracks between column and strut, significant spalling occurred underneath the bridge deck.

At the curved part of the bridge, the bridge is likely subjected to higher deformation and stress under the earthquake, resulting in collapse. Even for the straight part of the bridge, because of tall columns,

TABLE 1 Parameters of Baihua Bridge

Section	No. of Spans	Span Length (m)	Section Length (m)
1	5	25	125
2	4	25	100
3	1	50	50
4	3	25	75
5	5	20	100
6	2	25	50

FIGURE 14 Postearthquake damage. (Source: CNS.)


(a)

(b)

(c)

FIGURE 15 Damage at various bents: (*a*) Bent 3, (*b*) Bent 9, and (*c*) Bent 18.

the damage in various sections under the earthquake results in tilting of the columns that would push the superstructure almost off its support at several locations.

The Baihua Bridge could have been damaged by surface faulting, though there is no clear surface fault feature that the reconnaissance team has found near the bridge site. Considering the complex vibration system of the irregular structure with varying column heights and lack of continuity between the substructure and superstructure, severe shaking alone could result in collapse. Still, the bridge is very close to the fault, and several photos (taken by Kehai Wang immediately after the earthquake) show what looks to be a surface fault under the bridge (*2*).

LESSONS LEARNED FROM POSTEARTHQUAKE RECONNAISSANCE

The bridge damage observed during the May 12, 2008, Wenchuan earthquake is reminiscent of what California suffered during the February 9, 1971, San Fernando earthquake. The United States in the 1960s and 1970s was expanding its highway network similar to China's efforts today. Before the San Fernando earthquake, the California Department of Transportation's (Caltrans') maximum seismic coefficient was 0.10*g,* similar to China's current maximum seismic coefficient of 0.10*g.* After the San Fernando earthquake, Caltrans greatly increased the seismic hazard used to design California's bridges. Similarly, Japan increased the hazard for its bridges following the 1995 Kobe earthquake. It is hoped that this earthquake will have the same significance for China's bridge engineers and the expectation for seismic hazard near known faults will be greatly increased. Furthermore, the bridges studied had few seismic details, such as long seats, large shear keys, or tightly spaced transverse reinforcement. These details would greatly reduce bridge damage during earthquakes. The various fault traces through the region need to be carefully identified and bridges should be designed for the seismic hazards at the bridge site, based on a low probability of the hazard being exceeded during the life of the bridge. This would ensure that China could rely on its highway infrastructure during the frequent earthquakes that strike this and other regions.

Based on the field reconnaissance, the following observations can be made:

- The collapse of most arch and girder bridges is associated with surface rupturing of the faults in the Longmen-Shan thrust zone because of near-field fling effects. A significant portion of roadways and bridges were pushed away or buried by overwhelming landslides in the mountainous terrain of steep slopes.
- The representative damage types in bridge superstructure include unseating of girders, longitudinal and transverse offset of decks, and shear key failure.
- The bearings of several girder bridges were either crushed or displaced significantly.
- The substructure and foundation of bridges were subjected to shear and flexural cracks, concrete spalling, stirrup rupture, excessive displacement, and loss of stability.
- More damage occurred in simply supported bridges in comparison with continuous spans. The curved bridges either collapsed or suffered more severe damage.
- The directivity effects on the bridges near the earthquake epicenter were evidenced during the earthquake.

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