The Lessons Learned from Wunchuan Earthquake on Highway Bridges

by

W. Phillip Yen[1], Genda Chen[2], Mark Yashinski[3],

ABSTRACT

A strong earthquake of M7.9 occurred in the Wenchuan County in Sichuan Province, China, on May 12, 2008. Shortly after the earthquake, the Turner-Fairbank Highway Research Center of Federal Highway Administration led a reconnaissance team, partnering with Chinese counterpart, the Research Institute of Highway from the Ministry of Communication of China, to conduct a post-earthquake bridge performance investigation in the earthquake affected areas of transportation system. The U.S. transportation system reconnaissance team visited the earthquake affected areas on July 20 – 24, 2008. This report is a briefing of the findings and lessons that the team learnt from the earthquake event.

KEYWORDS: bridge engineering, earthquake engineering, post earthquake investigations.

1.0 INTRODUCTION

A team of five U.S. engineers was invited by the Ministry of Communication of China to study bridge damage from the M7.9 (M8.0 according to China Earthquake Administration or CEA) Wenchuan earthquake of May 12, 2008. The team included Dr. Phillip W. Yen (Team Leader) from the Turner-Fairbank Highway Research Center of Federal Highway Administration (FWHA), Mr. Mark Yashinsky from the California Department of Transportation representing the Earthquake Engineering Research Institute (EERI), Dr. Genda Chen from the Center for Transportation Infrastructure and Safety (CTIS), a national University Transportation Center at Missouri University of Science and Technology, Dr. Youssef Hashash from Geo-Engineering Earthquake Reconnaissance (GEER), and Mr. Curtis Holub from the Mid-America Earthquake Center (MAE). The reconnaissance team was hosted by Dr. Kehai Wang of the Research Institute of Highway from the Ministry of Communication of China and Mr. Xiaodong Guo of the Sichuan Province Highway Planning, Survey, Design, and Research Institute.

2.0 EARTHQUAKE AND SURFACE RUPTURE

The May 12, 2008, Wenchuan Earthquake:

The M7.9 Wenchuan earthquake occurred at 06:28:01 (UTC) on May 12, 2008 in the Longmen-Shan thrust zone. Its epicenter is located at 30.989° N /103.329° E near a town called Yingxiu in Wenchuan County, Sichuan Province. The focal depth of the earthquake is approximately 10 km. The highest recorded peak ground acceleration is 0.65g (Xie et al., 2008). At least 35 aftershocks with magnitudes equal to or greater than M5.0 were recorded within the first three months after the main shock with the strongest aftershock of M6.4 (M6.5 according to CEA). This region has continually experienced large earthquakes as indicated in Table 1 & Figure 2. The largest earthquake over M7.0 prior to the Wenchuan earthquake occurred in 1973.

The Longmen-Shan thrust zone was formed by the Eastern Tibetan Plateau pushing against the Sichuan Basin (Burchfiel et al., 2008). The thrust zone has three faults: the front fault (Guanxian-Jiangyu-Guangyuan), the center fault (Yingxiu-Beichuan-Chaba-Linjueshi), and the back fault

1 Seismic Research program Manager, Turner-Fairbank Highway Research Center of Federal Highway Administration (FWHA)
2 Professor, the Center for Transportation Infrastructure and Safety (CTIS), a national University Transportation Center at Missouri University of Science and Technology
3 Senior Bridge Engineer, California Department of Transportation representing the Earthquake Engineering Research Institute (EERI)

(Wenchuan-Maoxian-Qingchuan). Based on the distribution of aftershocks, approximately 300 km of the faults was 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. (2008), the vertical fault displacements measured were over 5 m.

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 $110B. 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 rooms for detour. Massive landslides covered or undermined the roads, making it difficult to bring in equipment and supplies.

2.1 Surface Feature of Fault Rupture at the Earthquake Epicenter

The epicenter of the May 12 Wenchuan earthquake is located near Yingxiu in Wenchuan County, Sichuan Province. The surface rupture of the center fault in the Longmen-Shan fault zone was observed in Yingxiu as illustrated in Figure 5. The thrust fault appeared to cross the Ming River in right angle. As shown in Figure 5, the earthquake left behind a distinct dislocation on the river bed at the northeast (NE) end of the surface rupture. 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 expressway elevated bridge was still supported by one pier in Figure 3 indicated the sudden push by a near-field pulsing effect.

On the other side of the Ming River was a five-story building with a construction joint between two similar parts. The right side of the building as shown in Figure 5 was completely collapsed while the left side of the building only lost the second story and suffered structural damage in walls. A sudden change was also evidenced as shown in Figure 5 on the slope of the mountain behind the building. A closer look at the old Dujiangyan-Wenchuan highway in front of the building indicated that the vertical dislocation is approximately 1.5 m as illustrated in Figure 4.

3.0 OBSERVED BRIDGE DAMAGES

Although many bridges performance were inspected, only the three most severely damaged and collapsed bridges are discussed due to the limitation of the paper size. More discussions on other bridges will be published soon.

3.1 Bridges in Nanba Town

Three bridges crossed a river (river's name was not known) near Nanba Town as shown in Figure 5. The west structure was a concrete and masonry three-span arch bridge built in the 1970s. The old arch bridge completely collapsed during the earthquake as shown in Figure 6. 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 7. Each 6 m long span was simply supported on two-column bents and seat-type abutments with 560 mm seats. As shown in Figure 8, each span consisted of eight precast box girders with a cross section of 1067 mm by 1520 mm. Each girder was supported on two 200 mm round elastomeric bearings at each end. The girders were in place but the concrete deck had not yet been poured at the time of the earthquake as seen from Figure 5.

As shown in Figures 7 and 8, 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. The deck hadn't been poured, there wasn't any real transverse bracing or shear keys, and girders were on a slight skew, all of which contributed to the damage. Also, many of the bents were leaning or distorted, but with no damage visible above the waterline.

There was no indication that the ten-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 have been also responsible for the distortion of the two column bents. The reconnaissance team was not able to discern what type of foundation system the bents were supported on, 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 RC pier walls at the time of field reconnaissance. As shown in Figure 9, vehicles were driving across the river on fill material laid over culverts in the meantime.

3.2 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 10. The Tunnel is shown in Figure 11 and 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 long consists of three parts: a main span and two approach spans as shown in Figure 12.

As shown in Figure 13, the approach span near the tunnel is 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. As indicated in Figure 13, the bridge deck is continuous but the girders are simply supported on the bents. The main bridge is a continuous, non-prismatic, three-span structure supported on two intermediate wall piers with 125 m, 220m, and 125m length, respectively. The superstructure is a single-cell box girder structure. The depth of girders varies to a maximum depth of 4.0 ~ 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. Any of the first three parts has five spans of 50 m long, supporting ten 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 used between the parts and between the approach and main 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, 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. The barrier rails were overlapped by about 300 mm at the southeast expansion joint. The barrier also displaced 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 50. 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 in order to guide two ways of traffic in alignment with the twin tunnels as indicated in Figure 16. Over the southeast approach is a four-span RC girder bridge built in 2004. The bridge 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 shown in Figure 17.

In the vicinity of Miaozhiping Bridge there are several RC girder bridges as shown in Figure 18.

These bridges appeared to suffer little damage. No weight limits were posted on these bridges.

3.2 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 19, 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 curve spans. For convenience, the bridge structure can be divided into six sections as summarized in Table 2. 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, and at the two seat-type abutments. For the drop-in span, the bridge deck just rested on the bent cap at its both ends.

During the earthquake, the more highly curved section of the bridge completely collapsed as illustrated in Figure 20. The rest of the bridge suffered varying degrees of damage, including shear cracks and failure at columns and struts, shear key failure, and bearing failure as shown in Figures 21-24 for Bents 3, 9, 15, 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 completely collapsed due likely to the shear and flexural failure of columns. At Bent 18, in addition to cracks between column and strut, significant spalling occurred underneath the bridge deck.

At the curve 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, due to tall columns, the damage in various sections under the earthquake results in tilting of the columns that would push the superstructure almost off their support at several locations. A detour had been graded along the side of the damaged bridge. Considering the high risk of a further collapse during an aftershock, endangering people using the detour, the rest of the bridge was demolished with dynamite as illustrated in Figure 25.

Similar to the previously described Xiaoyudong Bridge, this bridge could have been damaged by surface faulting though there is no clear surface fault feature that the reconnaissance team has ever 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 immediately after the earthquake) show what looks to be a surface fault under the bridge. During the field reconnaissance after nearly three months later, all signs of the fault were gone and the bridge was lying on the ground.

4.0 LEASSONS LEARNED FROM EARTHQUAKE RECONNAISSANCE

The bridge damage observed during the May 12, 2008, Wenchuan Earthquake reminded us of what California suffered during the February 9, 1971 San Fernando Earthquake. The U.S. in the 1960's and 1970's was expanding their highway network similar to China's efforts today. Before the San Fernando earthquake, Caltrans' maximum seismic coefficient was 0.10g, similar to China's current maximum seismic coefficient of 0.10g. After the San Fernando earthquake, Caltrans greatly increased the seismic hazard used to design California's bridges, similar to how 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 seismic hazard for areas near known faults will be greatly increased. Also, the bridges we 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 future 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.

4.1 Based on the field reconnaissance, the following are the observations:

- The collapse of most arch and girder bridges is associated with surface rupturing of the faults in the Longmen-Shan Thrust Zone. 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, pounding at expansion joints, 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 curve bridges either collapsed or suffered more severe damage.
- The directivity effects on the bridges near the earthquake epicenter were evidenced during the earthquake.

5.0 REFERENCES

Burchfiel, B.C., L.H. Royden, R.D. van der Hilst, B.H. Hager, Z. Chen, R.W. King, C. Li, J. Lü, H. Yao, and E. Kirby, 2008, A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China, GSA Today, 18, p. 4-11.

Stone, R., 2008, Landslides, flooding poses threats as experts survey quake's impact, Science, 320, p. 996-997.

Wang, Z. M., 2008, "May 12, 2008, Sichuan China Earthquake Reconnaissance." Presentation posted at http://www.uky.edu/KGS/geologichazards/Sichuan_Earthquake.pdf, Kentucky Geological Survey, 228 MMRB, University of Kentucky, Lexington, KY 40506, zmwang@uky.edu .

Xie, F.R., Z. M. Wang, Y. Du, and X.L. Zhang, 2008, Preliminary observations of the faulting and damage pattern of M8.0 Wenchuan, China, earthquake, submitted to a journal for possible publication.

Table 1: Longmen-Shan Significant Earthquake M≥7.0

Year	Month	Day	Time	Latitude	Longitude	Depth	Magnitude
1917	07	30	2354	29.000	104.000	0	7.3
1923	03	24	1240	30.553	101.258	25	7.2
1933	08	25	0750	31.810	103.541	25	7.3
1947	03	17	0819	33.000	99.500	0	7.5
1948	05	25	0711	29.500	100.500	0	7.2
1950	08	15	1409	28.500	96.500	0	8.6
1955	04	14	0129	29.981	101.613	10	7.5
1967	08	30	0422	31.631	100.232	8.1	7.0
1973	02	06	1037	31.361	100.504	6.6	7.4

Table 2: Parameters of the Baihua Bridge

Section	No. of Span	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

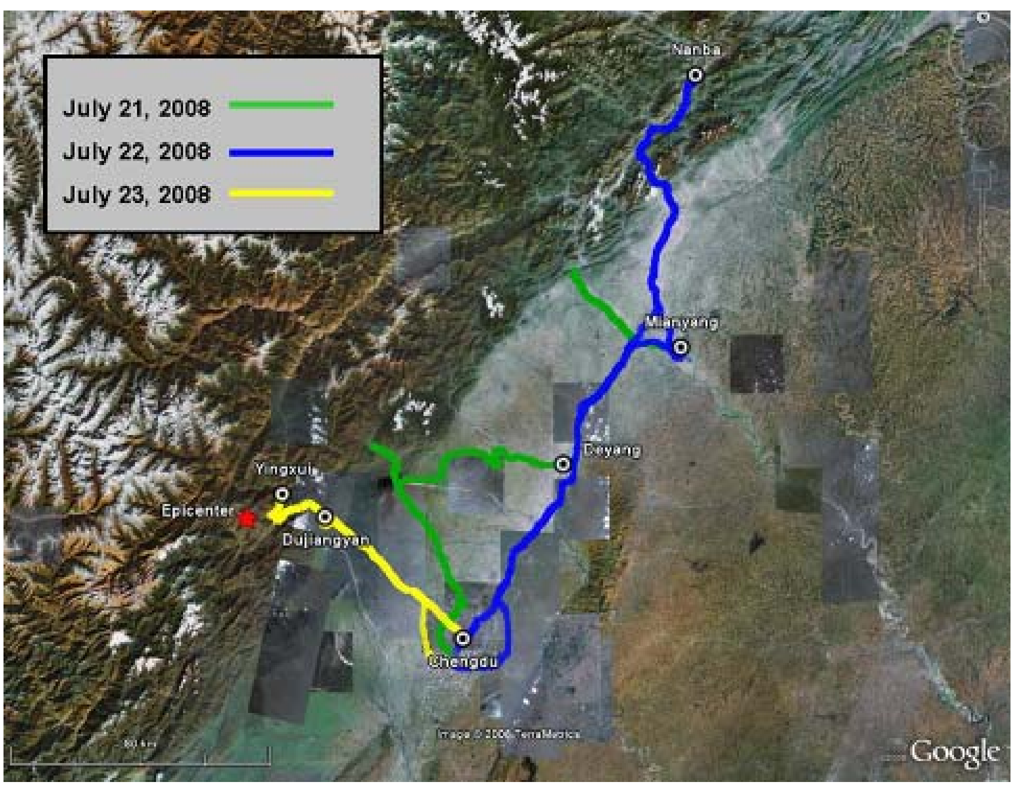


Figure 1: Bridge Sites Investigated by Reconnaissance Team

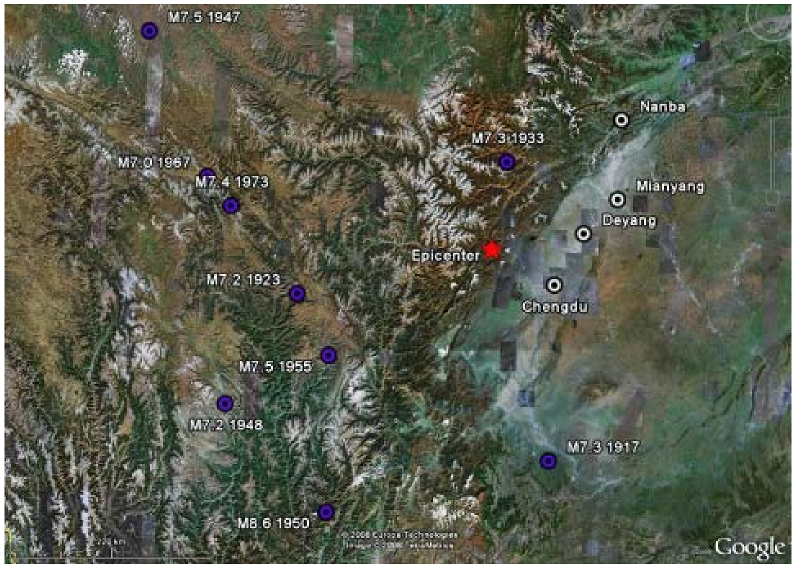


Figure 2: Historical Earthquake Activity

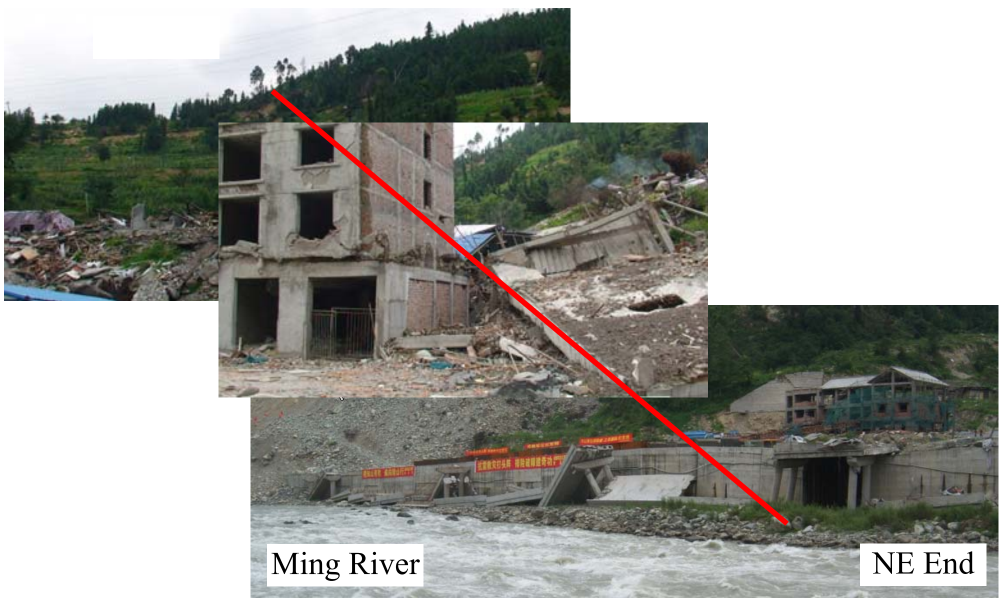


Figure 3: Surface Rupture of the Earthquake Fault

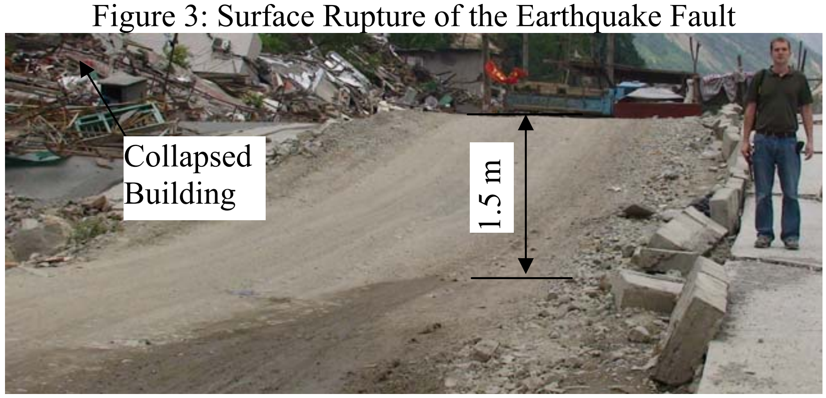


Figure 4: Surface Rupture along the Old Highway near the Collapsed Building

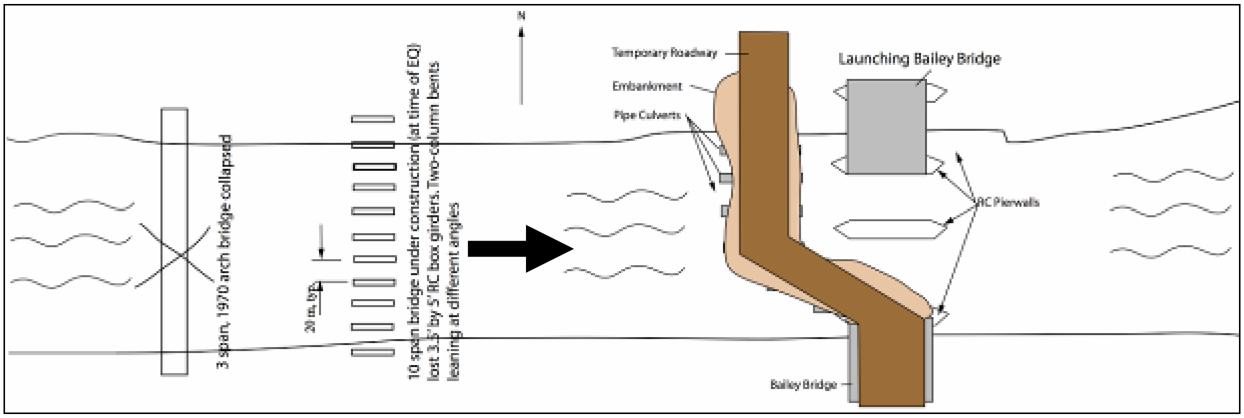


Figure 5: Three Bridges at Nanba Town

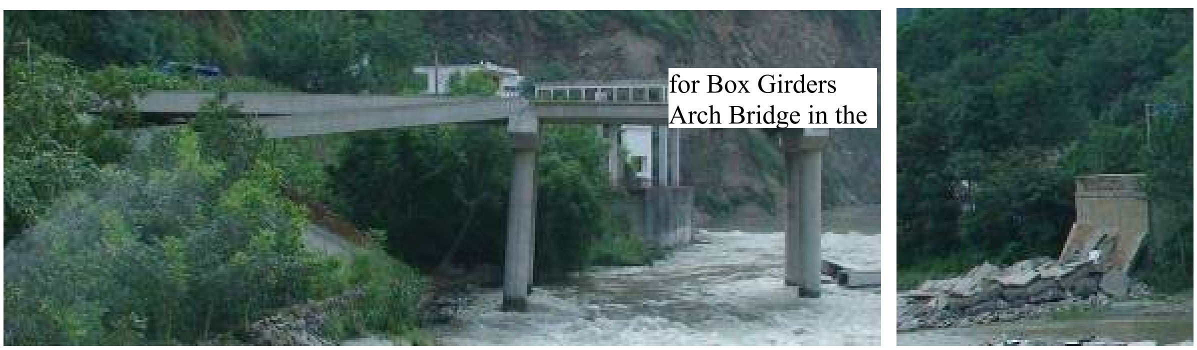


Figure 6: Collapse of the Old Three-Arch Bridge

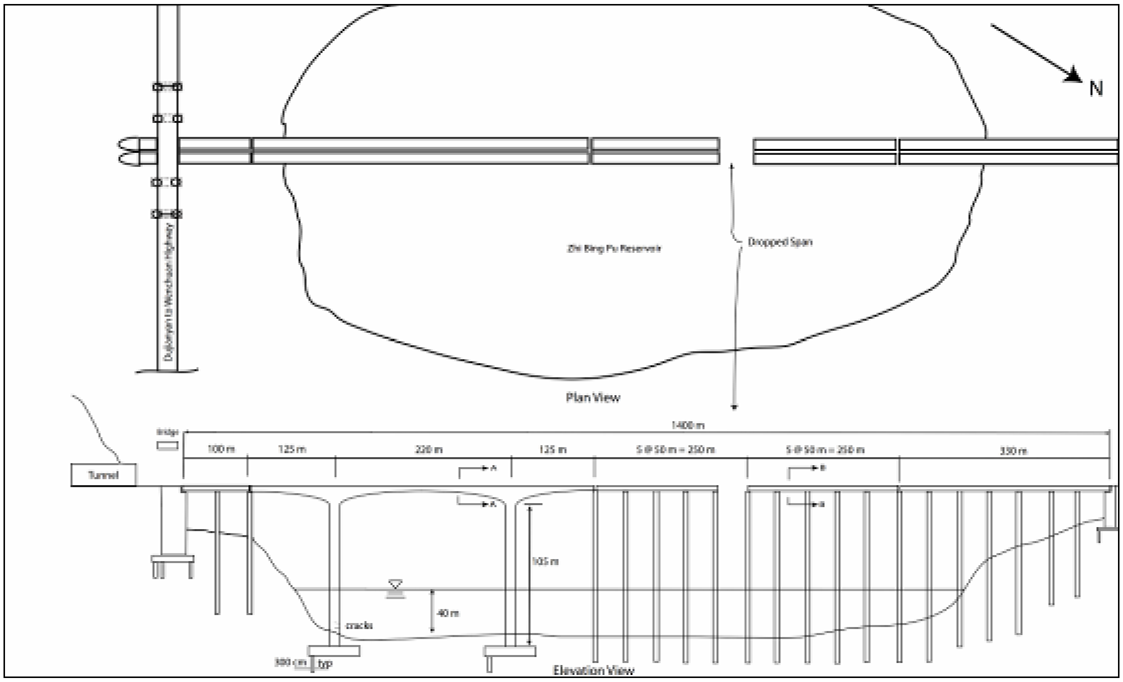
Figure 7: Damage Scenario of the 10-span Bridge under Construction during the Earthquake

Figure 8: Damage to the 10-Span Bridge under Construction

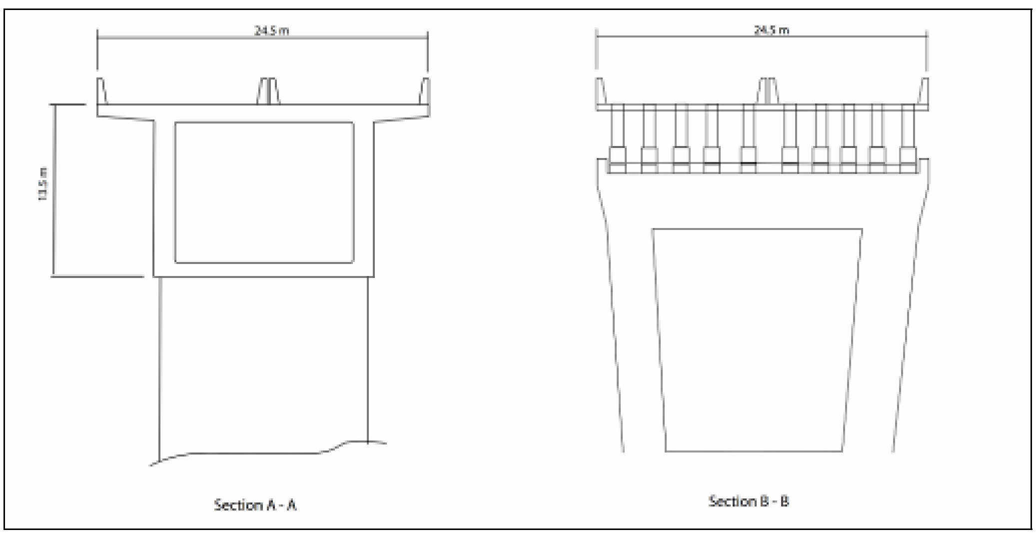
(a) Overview of a Temporary Bridge Construction

(b) Bailey Bridge Pushed in Place

Figure 9: Construction of a Temporary Bridge



(a) Plan and Elevation



(b) Cross Section of Main Span and Approach Bridge

Figure 10: Schematic View of the Miaozhiping Bridge

Figure 11: Miaozhiping Tunnel

Figure 12: Overview of the Miaozhiping Bridge

Figure 13: Drop-off Span and Construction Details between Two Spans

Figure 14: Longitudinal and Transverse Offset of Bridge Deck

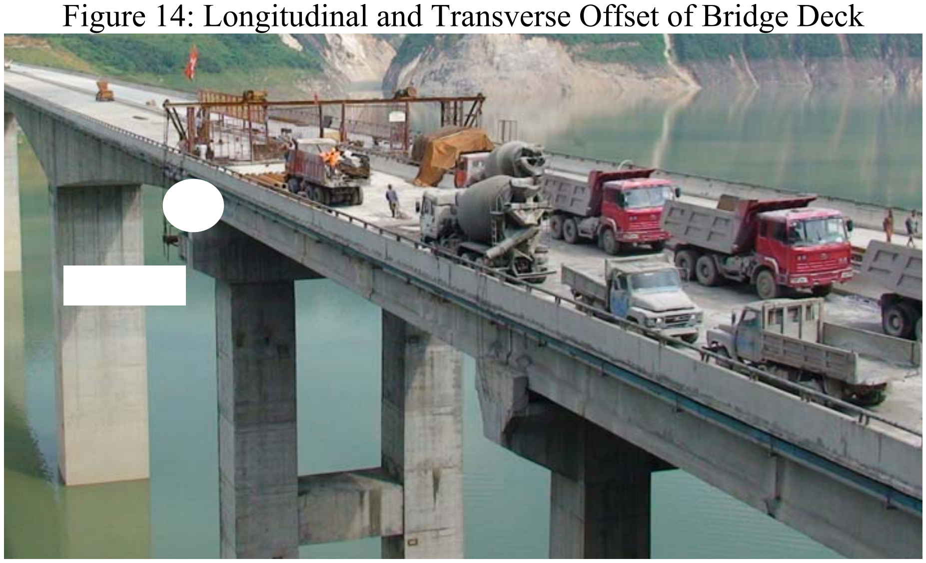


Figure 15: Shear Key Failure

Figure 16: End of the Miaozhiping Bridge and its Overpass for the Old Highway

Figure 17: Damage to Shear Key and Embankment of the Overpass

Figure 18: Bridges in the Vicinity of Miaozhiping Bridge

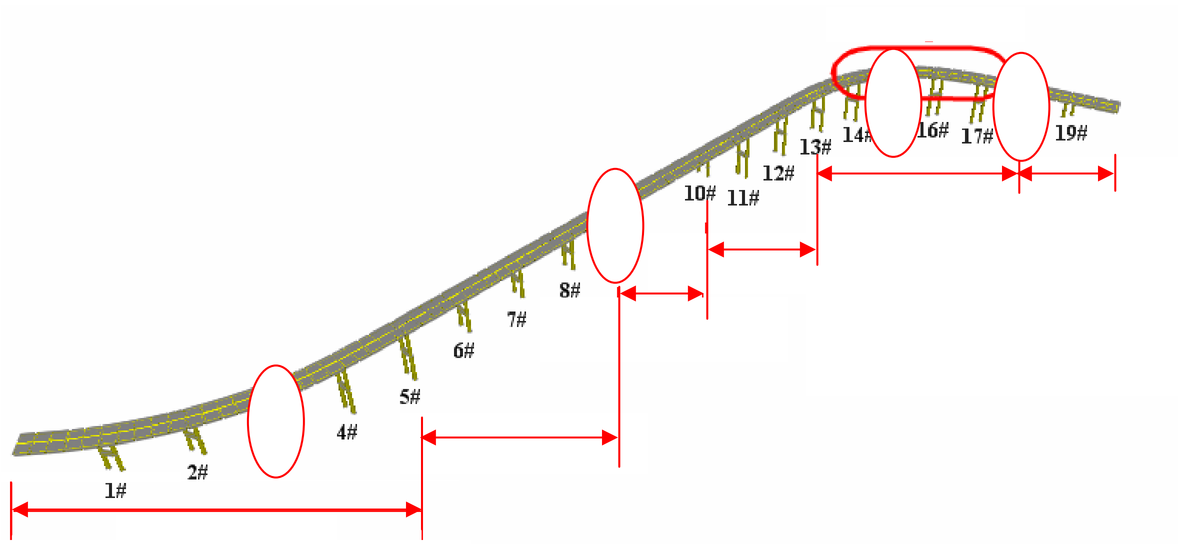


Figure 19: Schematic View of the Baihua Bridge before the Earthquake

Figure 20: Post-Earthquake Damage

Figure 21: Damage at Bent 3

Figure 22: Damage at Bent 9

(a) Column Shear and Flexural Failure

(b) Column Shear Failure and Section 5 Collapse

Figure 23: Earthquake Damage at Bent 15

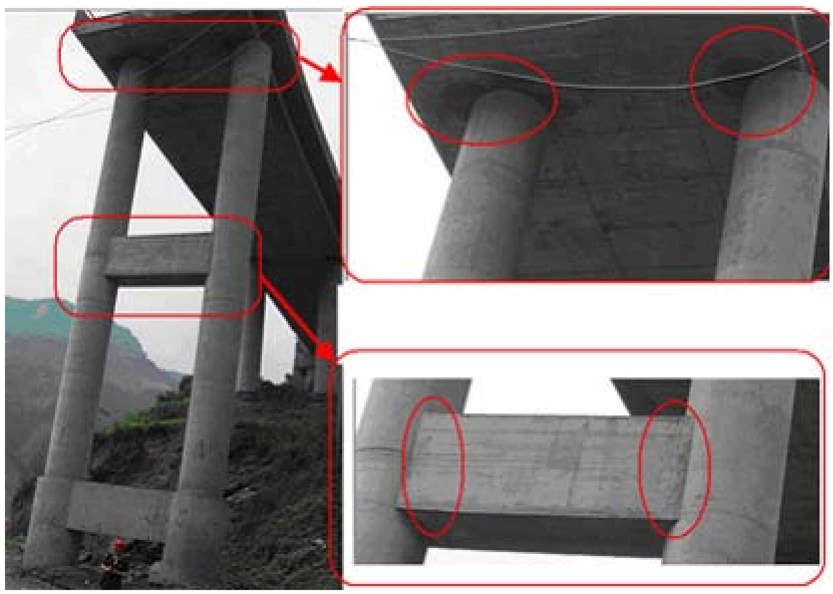


Figure24: Damage at Bent 18

(a) Blast Demolition

(b) After Demolition

Figure 25: Post-Earthquake Demolition of Baihua Bridge