Lessons Learned from the 2008 Wenchuan Earthquake and Recent Research on Seismic Design of Highway Bridges

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LISBOA 2012

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SUMMARY:
The great Wenchuan earthquake, which measured as 8.0Ms and occurred on May 12, 2008 in Sichuan province of China, has caused severe damage to many highway bridges. Field investigations of the collapse damage and the probable causes are carried out for the typical bridges including Baihua Bridge, Xiaoyudong Bridge, Miaoziping Bridge and Longwei Bridge. Lessons learned from the seismic damages of highway bridges are presented which include: special attention should be paid to bridge seismic response and unseating damages subjected to near-fault ground motions, preventions of collapse damage to curved bridges with small radius, ductility and seismic design details of bridges and damage control of high bridge columns under the water. Recent research progress on seismic performance of highway bridges are summarized in this paper. i.e. unseating protections of highway bridges, deformation capacity of bridge columns, numerical simulation of seismic performance of curved bridges with small radius.

Keywords: Wenchuan earthquake, Highway bridges, Seismic damage, Lessons learned from the earthquake

1. INTRODUCTIONS

The magnitude 8 Wenchuan earthquake that occurred on May 12, 2008 in China's Sichuan Province caused a number of casualties. The complete transportation interruption in the epicentral area caused by landslide, Debris flow obstruction, the collapse of bridges and damage to highways brought great difficulty to earthquake rescue, and highlight the importance of lifeline engineering.

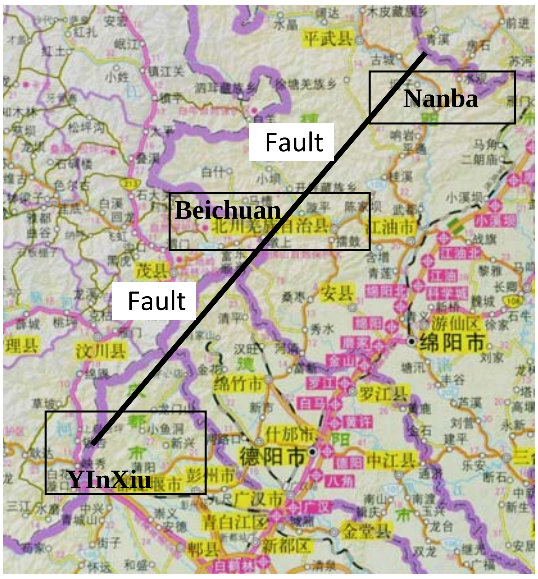

Fig.1 Scopes of seismic damage bridge in Wenchuan earthquake

To better understand the effects and damage reasons of earthquakes on the highway bridges, and to provide technical support for seismic design and seismic strengthening of bridges, In Aug. 2008, the project group carried out more detailed investigation of seismic damage to the bridges, including more than 20 bridges. They mainly investigated all the bridges between Minjiang Bridge, Yingxiu County of 213 National Road and Shoujiang Bridge, Nanba Bridge, Pingwu County of S105 National Road, Longwei Bridge at Beichuan County, Xiaoyudong Bridge at Pengzhou, Chengdu, Gaoyuan Bridge at Hongkou, Dujiangyan, and Gaoshu Bridge at Yingxiu County (new bridge along Minjiang River). the nearly completed Miaoziping Bridge and Xinfangzi Bridge of Duwen road are also included.

Figure 1 illustrates the traffic distribution of the earthquake zone. The investigation almost covers the main fault of Wenchuan earthquake: Yingxiu-Beichuan fault.

2. DAMAGE OF TIPICAL BRIDGES DURING WENCHUAN EARTHQUAKE

2.1. Baihua Bridge

Baihua Bridge was composed of a five-span curved girder bridge and the straight multi-span continuous bridges，and Its girders were supported by the pier directly without the cape beam.　It was about 2-3km from the epicenter of the Yingxiu town or the Yingxiu -Beichuan fault. The main damage was integral collapse of 5 span curved beams (Figure 2(a) and Figure 2(b)), broken and stacking of part of the deck body(Figure 2(c)). Other seismic damage included: pier bending damage(Figure 2(d)), pier shear damage(Figure 2(e)), pier beam joint shear damage(Figure 2(f)) or plastic hinge formed at the bottom of the column(Figure 2(g)), pile foundation displacement and tilt caused by subsiding and sliding into the river middle of soft soil(Figure 2(h)), the transverse, longitudinal displacement and collision of main girder, as well as the damage of shear keys （Figure 2(i), Figure 2(j).

(a)　Baihua bridge

(b) collapse of the curved bridge

(c) girder damage

(d)　damage to columns

(e)　flexure-shear damage

(f) damage at the node

(g) flexure damage at the node

(h) sliding of soft soils

(i)　pounding of the girders

(j)　damage of the shear keys

(k)　damage of the link beam

Fig. 2　Damage of Baihua bridge

Reasons for the seismic damage to Baihua Bridge are considered as: (1) Support length is not long enough and lack of longitudinal, vertical restrainers at in-span hinges；(2)Strong seismic effect made the curve girder separate from the piers, and finally the beam collapsed and the pier damaged.　The first beam falling down seemed to be at the end of the side away from the Yingxiu Town.

2.2 Xiaoyudong Bridge

Xiaoyudong Bridge was an 4 span arch frame and built in a wider floodplain area, and the site had some liquefaction (Figure 3(a)). One associated fault rupture was in the northern side of the bridge (far away from the Xiaoyudong Town side), and it was approximately right angle through of 75 degrees more than 20 meters from the northern bridge (culverts), and the road was uplift (Figure 3(b)). its principal seismic damages were: complete collapse of the 2 spans from the southern side (Figure 3(c)), inclination of bridge pier and damage of foundation (Figure 3(d)); the 3rd span was almost in good condition, with a few piers slightly cracked; the shear failure of the 4th span happened to the arch (rib) at the foot and belly bar at the top joints, and the bridge collapsed (Figure 3(e), 3(f), 3(g), 3(h), 3(i), 3(j)), while the pier was almost intact. The abutment walls on both sides cracked and tilt, the parapet cracked, while there was no obvious displacing with the abutment (Figure 3(k)); there were no collision signs on the expansion joints of the other main decks.

(a) liquefaction at the site

(b) fault rupture went through culverts

(c)collapse of 2 spans(South)

(d) damage to columns

(e) damage of 2 Spans(North)

(f) shear damage of the ribs

(g) shear damage of ribs (North)

(h) shear damage of joints(South)

(i) shear damage of ribs(North)

(j) shear and slip damage

(k) crack and inclines of the abutment(South)

(l) stirrup hopping of the ribs

(m) welding of the steels

(n) damage mode of the ribs

Fig.3 Damage of Xiaoyudong bridge

Three reasons can be summarized for the seismic damage to Xiaoyudong Bridge. First were the structure design defects: the stirrup of arch rib and belly bar was low so as to cause shearing damages. It was ϕ6@200, and was single limb without encryption area, without a 135 degree hook, and was not embedded in the core concrete (Figure 3(1)). The longitudinal reinforcement protective layer was thick from 3cm to 5cm, and was partially truncated In the arch foot, while connected by tie welding, all of which led to bonding defects (Figure 3(m)). Figure 3(n) clearly displays the failure mode of arch: its vertical crack is caused by bending, its oblique crack is by shearing, while along the longitudinal rib is by bonding. Second was that the site liquefaction might be important factor for pier tilt and foundation damage. Third was the influence of strong ground motion near fault and surface rupture (displacement). Besides these, the bridge had no clear path for seismic load transfer during earthquake.

2.3 Miaoziping Bridge

Miaoziping Bridge was across Zipingku Reservoir, and it was nearly finished when the earthquake occurred. The main bridge was continuous rigid frame with 3 spans, the approach bridge was a 50-meters multi-span simply supported continuous bridges and there was expansion joint at one segment for 5 spans. the main bridge pier's height was above 100 meters.



（a）unseating of the bridge （b）relative displacement of joinst （c）damage of bearing and shear keys



（d）bearing(main bridge) （e） bearing(approach bridge) （f） shear keys(main bridge)



（g） pounding （h） pounding （i）pounding


（j） unseating of bridge （k） damage of bridge(213 road)

Fig.4 Damage of Miaoziping bridge

Major seismic damages were that a span of simply supported bridge fell down at the expansion joint (Figure 4(a)), and the main bridge and approach bridge were slightly misaligned laterally (Figure 4(b)). Other damages included the damage of bearing and stop block of the main and approach bridges (Figure 4(c), 4(d), 4(e), 4(f)); the collision at the expansion joints between main and approach bridges, as well as that between approach bridges, which mainly occurred at handrails, guardrails and isolation belt (Figure 4(g), 4(h), 4(i)). Seen from the damage condition, the collision was much more complicated than imagined. Special check was done to the collision at the expansion joint between approach bridge segments of similar pier height, and there was no obvious traces of collisions(Figure 4(j)). The piers had some cracks when check by robots under the water.

Miaoziping Bridge is the only one long-span bridge with high pier about hundred meters and that has been hit by earthquake so far. Judging by the stop block damage of the bridge of the State Highway 213,which was almost perpendicular to the Maioziping Bridge (Figure 4(k)), the ground motion was mainly along the Miaoziping Bridge longitudinally. One reason for the seismic damage was the amplification effect of high piers' flexibility to displacement response, the other was that the box girder was heavy and damage to the bearing and block more easily happen.

2.4 Longwei Bridge

Longwei Bridge in Beichuan County was 11 spans simply supported bridge with frame bent columns. The main seismic fault crossed Beichuan County in north –eastern direction. The bridge is located in up-faulted block, and within a few hundred meters away from the fault.


（a） Beichuan before earthquake


（b） liquefaction


（c） transverse displacements


（d）longitudinal displacements


（e） damage of the road


（f）damage of the frame


（g） after the flood


（h） flexure crack


（i） shear crack


（j） damage of the abutment

Fig.5 Damage of Longwei bridge

Beichuan County is located in wide valley, and the site of Longwei Bridge had liquefaction (Figure 5(b)).Major seismic damages of Longwei Bridge are listed as follows. 1) There was transverse and longitudinal displacement of main girder, and transverse displacement was more than 2 meters. The stop block was damaged, and partial girder fell down. 2) Because of different transverse displacement, the bridge deck longitudinally, meanwhile one end of the beam separated from the support and pad, and the deck became rugged (Figure 5(c), 5(d), 5(e)). 3) The pier of the 7th span far away from Beichuan tilted significantly, and nearly collapsed, and now it has been shattered by the flood water(Figure 5(f), 5(g)), at the top of the column adjacent to the collapsed span formed flexure hinge and certain bent cap beam had oblique shear crack (Figure 5(h), 5(i)). 4) The abutment (Beichuan bank) had no displacement on the whole, but the wing wall had a transverse crack, and the front wall might be crashed. The girder got almost 2 meters into the ground in the longitudinal direction and uplift (Figure 5(j)).

Major reason for the damage of Longwei Bridge was that strong transverse and longitudinal seismic effect near fault, and the tilting and nearly-collapse of the 7th span's columns were caused by site liquefaction.

3. LESSONS LEARED FROM THE WENCHUAN EARTHQUAKE

3.1 **Bridge response and unseating damages subjected to near-fault ground motions**

Almost all highway bridges in the area affected by the earthquake are simply supported continuous girder bridges with rubber bearing placed on the cap beam directly and the connection between bridge columns and girders are weak, this caused the bridge girders to slide laterally or longitudinally and even unseating under earthquake actions, especially under the near-fault ground motions effects which include pulse-like wave, permanent displacement and vertical ground motion. The horizontal acceleration record at Qingping Station far away from the fault 0.7km is 0.8g and the vertical acceleration is 0.6g. Fig.6 shows a pulse-like wave of the velocity record and the permanent displacement can reach to 3m. The fault ruptures also make some bridges to damage.

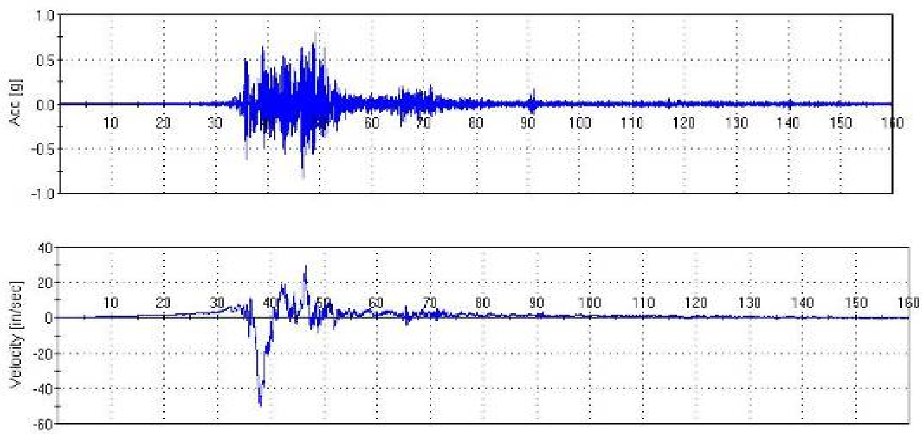

Fig. 6 Ground motion record at Qingping Station(0.7km to fault)

3.2 **Damage control of high bridge columns under the water**

The Miaoziping Bridge's high piers under the deep water had cracked during Wenchuan Earthquake and it is very difficult to check. The cost for retrofit is also very high. Usually the seismic design of bridge columns under the water is almost as the same as that standing in the land, the Performance based design or Sequence based design may be developed for the bridges considering the work condition of under-water, and skills or new materials for reducing cracks, e.g. pre-stress steel, Steel jacket and FRP jacket may be used.

3.3 **Preventions of collapse damage to curved bridges with small radius**

The curved bridges have much different response characteristics, effects of bending-torsion interaction of the superstructures and the others made it more fragility than the straight bridges. During1971 San

Fernando earthquake and 1994 Northridge earthquake the SR14/I15 interchange had suffered both damages, the from was due to the narrow seating length and falling down of the deck happened, the latter was due to the short columns with flexure-shear damage(Williams D et al,1979; Fenves G et al,1998). With the same reasons The Baihua bridge and Huilan interchange were also damaged during Wenchuan Earthquake. More attention should be paid to the seismic deign of the curved bridges (Sun Zhiguo et al, 2012).

Fig.7 Damage of Huilan ramp bridge (R=20m)

3.4 **Ductility and seismic design details of RC members**

The poor bearing conditions of the bridges also have some isolation effects, which lead to the decrease of seismic loads carried by bridge columns and the damage of bridge columns is usually not severe, but some inductile damage of columns, arch ribs or cap beams due to shear or combined shear and flexure should be concerned.

Fig.8 Shear damage and design details of RC members

4. RECENT RESEARCH ON SEISMIC DESIGN OF HIGHWAY BRIDGES

4.1 Unseating protections of highway bridges

The seating length of the supports is an effective measure to prevent the unseating damage to bridges. In order to determine the seating length of the supports, a relative displacement spectral model (S_r

spectra) based on earthquake experience is developed, which can be used to evaluate the maximum relative displacement between bridge girders and cap beams. The model is illustrated in Fig.9 and the bearing sliding is modeled use Coulomb friction theory. The SDOF system response is depended by period *T*, damping ratioξ, friction factor μ and input ground motions. It is as the same as the inelastic response spectra theory.

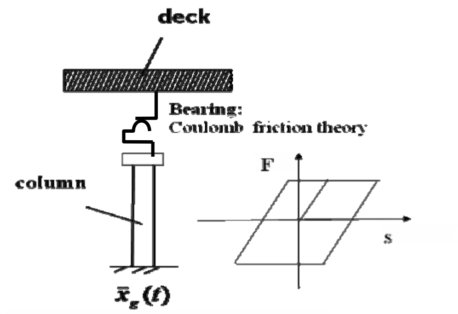

Fig.9 Relative displacement analysis mode

The S_r spectra is defined as:

$$S_r = S_b(t)\big|_{\max} + \alpha \cdot S_c(t)\big|_{\max} \tag{4.1}$$

Where, $S_b(t)\big|_{\max}$ is the maximum displacement of the deck; $S_c(t)\big|_{\max}$ is the maximum displacement of the column; α is an factor, when sliding α=1.0 and no sliding α=0.

The statistical analysis show that near-fault ground motions, soil conditions, structure vibration periods and stiffness of the bearings after damage are key factors influencing unseating damage of simply supported bridges.

The seating lengths are proposed to bridge seismic design code in China which shown in Table 4.1. When the bridge is not far from the fault than10km, length should be multiplied 2.0.

Table 4. 1 Seating length provided by cap beams

Site type (China code)	I(stiff)	II(hard)	III(medium)	IV(soft)
Seating length (cm)	30	30	70	100

4.2 Deformation capacity of bridge columns

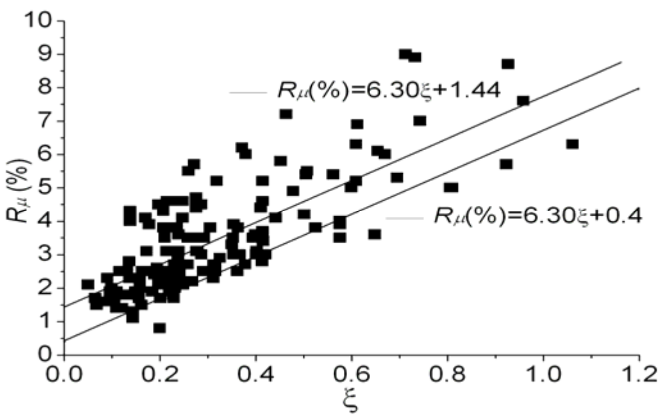

Fig. 10 Regression of the ultimate drift ratios for RC bridge columns

Confining reinforcement in the potential plastic hinge regions plays a crucial role for the ductility of RC bridge columns. 234 cyclic test results for bridge columns were collected from PEER (Pacific Earthquake Engineering Research Center) database, Kawashima Laboratory and other literature. The relationship between the ultimate drift ratios and the amount of confining reinforcement with 85% assurance rate are proposed based on regression analysis (Eqn. 4.2).

$$R_\mu(\%) = 6.3 \times \frac{A_{sh}}{sh_c} \times \frac{f_{yt}}{f_c} \times \frac{1}{(1.3-\rho_t m)\times\eta_k} \times \frac{A_c}{A_g} + 0.4 \qquad (4.2)$$

Where, R_μ is the drift ratio of the columns, A_{sh} is the area of the hoop steels, A_c is the area of the core section and A_g is the gross area, s is the space of the hoop steels, h_c is the depth of the section, η_k is the axial ratio, ρ_t is longitudinal steels ratio, f_c is the strength of the concrete, f_{yt} is the strength of the hoop steels, f_y is the strength of the longitudinal steels, $m = \frac{f_y}{0.85 f_c}$.

4.3 Numerical simulation of a seismic damaged curved bridges

The Huilan interchange, constructed in 2004 in Mianzhu City, consisted of a viaduct and four horizontally circular ramp bridges with continuous box girders. Field investigations found that the seismic damage to the ramp bridges was especially heavy(Fig.7, Fig.11); one or two short piers in all but one of the ramp bridges experienced severe failure, and the box girders over the failed piers were fractured. Other piers of the ramp bridges suffered minor-to-moderate damage, including concrete cover spalling, concrete cracking, and slippage damage of the rubber bearings. The viaduct suffered only slight damage, including slippage damage of the rubber bearings and pounding damage of the superstructure.

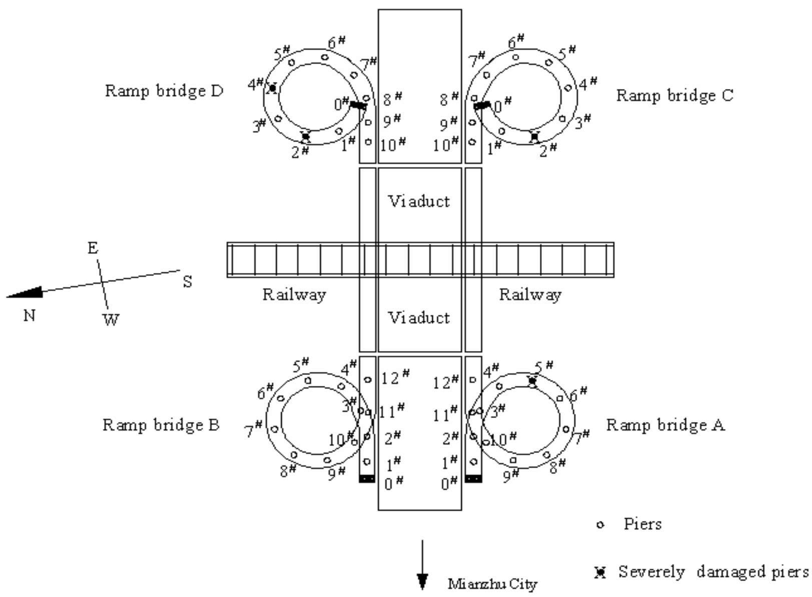

Fig. 11 Schematic diagram of the Huilan interchange and ramp bridge piers

The seismic performance of the bridge was evaluated by finite element modeling and compared with field observations. It was found that the bearing on top of the shortest pier, Pier 1, was damaged first. Then, the seismic action was concentrated on the next shortest pier, Pier 2, which had the largest flexural stiffness. Pier 2 first yielded in flexure, and, as the lateral displacement increased, the ultimate response of this pier was dominated by its shear capacity and it eventually failed in flexure-shear mode.

AKCNOWLEDGEMENT
The writers gratefully acknowledge the support for this research by the National Natural Science Foundation of China under Grant Nos. 50878033, 50978042 and 51178071, National Special Foundation of Earthquake Science of China under Grant No. 200808021, and the Fundamental Research Funds for the Central Universities under Grant No. 2011JC034.

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