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BRIDGE SEISMIC DESIGN LESSONS LEARNED FROM WENCHUAN EARTHQUAKE OF CHINA

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ABSTRACT

M8.0 Wenchuan Earthquake, which is a shallow earthquake, occurred in Wenchuan County, Sichuan Province, China on May 12, 2008. Millions of buildings and thousands of bridges were totally or partly damaged in the affected region. Investigation of the destructive earthquake was a meaningful research work, from which we can get more lessons and experiences for seismic design code modification. After the earthquake, authors have been to the affected areas for more than sixteen times and noticed that different structural type behaved in different seismic performance. Span collapses due to unseating at expansion joints, partial collision damage and horizontal displacement were prevalent on superstructure. Concrete spalling, buckling of longitudinal steels, stirrup rupture, shear key failure and pier shear failure occurred on the substructure. Above-mentioned damages of girder bridge and arch bridge will be presented briefly in the paper. Then Baihua bridge is discussed in detail. Finally, seismic design lessons learned from the earthquake were introduced.

Introduction

Wenchuan Earthquake was a deadly earthquake with a magnitude of 8.0 MS occurred at 14:28.04 CST on May 12, 2008 in Sichuan Province of China. The epicenter was located in Yingxiu Town (N31.0°,E103.4°), with a depth of about 14 kilometers. Official figures (as of September 5, 2008 12:00 CST) state that 69,227 are confirmed dead, and 374,643 injured, 17,923 missing. The earthquake left about 23 million people homeless, the direct economic loss run higher than 845.136 billion RMB. It was the deadliest earthquake to hit China since the 1976 Tangshan earthquake, which killed at least 240,000 people.

The highway system in Sichuan Province was dealt a death blow. Express highways, national and provincial arterial roads, rural roads in 22 cities were damaged at different levels. According to incomplete statistics, highway structures of 17 express highways, 16 national and provincial arterial roads, and 24,000 km rural roads in Sichuan Province were damaged by the earthquake. The total damaged mileage of the damage highway approximately reaches 28,000

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km. 670 Bridges on national and provincial arterial roads were damaged.

The authors have been to the affected areas for more than sixteen times, and attended in several field investigation teams, which are: two reconnaissance teams organized by the Ministry of Transportation of the People's Republic of China between May 20 and June 12 in 2008; two field investigation teams organized by the Research Institute of Highway, one of which was at July, 2008, the other one at February, 2009; China-US Investigation Team co-organized by Kehai Wang and W. Phillip Yen from July 20 to July 24, 2008.

Typical Failure Types

Bridges along the Longmengshan fault were more seriously damaged than bridges in other areas in Sichuan Province. Some of the bridges entirely collapsed, most of the bridges were damaged in a less severe way. There are 129 bridges the authors observed carefully , in which 75 are girder bridges, 54 are arch bridges. The failure summary tables of bridges are listed in Table 1 and 2.

Table 1. Failure summary table of Girder Bridge

Failure type \ Category		Group 1		Group 2		Group 3	
		Skewed	Orthogonal	Curved	Straight	Rubber pad bearing	Basin rubber bearing
Total Number		34	41	27	48	61	6
Entirely collapse		--	--	4	5	--	--
Superstructure	Pull-off-and-drop	--	--	1	5	--	--
	Offset	22	23	--	--	--	--
	Collision	18	7	--	--	--	--
	Shear key	21	19	--	--	--	--
Substructure	Shear	--	--	3	0	--	--
	Buckling	--	--	2	0	--	--
	Stirrup rupture	--	--	2	0	--	--
	Crack/ spalling	--	--	6	1	--	--
Bearing	Fall off	--	--	--	--	5	0
	Offset	--	--	--	--	11	1
	Shear	--	--	--	--	20	0

Table 2. Failuresummary table of Arch Bridge

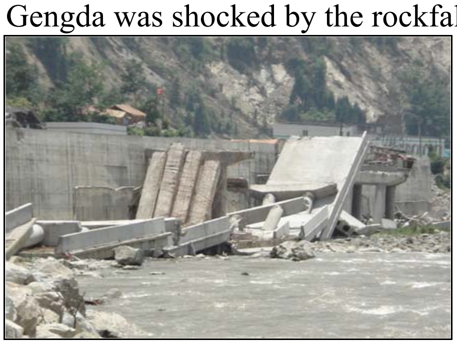
Failure type \ Category		Group 1		Group 2	
		Span ⩾ 40m	Span <40m	Masonry	Reinforced
Total Number		15	39	22	27
Entirely collapse		5	1	1	5
Crack	Arch ring	2	0	0	2
	Spandrel arch	4	1	--	--
Spalling of pave seam		5	4	--	--
Dislocation of arch ring		0	2	2	0
Railing offset		3	4	--	--
Expansion joint deformation		3	0	--	--

Entirely Collapse

There were more girder bridges that entirely collapsed due to the ground movement in our itinerary as compare to arc bridges, such as the Shunhe Bridge in Yingxiu Town, Nanba Bridge in Nanba Town, Caopo No.2 Bridge at G213, the curve part of Baihua Bridge, Yingxin Bridge at XF05 in Shifang City, Jueyuan Bridge in Hanwang Town, and Yuzixi No.2.

Shunhe Bridge in Yingxiu town(See Figure 1), whose main part was already completed when the earthquake occurred, is along the Minjiang River. Most of the main girders dropped off, piers experienced damages of collapse, leaning, shear failure on the top part. There was a frame structure nearby (not more than 50m), whose long axis direction is also along the Minjiang River, the second floor of which is totally crushed; and there is a longitudinal displacement of about 1m between the first floor and the rest (Shown in Figure 2). There was a bridge cross the Minjiang River and about 100m away from the Shunhe Bridge, suffered less damage in the earthquake, the main girder of which displayed a little transverse offset(See Figure 3). From that, we can draw a conclusion that main part of the seismic wave near the Shunhe Bridge was along the Minjiang River, and the performance of the bridge was closely related to the direction of the bridge and the seismic wave.

And most of the totally collapsed girder bridges was shattered by the secondary disaster , such as landslide, rockfall, and debris flow. Yuzixi Bridge No.2(See Figure 4) at S303, crosses the Yuzixi River, the superstructure of which is consists of 4 continuous spans of 25m each, the piers of which are consist of one-column bents and two-columns bents, 113m total. The first span near Gengda was shocked by the rockfall, and then the bridge totally collapsed.



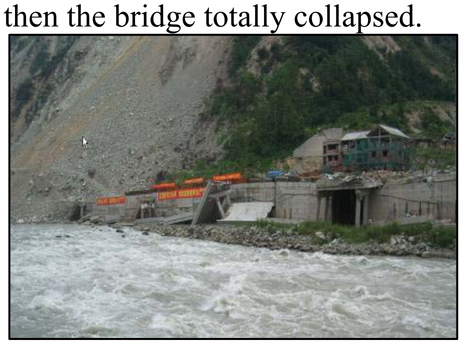


Figure 1. Shunhe Bridge

Figure 2. Frame structure

Figure 3. Bridge cross the river

Figure 4. Yuzixi No.2 bridge

The samples of entirely collapse arch bridge were Jingtianba Bridge and Hongdong Bridge. Jingtianba Bridge is a box arch bridge with two spans, each of which is 85m. Hongdong Bridge is a masonry arch bridge with a span of 55m, built in 1955.

As compare to girder bridge collapse in result of secondary disaster, the arch bridges can endure the rockfall, small landslide and debris flow. Arch bridges were more sensitive to the different movement between the abutments or piers. Yuzixi 1-6# bridges along the provincial arterial road 303 were living proof. All of the six bridges were girder bridges with an old arch bridges nearby. The old arch bridges were along the old provincial arterial road 303 that was intent to desert. In the Wenchuan Earthquake, all of the girder bridges were severe damage, but the old arch bridges suffered little damage. The most living example was the Yuzixi 2# Bridge as shown in Figure 5. The new girder bridge was a continuous box bridge with four span, each of which is 25m, while the old arch bridge was masonry bridge with two spans, each of which is 20m. The distance of the two bridge is less than 10m. The new girder bridge totally collapsed because of the rockfall and ground movement, but the old arch bridges can open to the traffic after the earthquake.

Superstructure

There are several failures types of girder bridge superstructure, including pull-off-and-drop collapse of bridge decks, offset in longitudinal or transverse direction, collision between the girders, and shear keys failure. The girder falling failure was quite prevalent, such as the bridge under construction in Nanba town (See Figure 7), and the Miaoziping bridge (See Figure 8). The failure of offset in longitudinal or transverse direction appeared in most of the girder bridges in the worst-hit areas, such as Baihua bridge, Yuzixi No.1 bridge. There was s severe transverse offset on the top of pier 10 of Baihua bridge, the shear keys of which experienced shear failure(See Figure 9). Yuzixi No.1 bridge under construction also displayed severe transverse offset, that caused the shear keys failed(See Figure 10). The failure of shear keys was quite prevalent in Wenchuan earthquake. Based on our observation, the lack of reinforcements and anchor length, insufficient thickness of the shear keys and construction measures exist in some bridges. Collision between the girders may induce the loss of bearing capacity of the bridge.

Figure 6. Yuzixi 2# Bridge

According to our observation, the damage of the skewed bridges was damaged more serious than the orthogonal bridges. The behaviors expressed as collision between the girders or girder and the abutments, shear keys failure, offset in the longitudinal and transverse direction. In most cases, the superstructures of the skewed bridges may rotate by a small angle along the vertical axis, such as the Maweihe Bridge in Mianzhu City(See Figure 11).

Figure 7. Nanba bridge

Figure 8. Miaoziping bridge

Figure 9. Transverse offset of Baihua bridge

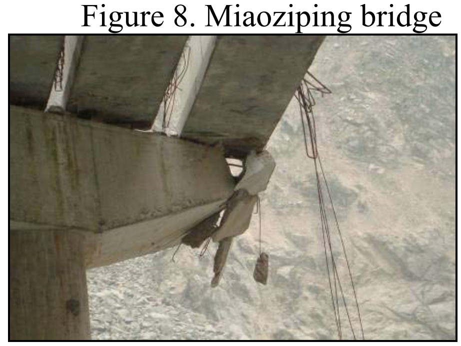


Figure 10. Transverse offset of Yuzixi No.1

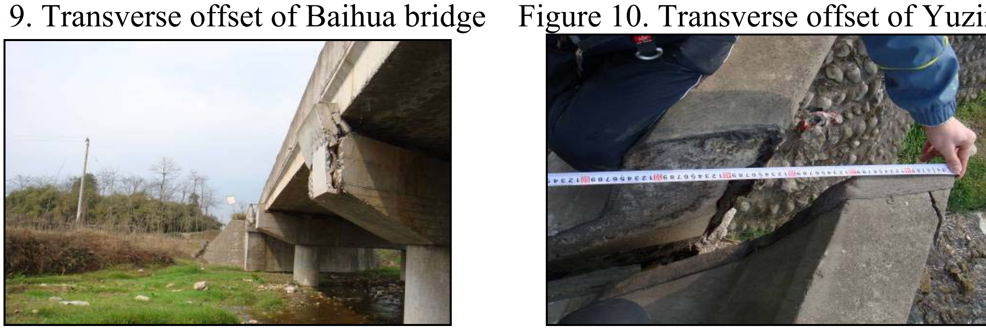


Figure 11. Maweihe Bridge in Mianzhu City

There are several failures types of arch bridge superstructure, including crack in the arch ring, crack in the spandrel arch, spalling of the pave seam, dislocation of the arch ring, railing offset, expansion joint deformation. Quhe Bridge in Qingchuan appeared the failure of crack in arch ring as shown in Figure 12, It is a double convex arch bridge with a span of 75m. The crack in arch ring isn't the essential to the bridge. The crack in spandrel arch is more severe, as shown in Figure 13.

Figure 12. Crack in Arch Ring

Figure 13. Crack in Spandrel Arch

Substructure

The failure of substructure was not quite prevalent in Wenchuan earthquake. But once occurred, the damage to the bridge was great. The failure types of substructure observed in the earthquake consist of collapse, shear failure, buckling of longitudinal steels, stirrup rupture, crack and concrete spalling. The most typical samples of shear failure of piers was Mianyang Airport Bridge.

Mianyang Airport Bridge was a viaduct with two floor at Mianyang Airport(See Figure 14). The shear failure appeared in the tow piers circled by the red line in Figure 14, as shown in Figure 15(a) and 15(b). There are may be two reasons that why these two piers suffered such severe damage: a)the top of the pier was fixed the bridge deck, the corresponding piers at the other side(circled by the blue line in Figure14) performed well in the earthquake; b) short-column effects, the effect length of these two piers are shorter than other piers at the approach bridge because of rigidly connected to the first floor.

According to incomplete statistics, the damage of piers in Wenchuan earthquake was less severe. The reason was related to the widely use of plate rubber bearing, the connection of between the deck and piers is weak then.

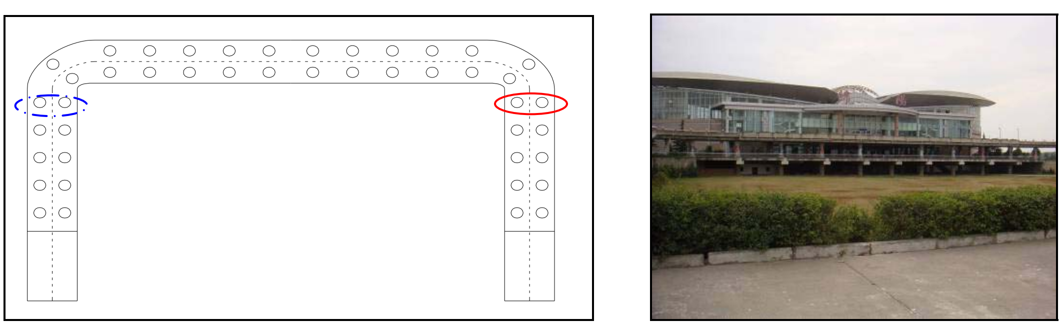


Figure 14. Mianyang Airport Bridge

The most prevalent failure type of girder bridges abutment was the collision between the superstructure decks and abutment in Wenchuan Earthquake. Due to the transverse offset of girders, the shear keys also fails in most cases. And some cases, there were cracks in the wing wall(See Figure 16 and Figure 17). The prevalent failure types of arch bridges abutment included sinkage, crack in the wing wall. As compared to the girder bridge, the abutment of the arch bridge suffered more severe damage. Ganxihe Bridge in Guangyuan suffered severe abutment failure, as shown in Figure 18. The cracks in the wing wall was perforative. According to our observation, the failure in the abutment was very prevalent in the earthquake for both girder bridges and arch bridges.

(a)pier inside (b)pier outside

Figure 15. Shear failure in piers of Mianyang Airport Bridge

Figure 16. Baimayan bridge No.2

Figure 17. Ganhezi bridge

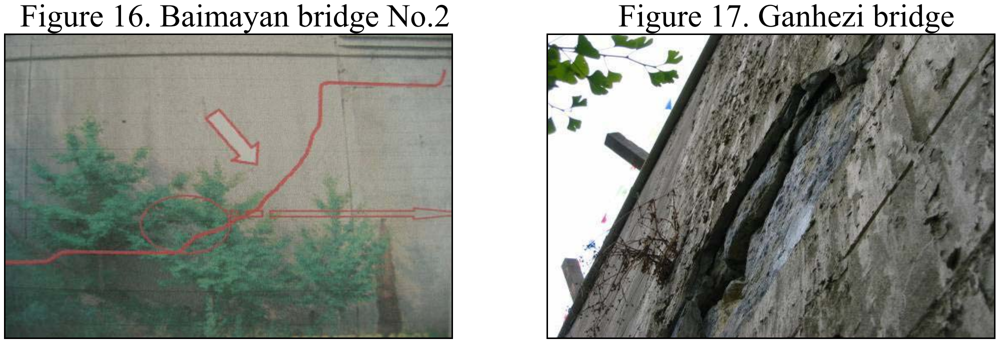


Figure 18. Ganxihe Bridge

Bearing

According to our field investigation, most of girder bridges’ bearing were rubber pad bearing and basin rubber bearing. For the rubber pad bearing, the failure expressed as fall off, offset and shear failure (See Figure 19). For basin rubber bearing, the failure expressed as offset in longitudinal or transverse direction in most cases (See Figure 20).

(a) fall off (b) shear failure

Figure 19. Rubber pad

Figure 20. basin rubber bearing

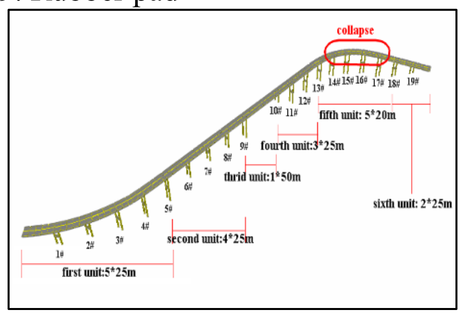


Figure 21. Baihua bridge

Baihua Bridge

Baihua bridge was constructed in 2004, consisted of 18spans, and the total length was 450 m. It contained six units (See Figure 21). The bridge is just about 9 kilometers away from the epicenter of the earthquake, and in the fault belt zone. The fifth unit, the curve part, totally collapsed in the earthquake, and the rest parts of the bridge also deserved severe damage. To protect the rescue troops who went through right under the bridge and citizens around the area, the bridge was demolished in May 28, 2008.

The failures included piers flexural and shear failure, bearings offset failure, abutment collision failure and tie beams shear failures. The detail of each pier’s failure are shown in Table 1.

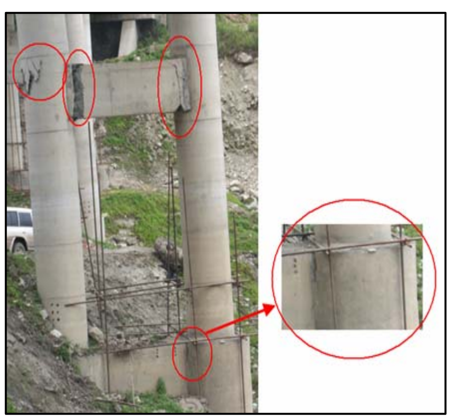


Figure 22. Pier 3# of Baihua Bridge

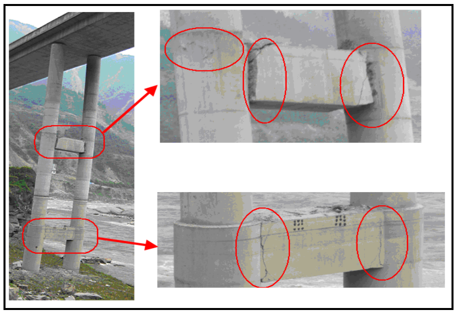


Figure 23. Pier 12# of Baihua Bridge

Figure 24. collapsed unit 5

Table 1. The Failure of Piers

Pier Number	Description of Failure
1	bearing failure, tie beam failure
2	tie beam failure, the bottom of the pier crack
3	tie beam failure, pier at the beam-column joint crushed (See Figure 22)
4	tie beam failure, the bottom of the pier crack
5	bearing failure, tie beam failure, the bottom of the pier crack
6	bearing failure, pier at the beam-column joint crushed
7	tie beam failure, the bottom of the pier crack
8	tie beam failure
9	shear keys failure
10	shear keys failure
11	bearing failure, tie beam failure
12	tie beam failure, pier at the beam-column joint crack (See Figure 23)
13	Shear keys failure, tie beam failure
14-17	totally collapsed (See Figure 24)
18	bearing failure, tie beam failure
19	bearing failure(offset in the longitudinal direction), the bottom of the pier crushed

The reasons of severe damage of Baihua bridge were as follows:

(1) Strong ground motions

There are three strong ground motions monitor station around the bridge, included: Wenchuanwolong station, Pixianzoushishan station and Shifangbajiao station(See Figure 25), the distance of which between the bridge are 28 km, 35km and 56km respectively, the peak accelerations of which are 0.958g, 0.142g and 0.58g, respectively. The distance of Baihua bridge between the microscopic epicenter is about 9km, the distance of Baihua bridge between causative fault is about 2-3km. The distance of Wenchuanwolong station between the microscopic epicenter is about 20km, the distance of Pixianzoushishan station between the microscopic epicenter is about 40km, the distance of Shifangbajiao station between the microscopic epicenter is about 57km. The resistance level of the bridge is equal to 0.1g, so the practical seismic load is much greater than the fortification level.

(2)The quality of construction

The damage of joints between the tie beam and pier is very fragile as shown in Figure 26, we can draw a conclusion that the quality of joints may be in low-level.

(3)Design philosophy

For two-column piers, the design philosophy should be “Strong column weak beam”, that will resulted in the damage of tie beam not the pier in a strong earthquake. The ideal damage mode is indicated in Figure 26, in which the joint part and the pier are in great condition, the beam suffered flexural damage.

The irregular stiffness of the bridge may be another reason, especially the stiffness between unit 5 and unit 6. The piers in unit 5 are 13#-18#,the height of which are 30.3m, 21.9m, 23.4m, 21.6m, 21.8m, 16.8m . As compared to this, the pier height of unit 6 is just 7.1m. So under the seismic load, the two units may not appear in the same direction, result in the great relative displacement, when that displacement exceed the supporting length, unit 5 will have to experience internal force redistribution.

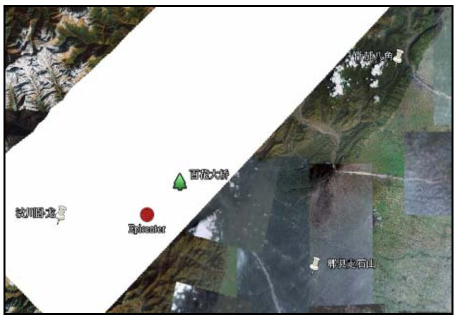


Figure 25 Site of Baihua bridge

Figure 26 Ideal damage mode

Lessons Learned From The Earthquake

From the field investigation and observation, the following lessons may be valuable for the future bridge construction:

(1)Skewed bridge and curved bridge should be avoided in high intensity zone

Skewed bridge suffered more serious damage than the orthogonal bridge in Wenchuan Earthquake. The collision between girders and abutments may induce the loss of bearing capacity. The reason of collision failure was that the bridge bears two perpendicular horizontal ground movements.

Curved bridges suffered more damage in the Wenchuan Earthquake as compared with straight bridges, the most typical sample was Baihua Bridge, cure part of which totally collapsed, straight part of which suffered less serious damage.

(2)Near-field ground motions should be considered

Baihua bridge and Miziping bridge was severely damaged because of the near-field ground motions. For the important bridge, the near-field ground motions shouldn’t be neglected in the design process. If one bridge has to be constructed across a fault , simply supported bridge should be preferentially considered.

(3)Shear failures must be avoided in piers

The shear failure can induce the loss of bearing capacity , such as the Mianyang Airport Bridge that the upper bridge was blocked. And the shear failure was fragile without little ductility. Piers with reluctant ductility may cause less casualties and economic loss.

(4)Shear keys are required to prevent spans falling transversely

The most prevalent failure type for girder bridges was the shear keys failure. Although bridges with shear keys failure were damaged, but few bridge decks fall, and the offsets in the transverse direction were not that big that may not affect the normal usage .According to our observation, the transverse offsets of bridges without shear keys were greater. In one word, the shear keys play an important role for the girder bridges once earthquake occur, shear keys should not be abandoned in the construction; on the other hand, shear keys failure was too prevalent in Wenchuan Earthquake, the design philosophy and technology of shear keys should be deeply researched in the future.

(5) Longitudinal restrainer should be considered in the future

In our itinerary, there weren't any bridges with longitudinal restrainer in the Wenchuan Earthquake. In most cases, the longitudinal offset was greater than the transverse offset. Longitudinal restrainer was proven to be effective in the past Japan earthquake and U.S. earthquake. Longitudinal restrainer was already used in small range in China, and should be paid more attention to and attached more importance to in the future.

(6) The connection of plate rubber bearing should be attached importance to

There are a lot of bearing failure in Wenchuan earthquake because of the installation method, in which the plate rubber bearings are directly place between the piers and the decks. If there are some kind of displacement-limit measures, the effect may be better.

(7)" Strong column weak beam" should be attached importance to

For two-column or multi-column piers, the design philosophy should be "Strong column weak beam", that will resulted in the damage of tie beam not the pier in a strong earthquake.

(8)Long-span arch bridges were sensitive to ground movement

From the observation, most of the entire collapse arch bridges' spans were greater than 40m. Arch bridges belongs to statically indeterminate structures, are sensitive to ground movement.

(9)Masonry arch bridges can also resist the earthquake dynamic load

Most of the masonry arch bridges still stand after the earthquake, especially in the provincial arterial road 303, all of the old arch bridge still open to the traffic after the earthquake. When the span isn't too long, and the foundation is great, masonry arch bridges should be considered in the practical bridge design, especially when considered about the secondary disaster.

Acknowledgments

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