The performance of girder bridges in the Wenchuan Earthquake and a new method for seismic protection

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ABSTRACT:
This paper reports some typical damage samples of the girder bridge in the Wenchuan earthquake, based on an inspection visit to the earthquake site. The causes and regular patterns of the earthquake damage are analyzed. Meanwhile, a new method for seismic protection in strong seismic excitation is proposed. To avoid earthquake damage, the new method uses proper constructional measure to change the transmission of earthquake energy, reduce the relative displacement between superstructure and substructure, and assure the safety of substructure.

KEYWORDS:
Wenchuan Earthquake; girder bridges; causes of earthquake damage; new method for seismic protection

1. INTRODUCTION

On May 12, 2008, a huge earthquake with *M8* occurred in Wenchuan of Sichuan Province in China, whose intensity of the meizoseismal area was up to Ⅺ. Earthquake damages covered all the Sichuan Province, and spread to Chongqing, Qinghai, Yunnan, Guizhou, Shanxi, Gansu, etc. According to CCTV's reports, till June 19, 2008, the Wenchuan Earthquake has caused 67 billions RMB in losses from the damage of roads, bridges, tunnels, and other highway structures, and has resulted in damages of 24 freeways, 161 national and provincial highways, 8614 rural highways, 6140 bridges, 156 tunnels. The huge damage of highway systems blocked resisting earthquake and providing disaster relief severely. In this earthquake, many of the damaged bridges are girder bridges. This paper will start with some typical damage samples of girder bridges, analyze the causes and regular patterns, and propose a new method for seismic protection in strong seismic excitation.

2. TYPICAL DAMAGE SAMPLES

2.1. Baihua Bridge

The Baihua Bridge is located at the national highway G213 between Dujiangyan and Yinxiu. The bridge was completed in 2004, which was a 17-span, 495-meter-long, 7-meter-wide, prestressed reinforced concrete, girder bridge. The plan and elevation drawings of this bridge are shown in Figure 1. The superstructure is composed of six different segments. From Xuankou direction there are a continuous span concrete slab (A1 to P2), then a cantilever span concrete curve slab (P2 to P5), a continuous span concrete slab (P5 to P8), a simple span T-shaped girder (P8 to P9), a continuous span concrete slab (P9 to P13), and a cantilever span concrete curve slab (P13 to A2). Concrete distyle piers are its substructure and which are supported by concrete piles. Laminated rubber bearings attach the superstructure to the substructure. The geological structure near the bridge is shown in Figure 2. The information of strong ground motion station network near the bridge is shown in Table 2.1.
The bridge site is in the meizoseismal area. The landslide and collapse occurred in the mountain body beside the bridge, and the surface rupture near Abutment A1 which shifted towards the river side slightly can be found. There was a transverse crack on the wing wall of Abutment A1, and 1# girder shifted along the longitudinal axial of bridge (Fig.3). Plastic hinge appeared in the region of bottom of Pier P1, and the pier body inclined back (Fig.4). Pier P2 distorted. All of Pier P3 and P4 broke completely, and 2# cantilever span concrete curve slab fell down (Fig.5). As same as P8 and P9, one of the blocks on Pier P5 broke, and there were some cracks at

the joint between the transverse beam and the columns of the piers. The girder 4# and 5# shifted transversely.

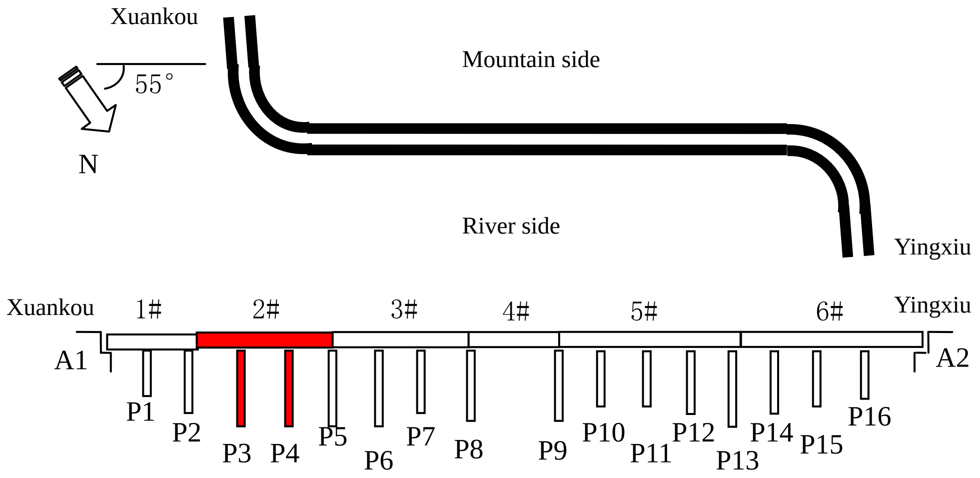

Fig.1 The plan and elevation drawing of Baihua Bridge

Table 2.1 The information of strong ground motion station network near Baihua Bridge

Station	Max peak acceleration (gal)			The distance between bridge and station(km)	The distance between station and epicentre(km)	The distance between bridge and epicentre (km)
	EW	NS	UP			
Wenchuan Wolong	956.7236	652.186	947.1365	28	30.8	4.2
Lixian Taoping	339.7329	342.3814	379.5771	54.6	50.4	
Shifang Bajiao	581.5923	556.1694	633.0923	51.8	49	
Pixian Zhoushishan	120.5148	142.2059	99.1222	44.8	46.2	
Dayi Yinping	127.6421	135.108	82.6923	47.6	51.8	

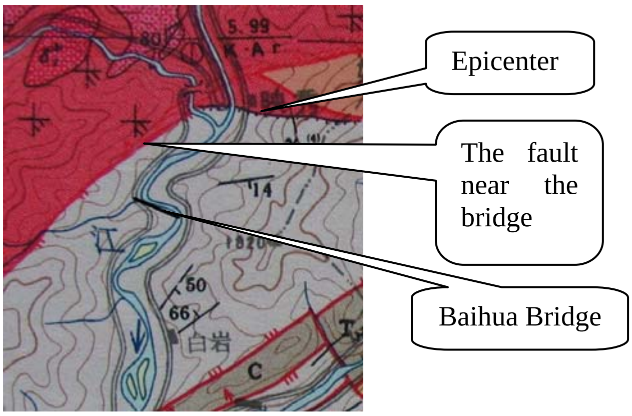

Fig.2 Geological structure near Baihua Bridge

Fig.3 Crack on the wing wall of Abutment A1

Several factors influenced this bridge's performance during the earthquake. From Fig.2, we can find that there is a fault which is less than 1 km away from the bridge, and the bridge site is only 4.2 km from the epicenter. The short distance from the epicenter meant that very large accelerations were arriving at the bridge. This is also reflected in the ground motions record near the site. Form Table 2.1, we can find that the peak acceleration on the ground of Wenchuan Wolong Station, which is on the west side of the bridge and is the nearest station from the site, is up to 0.96g on EW. The large displacement of the ground near Abutment A1 resulted abutment and piers moving and deflecting. Meanwhile, the inertia force of superstructure pushed the piers which support the cantilever span curve slab, and resulted the piers broken, the decks of 2# girder fell down.

Fig.4 Rupture of concrete at Pier P1

Fig.5 Fall of 2# girder

2.2. Jianjianghe Bridge

The Jianjianghe Bridge is located at the provincial highway S302 between Maoxian and Beichuan. It actually consists of two separate bridges and a tunnel. The plan and elevation drawing of this bridge is shown in Figure 6. The east part is named as Shisuoyi Bridge, which is an 11-span, 232-meter-long, 9-meter-wide, prestressed reinforced concrete, plate girder bridge. The west part is named as Xiayu Bridge, which is a 5-span, 128-meter-long, 10-meter-wide, prestressed reinforced concrete, plate girder bridge. The middle part is an 80-meter-long tunnel which is called as Longwei Tunnel. The geological structure near the bridge is shown in Figure 7 and the information of strong ground motion station network near the bridge is shown in Table 2.2.

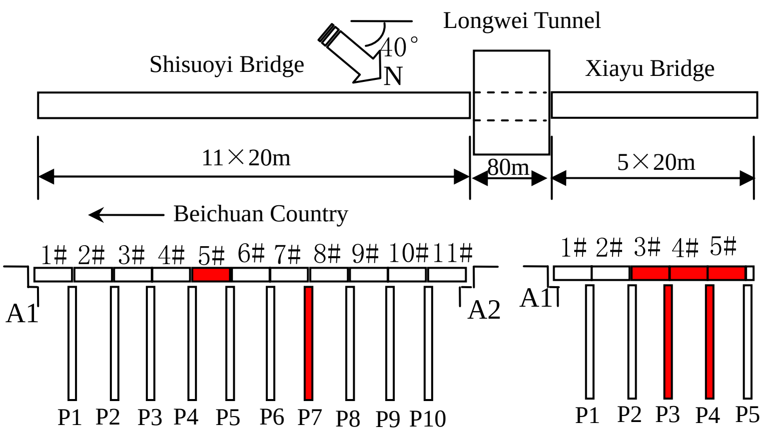

Fig.6 The plan and elevation drawing of Jianjianghe Bridge

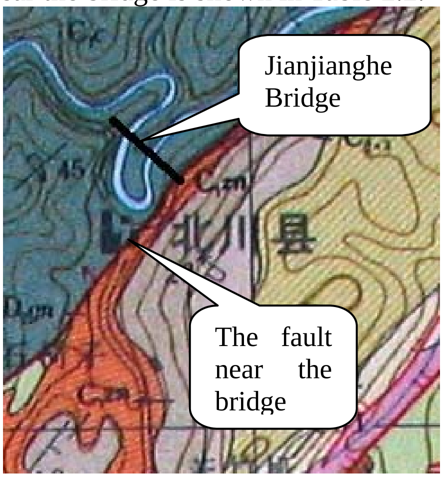

Fig.7 Geological structure near Jianjianghe Bridge

Table 2.2 The information of strong ground motion station network near Jianjianghe Bridge

Station	Max peak acceleration (gal)			The distance between bridge and station(km)	The distance between station and epicentre(km)	The distance between bridge and epicentre (km)
	EW	NS	UP			
Anxian Tashui	203.4545	289.5394	179.9261	40.6	96.6	121.8
Mianzhu Qingping	802.713	824.1283	622.9108	43.4	78.4	
Jiangyou ES	458.6844	511.3325	198.2779	28	142.8	
Jiangyou Hanzeng	350.1356	519.4967	444.331	15.4	128.8	
Jiangyou Chonghua	278.9646	297.187	180.4879	50.4	168	

The bridge is located in the Ⅺ intensity area. The girders of Shisuoyi Bridge moved along longitudinal axial toward Beichuan Country nearly 2 meters, and the bridge deck moved along lateral axial also nearly 2 meters. Part of the deck on 5# girder transverse fell down. Pier P7 inclined severely, and the concrete of coping cracked (Fig.8). The Piers of Xiayu Bridge P3 and P4 broke completely. Girder 3#, 4# and 5# fell down (Fig.9).
From Fig.7, we can find that there is a fault near the bridge. The motion of bridge during the earthquake was highly influenced by the fault. According to the Table 2.2, we can find that the peak acceleration on the ground of Jiangyou Hanzeng Station, which is on the east side of the bridge and is only 1.5km from the site, reached 0.52g on NS. As the strong ground motion, all of the girders moved severely. Excessive displacements and inertia forces of superstructure caused some piers deflected or broken, result some of girders fell down.

Fig.8 Shisuoyi Bridge deck moved severely

Fig.9 Fall of 3# -5#girder of Xiayu Bridge

2.3. Miaoziping Bridge

The Miaoziping Bridge is located at the Wendu freeway which is from Zipingpu to Xuankou (Ⅹ intensity area). It started construction in 2003 and would open to traffic in this year. Main bridge is a 3-span, 470-meter-long (125m+220m+125m), prestressed reinforced concrete, continuous frame bridge. The substructure is RC monostyle rectangular flexible pier which high is 102.47m. And they are supported on 16 piles which depth of embedment is 60m. Approach bridges are a 2-span, 100-meter-long (2×50m) and a 17-span, 850-meter-long (17×50m), prestressed reinforced concrete, continuous girder bridge, whose piers are RC distyle rectangular piers. The plan and elevation drawing of Miaoziping Bridge is shown in Figure 10. The geological structure near the bridge site is shown in Figure 11. According to the Reference (Zhou, H.W., She, Y.L. and Li, H. , 2007), there are more than 120 faults on the site.

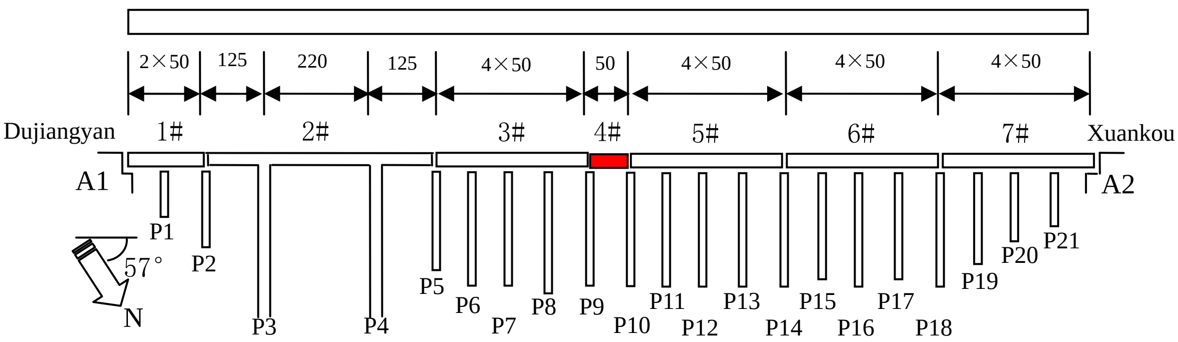

Fig.10 The plan drawing and elevation drawing of Miaoziping Bridge

During this earthquake, the severest damage of this bridge is 4# girder falling down. The other damages including the movement of 3# and 5# girder, the deflection of guardrail on Pier P5, and the ruin of block on P9 and P10.
Excessive earthquake action makes the excessive relative displacement between flexible pier and girder more than 1 meter that the bridge had originally been designed according to intensity Ⅶ (JTJ 004-89, 1990), which result in a span girder falling down.

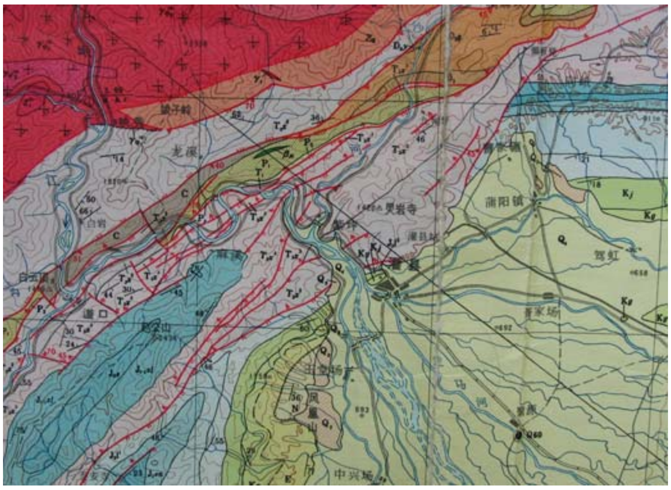

Fig.11 Geological structure near Zipingpu Reservoir

Fig.12 Left is 3# girder, right is 5# girder, 4# girder fell

2.4. Dujiangyan Gym Crossing

The Dujiangyan Gym Crossing is located at the national highway G213 (Ⅷ intensity area). The superstructure is composed of two bi-directional prestressed reinforced concrete continuous box girders and the substructure consists of RC circular piers. Laminated rubber bearings attach the superstructure to the substructure. The geological structure near the bridge site is also shown in Figure 11.

During the earthquake, the collision between girder and abutment at both ends of the bridge result in the wing wall of abutment cracked (Fig.13), expansion joint pulled off (Fig.14).

Strong inertia force caused the collision at the ends of girder, meanwhile continuous girder and rubber bearing accumulated the displacement at both ends of bridge, result in these damages.

Fig.13 Crack on the wing wall of abutment

Fig.14 Damage of expansion joint

2.5. Fanhua Bridge

The Fanhua Bridge is located in Mianyang city (Ⅶ intensity area), and which was completed in 2007. Main bridge is a 540-meter-long, 24-meter-wide, prestressed reinforced concrete, continuous plate girder bridge. Approach bridge is a 160-meter-long, 24-meter-wide, prestressed reinforced concrete, simply supported plate girder bridge. The superstructure is PC hollow core slab and the substructure is RC distyle pier.

In this earthquake, the concrete at the ends of girders were cracked. The guardrail at the expansion joint was damaged because of extrusion.

Strong inertia force caused the fixed bearings broken free, and the expansion side of girders slammed into each other.

Some of the characters of seismic disaster of girder bridges in the Wenchuan earthquake were as follows:

(1) Most of the severe bridge damage occurred in the region where there was geological structure change.

(2) Most of the damage occurred to bridges which design intensity is lower than actual intensity， even some of

them were rather new.
(3) Most of the damage was the result of inadequately designed connection details.
(4) Most of the bridge damage occurred along longitudinal axial.
(5) Generally, the performance of girder bridge damage includes: bearing breaking off, girder moving, girder slamming at the ends, concrete cracking, reinforced bar exposing, expansion joint pulling off, deck splitting, guardrail breaking, abutment or pier inclining, pier breaking, girder falling down. The most significant damage is the damage of substructure and the fall of girder, which will result to interrupt traffic. Other damages usually can not influence the capacity of bridge severely.

3. FACTORS CAUSING DAMAGE

There are two factors that caused damage to girder bridges. One is the influence of geological hazards, and the other is strong earthquake action.
During the Wenchuan earthquake, the geological hazards, such as collapse, landslides, mud-rock flow, soil liquefaction, mostly occurred in a mountainous area. Once the bridge was influenced by geological hazards, damage is always severe.
For the strong earthquake action, excessive inertia forces and displacements of structure are the main causes to result in the earthquake damages of girder bridges. The forms of earthquake damage are relative to the tectonic pattern of girder bridges. Generally, the design of girder bridge should satisfy the requirement of withstanding the level loads resulting from vehicle going forward or brake, in addition to satisfy all the requirements of vertical loads. Usually, the slight bend and slippage of beam slab are allowed to ensure normal using function of bridge. However, residual dislocation is not allowed. So the rolling bearing and the fixed hinge bearing are set at the end of every girder. Based on the tectonic pattern of girder bridges, the push load transferred by the rolling bearing is very small, and consequently, the earthquake energy will be mainly transferred from the substructure to the superstructure by the fixed hinge bearing when the strong earthquake motion comes, while the inertial force, resulting from the superstructure, will be transferred to the substructure by the fixed hinge bearing. Thereby the fixed hinge bearing on the longitudinal axial is easy to be damaged. Once bearings are damaged, the movement or collision of girder will occur. This kind of earthquake damage is often found in intensity Ⅶ or Ⅷ areas. When the inertia force of superstructure is larger, the bearing will be ruined, the movement and collision of girder will be more severe. For multi-span simply supported girder, the accumulation of displacement at some place may result in the girder falling down. Meanwhile, Stronger the inertia force of the superstructure feeding back to the substructure is, the more dangerous the substructure is. If the substructure is ruined, the bridge will surely collapse. In fact, the space between girders is so small that the fall of girder which results from the accumulation of displacement can be avoided, if the length with which the girder put on pier is proper. In practice, most of the collapse bridges result from the damage in the substructure. Once a span of girder falls, the vibration displacement of other spans will be out of control, and may result in the collapse of other spans. The earthquake damage of transverse bridge mainly is the dislocation of girder. If the integrality of superstructure is lack, may result in the side fall of partial edge girder.

4. COMMENT OF DEFENSE MEASURE

For the earthquake damage to girder bridges, the effective defense measures are as follows:
Firstly, choose the bridge site rightly, and avoid the areas where geological hazards maybe occur. If it can not be avoided, the proper measure should be taken to remove or prevent the possible unstable geology factors. Some rules in the highway bridge seismic design code (JTJ 004-89, 1990) are reasonable and feasible.
Secondly, for the strong earthquake action, it is the effective defense measure that isolates the influence of earthquake to superstructure and the feedback to substructure from superstructure to prevent the displacement of superstructure out of control, and assure the safety of substructure. Because the fall of girder is one of the severest earthquake damage to girder bridges, the current main measure of defense earthquake damage is to prevent the fall of girder. In addition to widen the width of support on pier, the measures usually includes: setting concrete blocks on the cap beam of pier, using the bolt and steel plate to link simply support girders,

thickening bearing anchor bar, setting the rubber bearings and dampers, and so on. In fact, the first three above can not reduce the inertia force of superstructure, on the contrary, may strengthen the action of the feedback to the substructure, and aggregate the risk of the substructure damage. Setting the rubber bearings and dampers only moderate forces generated from earthquake, can not eliminate fundamentally the inertia force of superstructure and feedback to substructure. For side fall of edge girder, it is an effective measure to strengthen the integrality of superstructure.

5. NEW METHOD OF DEFENSE MEASURE

As mentioned above, for the strong earthquake action, the current defense measure is not perfect. It is necessary to find a new method according to the earthquake damage regular pattern of girder bridges. The new method should isolate the earthquake energy to the superstructure as much as possible, and reduce the load of substructure. Furthermore it can not influence the normal using function of bridge. Accordingly, this paper proposes to change the construction of girder bridges as follows:
Firstly, change all the bearing to the rolling one. Consequently, the superstructure can keep basically isolating from the earthquake influence. Secondly, set the rubber pad or other elastic pad between the girders or between the girder and the breast wall of abutment. In this way, not only the possible impact action can be buffered, but the displacement of girder can be limited (Fig.15).
In these changes, normal using function of bridge is not to be influenced, but the horizontal aseismic computation model is changed, which is simpler and more reasonable (Fig.16). The inertia force of superstructure is primarily eliminated, and the action of earthquake at abutment or piers is reduced. It is benefit to assure the safety of substructure, avoid all the possible earthquake damages.

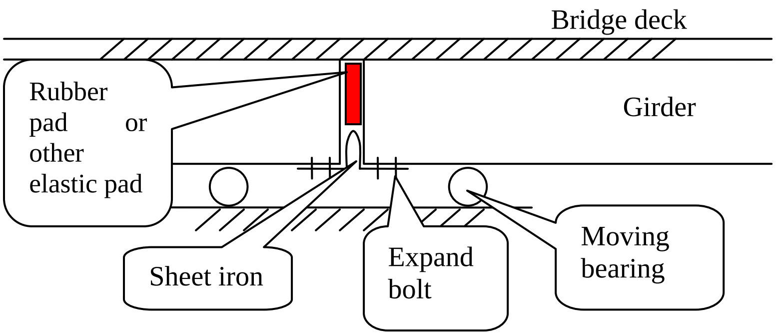

Fig.15 New constructional measure on girder bridge

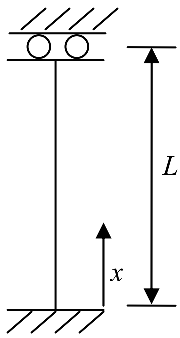

Fig.16 The sketch of pier

For example, a multi-span simply supported girder bridge is shown as Figure 17. The weight of a span superstructure G_{sp} is 1669.06kN. The coping on the pier is 7.4-meter-long, 1.4-meter-wide, 1.1-meter-high, which weight G_{cp} is 263.7kN.The distyle pier is 1.2-meter-dia, 6.9-meter-high, which weight G_p is 390.2kN. The Young's modulus E is 2.6×10^7kN/m^2. Cross-section moment of inertia I is 0.204m^4. The foundation is two lays footing. The type of site soil is Ⅱ. The result of account by conventional code method and new method is list in Table 5.1.

Table 5.1 The comparison of new method and code method

	T(s)	β	C_i	C_z	Intensity Ⅶ			Intensity Ⅷ			Intensity Ⅸ		
					Q_e(kN)	M_e(kNm)	M_t(kNm)	Q_e(kN)	M_e(kNm)	M_t(kNm)	Q_e(kN)	M_e(kNm)	M_t(kNm)
code method	0.513	1.33	1.3	0.3	105.3	0	842.5	210.62	0	1684.99	421.25	0	3369.984
new method	0.246	2.25			52.59	114	295.5	105.18	228	591	210.36	456	1182

In Table 5.1, T: fundamental period; β: amplification factor; C_i: significance modify coefficient; C_z: integration influence coefficient; Q_e: shear at the end of pier; M_e: moment at the end of pier; M_t: moment at the top of pier.

By all appearances, new method effectively reduced the relative displacement between girder and pier, also reduced the internal force, assure the safety of pier.

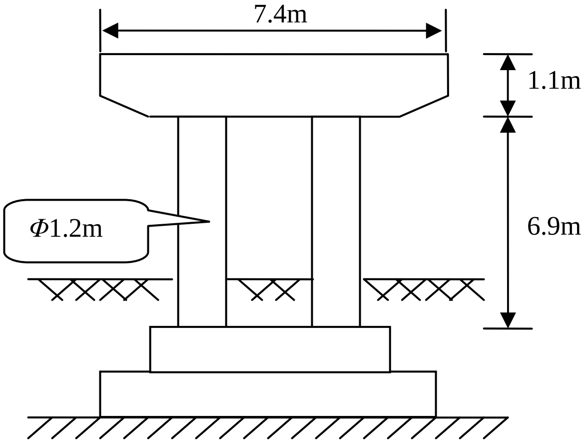

Fig.17 Example

6. CONCLUSION

During the Wenchuan earthquake, most seismic design intensities of girder bridges which meet with strong earthquake motion is Ⅶ. However, the actual intensities are much more than design intensities. This is out of the expectation. From earthquake damage, we also get some revelations. To avoid the damage of girder bridges in earthquake, the key is reasonable defense measure. For the damage caused from earthquake action, a new construction measure was proposed, which is simple, economical and effective and easy to take. It changes the transmission of earthquake energy, reduces the relative displacement between superstructure and substructure, and assures the safety of substructure, to avoid earthquake damage. Certainly, as a new measure, a lot of experiments should be done to check the feasibility and effectiveness of the one, which will be the coming work.

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