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Investigation of the Bridge Seismic Performance in the West of China

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SUMMARY

This paper discussed the active features of earthquakes in China, especially in the west of China. They are basically described as frequent, violent and active. The other feature of the earthquakes in West China is that the earthquakes develop in an undulatory rhythm. The writers get Tai Zaogou Bridge as an example to study the typical bridges' aseismic performances in West China.

INTRODUCTION

China is one of the most important earthquake areas in the globe. It lies between the two large seismic belts----Circum-Pacific and Eurasian seismic belts. Earthquakes began to visit China frequently since the old ages. According to the historical records, there were thousands of severe earthquakes that brought calamities to our people. The disasters caused by earthquakes took a large proportion among those caused by floods, droughts, earthquakes, winds, insect pets, hails and plague. To survey from the earthquakes occurred in our country in the past over two thousand years, the earthquakes in China are frequent, violent and widely scattered. This article will make a brief summary on the general characters of the earthquakes in China and the earthquakes' active features since the foundation of the People's Republic of China, and the calamities brought by earthquakes.

ACTIVE FEATURES OF EARTHQUAKES IN WEST CHINA

Basic Features of Earthquakes In The West of China: Frequent, Violent and Active

Our history has very rich records about the earthquakes, which could be traced back to more than three thousand years ago. The earliest record found out so far is the earthquake hit the Tai Mountain, Shandong

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in 1831 BC. But because of the differences in time and culture, the records are also differently specific. For example, there are a few records about earthquakes before AD1500, the records at that time were mainly about the earthquakes happened in the areas along the middle-lower reaches of Yangtse River and Yellow River. Although the records became richer since the Ming Dynasty, the records about earthquakes in West China kept few. With the help of instruments, our files about earthquakes got more integrated and systematic since 1900.

According to the facts mentioned above, the materials before the 20th century were based on historical documents, records and investigations. And the records since the 20th century mainly came from those got by instruments and investigation on the spot. The files（especially those about the earthquakes below 6） during the two stages make a sharp comparison in whether complete or not. Consequently, we concluded the basic data of the earthquakes before and after 1900. Please see the result as follow:

Before 1900, equal or above 8---eight times. The strongest (8.5) is the one attacked LV County and Yancheng in 1668. between 7.0 and 7.9---32 times; between 6.0 and 6.9---144 times; above 4.75---581 times. (Figure 1)

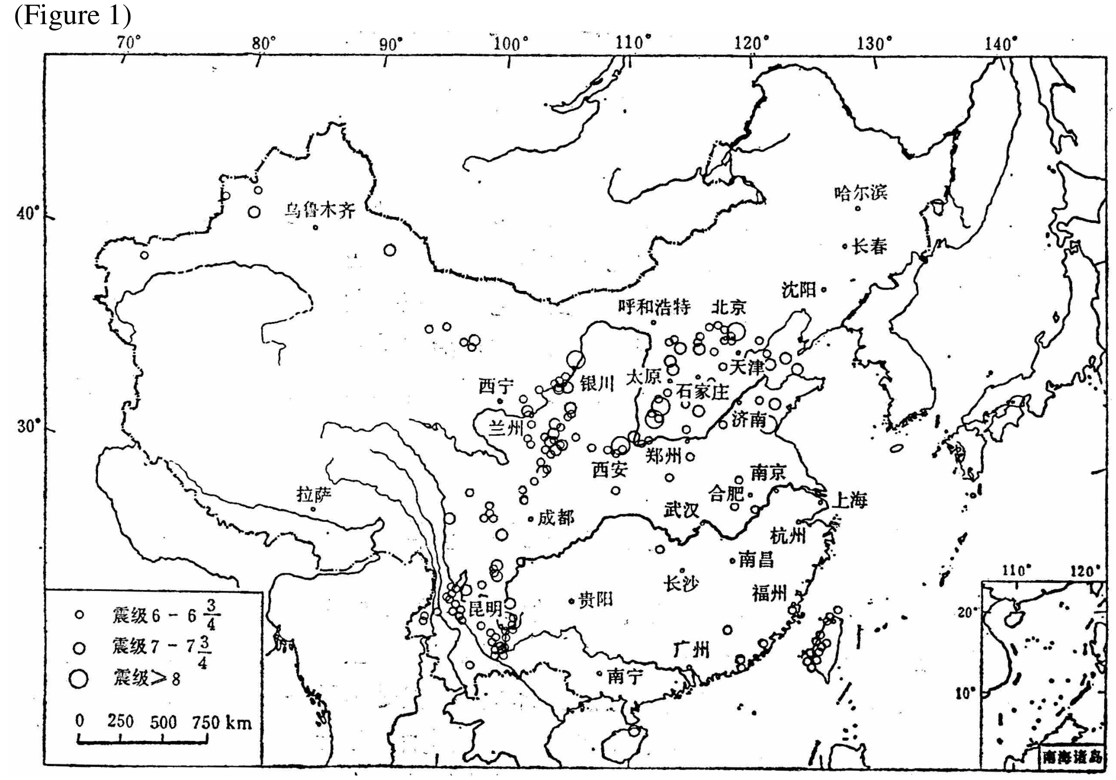

Figure 1 Distribution of Strong Earthquake Epicenters During 1831BC--AD1900

1900-1988: equal or above 8 .0 --- 9 times, of which seven times happened in mainland and twice in Taiwan. The most violent earthquakes are the ones happened near Chayu in Tibet (8.6) in 1950 and in Haiyuan, Ningxia (8.5) in 1920; 7.0-7.9 --- 94 times, of which 59 times in mainland and 34 times in Taiwan. 446 times 6.0-6.9, of which 271 times in mainland and 175 times in Taiwan; 3756 times above 4.75. (Figure 2)

According to the above statistic result, since the 20th century, the frequency of earthquakes above 7 happened in our country is 1.17 times per year, of which, 0.75 time per year in mainland and 0.42 time per year in Taiwan. The frequency of earthquakes above 6.0 is 6.24 times per year, of which, 3.83 times per year in mainland and 2.41 times per year in Taiwan. And the earthquakes equal or above 4.75 is 42.7 times per year.

It is not difficult to find that the earthquakes in China are surely frequent and violent. To compare all the earthquakes happened on the earth, our strong earthquakes take an important position. For example, there were 1529 earthquakes above 7.0 attacked the earth between 1897 and 1977. The average is 18.9 times per year. Our country took 6.5%. And among the earthquakes in the global mainland, our strong earthquakes took the larger and larger proportion. It's about 1/4 to 1/3.

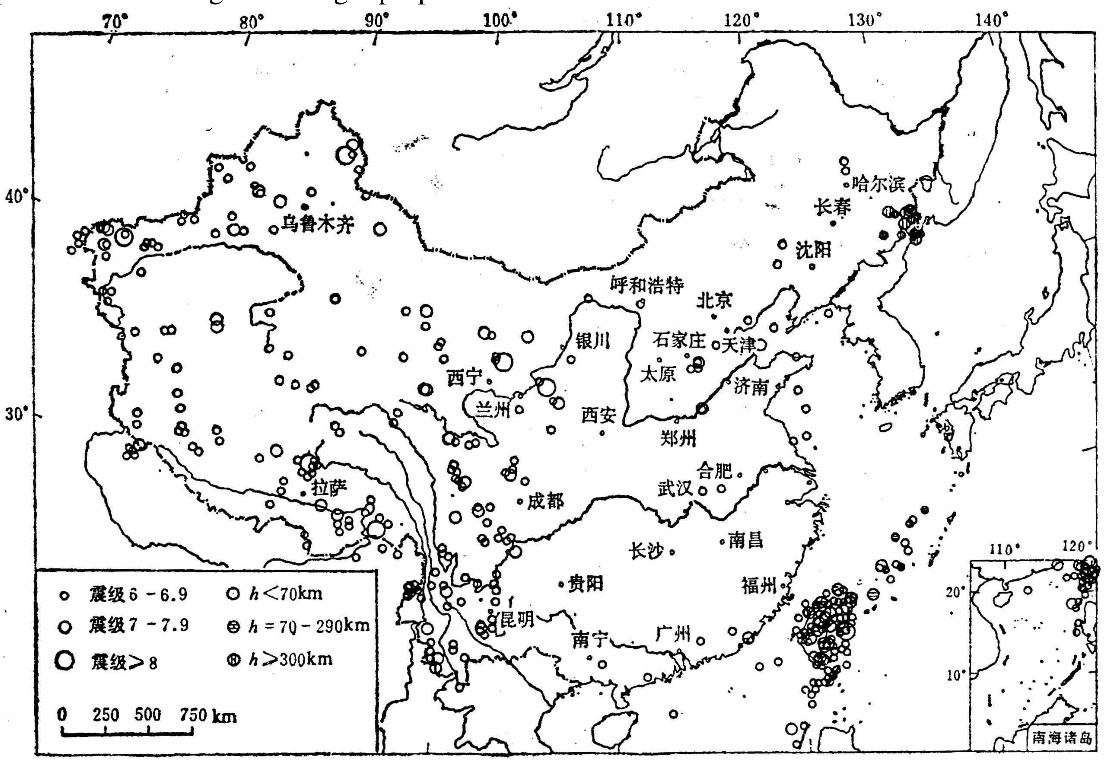

Figure 2 Distribution of Strong Earthquake Epicenters During AD1901-AD1969

The earthquakes occurred widely in China (Fig1, Fig 2). The 28 provinces (cities, autonomous regions) except Zhejiang province and Guizhou province were visited by earthquakes above 6.0. Among the 28 provinces (cities, autonomous regions), 18 provinces (cities, autonomous regions) had earthquakes above 7.0, which took 60% among the 30 provinces around China. Taiwan is the most active seismic area in China. Among the 549 times of earthquakes from 1901 to 1988, Taiwan occupied 38.6%, that is, 212 times. The earthquakes in China mainly take place in Qingzang Plateau, Sikiang and North China, and they scarcely go to Northeast, East China and South China. Most of the earthquakes in China are shallow earthquake, The depth of seismic origin of the earthquakes in eastern areas are generally within 30 kilometers, while those in western areas are within 50-60 kilometers. Middle-focus earthquakes distribute in Pamirs Area near Sinkiang (100-160 kilometers) and in Taiwan (270 kilometers at most). A few plutonic earthquakes could be seen, they only occurred along the border in the east of Jilin and Hei Longjiang province.

Rhythmic Undulatory Earthquakes In the West of China

With the changes in time, the earthquakes distributed uneven. It is a developing course with the alternation of relatively quiet and obviously active. The course that frequency is low, intensity is less violent and strong earthquake becomes relatively quiet could be called "quiet period", and in reverse, the course is called "active period". So by this principle, we can make out the earthquakes' undulatory features of our country's principal earthquake areas. The course like QUITE---ACTIVE---QUITE appeared in every earthquake area shows a quite clear rhythmic character. The intensity of the earthquakes in different seismic areas is quite different, too. For example, earthquakes' movement period in Taiwan and South Qingzang is shorter. It's about decades of years; and it is about one hundred years in the mid of Sinkiang and Qingzang, while the movement period in North China and North Qingzang is longer---it's about 300-400 years. In the 20^{th} century, the average of the strong shock in our mainland could be concluded as once quietude in 14 years and 3-4 palingenesis of active movement in 16 years.

Strong earthquakes in different active period have different relative concentrated areas, which are called leading role areas. And with the change of active periods, the leading roles change, too. At the beginning of the 20^{th} century, the earthquakes above 7 concentrate in the northwest of Sinkiang, and they transferred to Gansu and Ningxia and to the north of Sinkiang in the second active period. The strong shocks in the third active period mainly crowded in Qinghai and Tibet. And then they went to Sichuan, Guizhou and the two concentrate areas in North China during the fourth active period. The regular change of the strong earthquakes' leading areas has something to do with adjusting and changing the regional stress field of the inland tectonic body of our country and the dynamic factors of plates borders.

ASEISMIC ANALYSIS OF TAI ZAOGOU BRIDGE IN SHANXI PROVINCE

Project Summary

Tai Zaogou Bridge is an oversize bridge over the national highway trunk line Er Lianhaote—Yumenkou, Hekou Road—Yanliang segment. After comparing many plans and designs, the engineers finally decided to adopt 80m+130m+2*170m+100m prestressed concrete continuous rigid framed structure bridge. Two independent bridges—up track and down track, make up the whole bridge. The bridge pier adopted reinforced concrete thin-walled hollow pier and cast-in-site bored pile foundation. The construction method is main beam cantilever pour method.

Technical Standards

Class of Highway: High speed highway;

1) Width of Bridge Deck: 0.5m (bump-proof rails)+12m (carriage way)+3.0m (intermediate belt) +12m (carriage way)+0.5m (bump-proof rails)
2) Design Load: automobile---exceed 20 grade, trailer car---120
3) Basic Earthquake Intensity: 7.0; Crest value acceleration of earthquake is 0.15g.

Analysis of Structural Dynamics Characteristics

Foundation of Computation Mode

The bridge superstructure is prestressed concrete variable cross-section rigid framed structure box beam. The bridge deck is 28m in width, and it is formed by two left-right separated single cell box cross-sections. From the first hole closure section to the second hole closure section, the beam depth of the box beam base is 6m, the beam depth of mid-span beam is 3.2m, the thickness of web plate is 0.4m and the thickness of base plate are 0.3~~0.7m respectively. From the second hole closure section to the fifth hole closure section, the beam depth of the box beam base is 9m, the height of mid-span box beam is 3.2m, the thickness of web plate is 0.4m or/and 0.65m, the thickness of base plate is 0.3~1.0m. The width of all the box beams top plates is 13.5m. The base plates are 8m in width, the cantilevers of flange plates are 2.75m long. The curve of box girder changes as second-order parabola. All parts have no transverse diaphragm except No.0 board and the end of side span.

The bridge has four piers. All of them are thin-walled hollow piers. No.1 pier is left-right separated, and it is 26.9m high. The pier shaft is 8*4m, and the thickness of wall is 0.5m. No.2, No.3 and No.4 are also left-right separated. The heights of these piers are respectively described as 120.54, 86.63 and 75.14. In 30 meters upwards from the capped slab top of No.2 pier, the pier shaft changes from 8*10.5m to 8*6.5m, and the wall thickness changes from 1.05m to 0.55m. In 15 meters upwards from the capped slab top of No.3 pier, the pier shaft changes from 8*8.5 m to 8*6.5m, and the wall thickness changes from 0.8m to

0.55m. In 15 meters upwards from the capped slab top of the No.4 pier, the pier shaft changes from 8*8m to 8*6m, and wall thickness changes from 0.8 to 0.55m.

Both piers and main girders are analyzed by three-dimensional finite element beams method. The main girders are single cell box cross-sections. By referring to the division of the beams sections during construction period and the disposal of the prestressed bundle of reinforcements, and by considering the real conditions of the bridge, we divided the main beams into 194 units. The units in the range of variable cross-section are treated as variable cross-section unit; the whole bridge is divided into 255 units.

On the basis of the bridge's reality, we suppose the following boundary conditions: pier foundation is solid; the joints of main girders and piers have the same displacement, and they are treated as stiff connection; Both ends of main girders are set as rolling bearings along the bridge. Please refer to the following calculating chart (Fig 3).

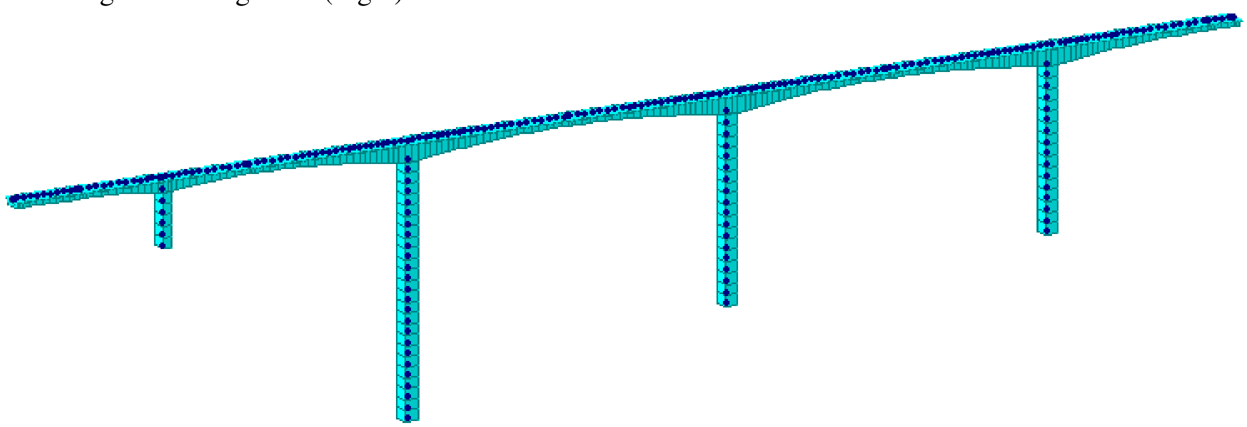

Figure 3 Calculating Diagram of Main Bridge Structure

Dynamic characters analysis

According to the above mentioned calculation mode, the writers calculated the structure's natural vibration characteristics. According to the necessity of anti-earthquake, the writers computed the former 80 steps vibration mode. Form 1 gives out the natural vibration features of the preceding 15 steps.

Form1 Structure's natural vibration feature of the preceding 15 steps

Model No.	Frequency (cycle/sec)	Cycle (sec)	Vibration Mode Features
1	0.220482	4.535512	main girder step 1symmetrical cross curve
2	0.274334	3.645187	No.2,No.3, No.4 pier longitudinal curve
3	0.326286	3.064798	main girder step1 antisymmetrical cross curve
4	0.556732	1.796195	No.3 pier cross curve
5	0.685993	1.457742	main girder step 1 symmetrical vertical curve
6	0.871747	1.147122	main girder step 1 antisymmetrical vertical curve
7	0.890953	1.122393	main girder step2 symmetrical cross curve
8	1.122136	0.891158	main girder step2 symmetrical vertical curve
9	1.231204	0.812213	No.1 and No.2 pier cross curve
10	1.433113	0.697782	main girder step3 antisymmetrical vertical curve
11	1.445398	0.691851	No.2 pier cross curve
12	1.586080	0.630485	No.1, No.2 pier cross curve
13	1.640473	0.609580	No.2 pier vertical curve
14	1.763890	0.566929	main girder step3 antisymmetrical cross curve
15	2.011049	0.497253	No.2 pier vertical curve

The study shows**:** to counting the former 20 steps vibration mode, their longitudinal and cross vibration contributive ratio are totally quite close to 100%. The ratio exceeds the requirement of UBC specification of America. In our country, there is no regulation about this in the specifications relates to bridge's anti-earthquake characters. So it shows that the former 20 steps vibration mode already included main dynamic characters of structure. The vibration mode reflected by three-dimensional finite unit is comprehensive, and we can primely grasp the structure's dynamic features.

Aseismic analysis of Structure
According to the design and the specification, we adopted Response Spectrum Method to calculate the seismic response of structure. From the above analysis, we know that the former 80 vibration modes from every direction are close to 100% in mass, so Response Spectrum Analysis using the former 80 steps modes can meet the precise requirements of the engineering.

In the aseismatic design of Tai Zaogou Bridge, the engineers adopted two kinds of response spectrum level----10% exceeds probability in 50 years (P1) and 20% exceeds probability in 50 years (P2). The vertical earthquake input response spectrum is the same as the horizontal one, but the crest value of acceleration of vertical direction is 2/3 times than that of horizontal direction. SRSS method is used in vibration mode combination.

Supposing the anti-violence is one degree more the basic seism intensity, and suppose we set protection at 8 degree. According to the geological conditions that structure is in, we get the field of second class; According to the highway conditions below the bridge, we get 1.3 as coefficient for importance adjustment of structure, and we get 0.2 as synthetical effect coefficient.

According to specification response spectrum, we respectively compute the seismic effect when three directions independently act on earthquake effects. Please refer the result on fig 4, fig 5 and fig 6.

By comparing the internal force under the effect of earthquake and the internal force under the force of permanent load and basic variable load, the former force is quite small. Hence earthquake does not control design.

Under the effect of earthquake load, the response of the continuous rigid framed structure bridge is decided by the distribution of its stiffness and mass. The inertia force of main girders is allocated to every pier to bear according to every flexible pier's stiffness. If there are many piers in the same design, we hope every pier bear average force because it is benefit for integrated earthquake resistance of structure.

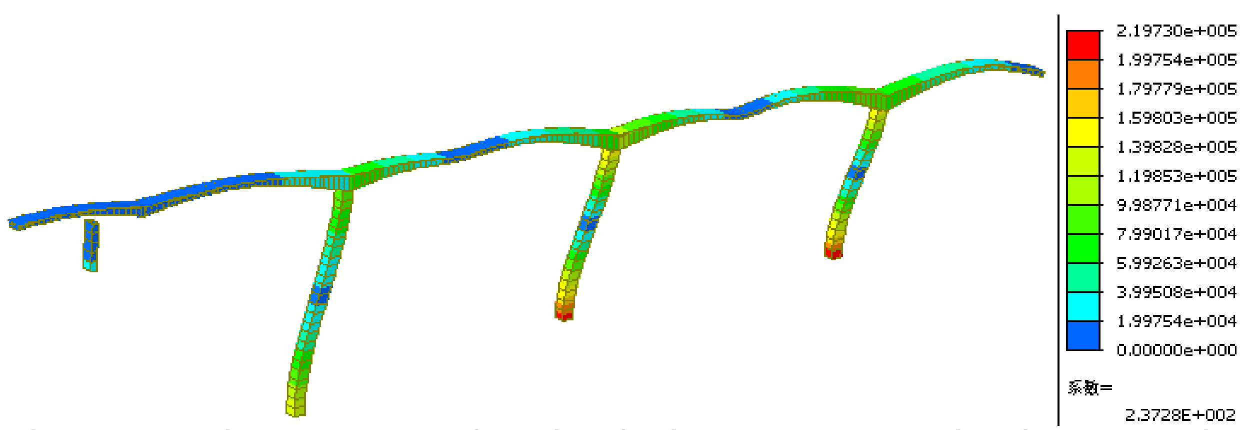

Figure 4 Bending Moment and Deformation of Main Beam Under the Action of Earthquakes in longitudinal direction

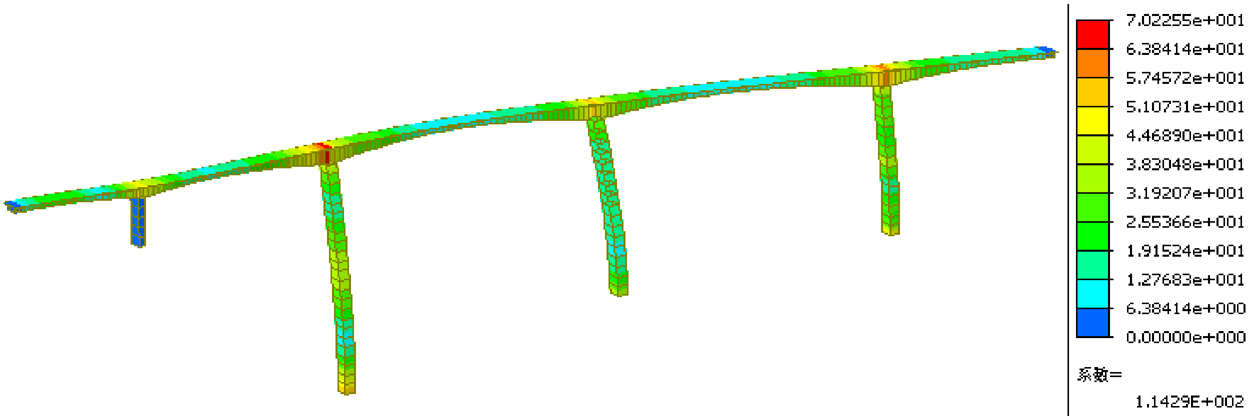

Figure 5 Bending Moment and Deformation of Main Beam Under the Action of Earthquakes in transverse direction

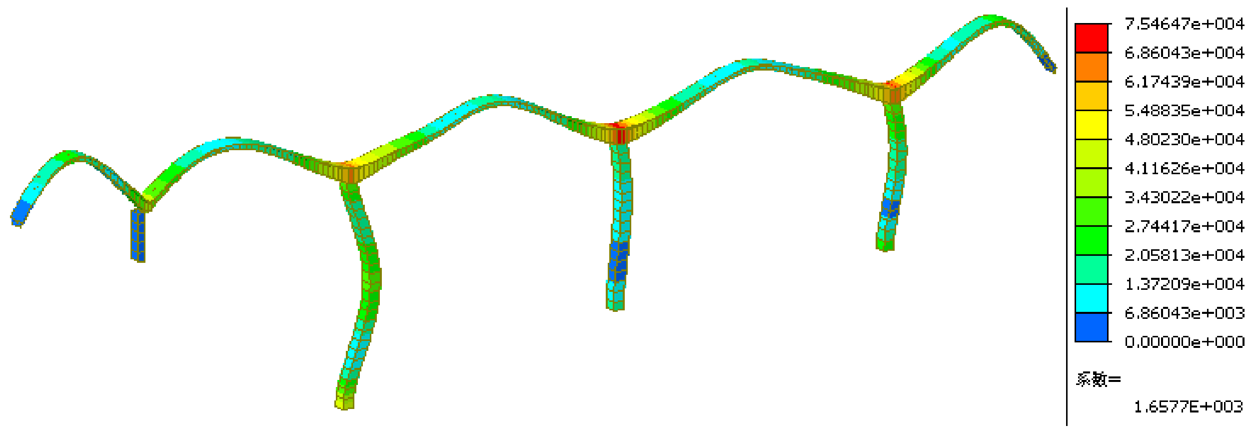

Figure 6 Bending Moment and Deformation of Main Beam Under the Action of Earthquakes in vertical direction

On the other hand, the main girder and pier of continuous rigid framed structure are reinforced. In the conceptual aseismatic design, the emphasis should be put on the choice of plastic hinge. As for bridge structure, plastic hinges usually appear on especially reinforced pier column, where they are easier to be examined and fixed.

In the aseismic computation of Tai Zaogou Bridge, we chose P1 response spectrum, and input respective along the directions of longitudinal + vertical, transverse + vertical to analyze the earthquake response of structure. We got the following internal force response enveloping charts. (fig7, fig8, fig9, fig10, fig11)

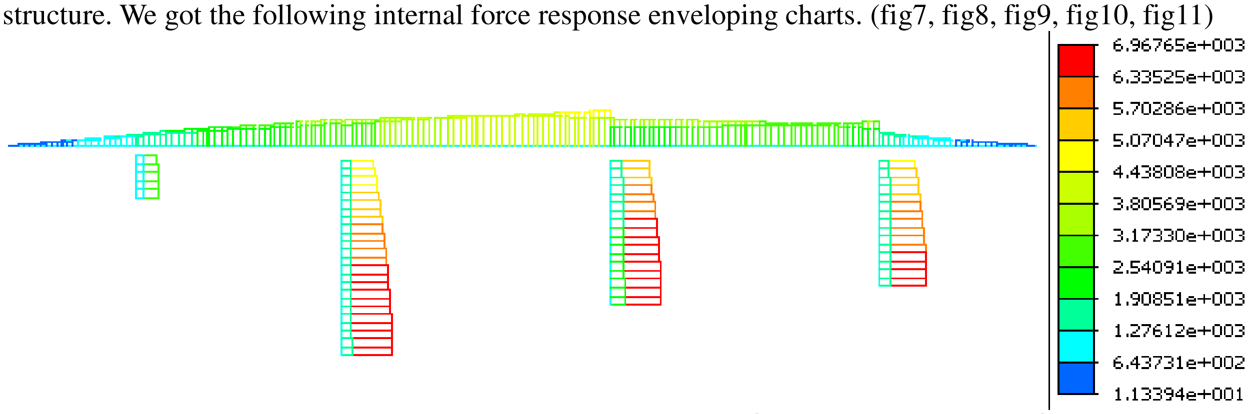

Figure 7 Axial Force Enveloping Diagram (longitudinal + vertical)

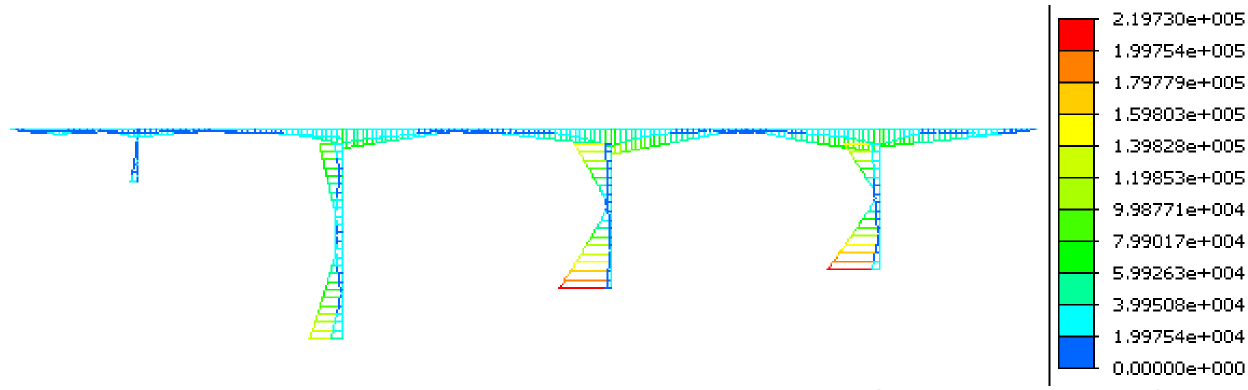

Figure 8 Longitudinal Bending Moment Enveloping Diagram (longitudinal + vertical)

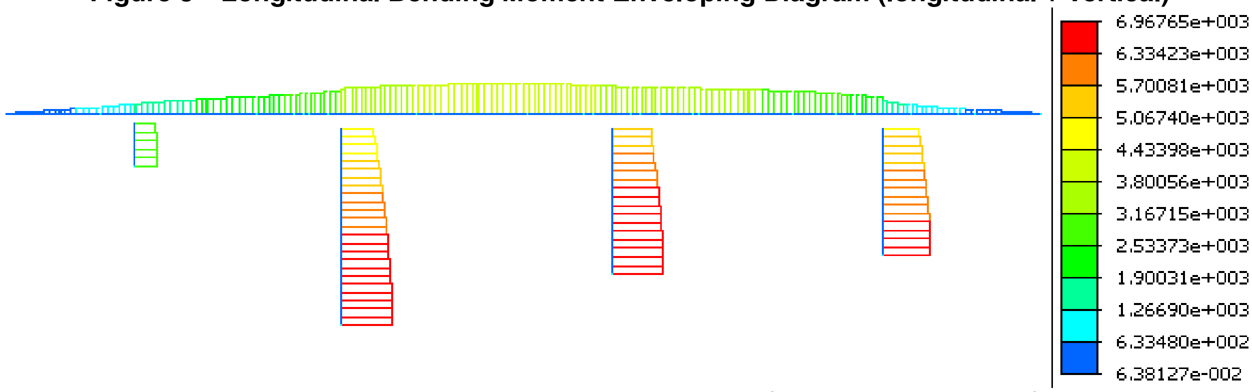

Figure 9 Axial Force Enveloping Diagram (transverse + vertical)

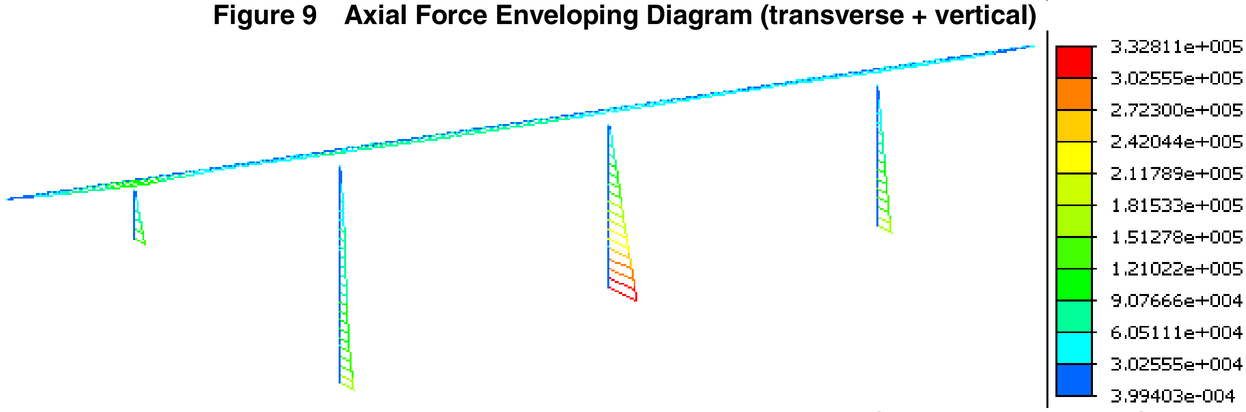

Figure 10 Horizontal Bending Moment Enveloping Diagram (transverse + vertical)

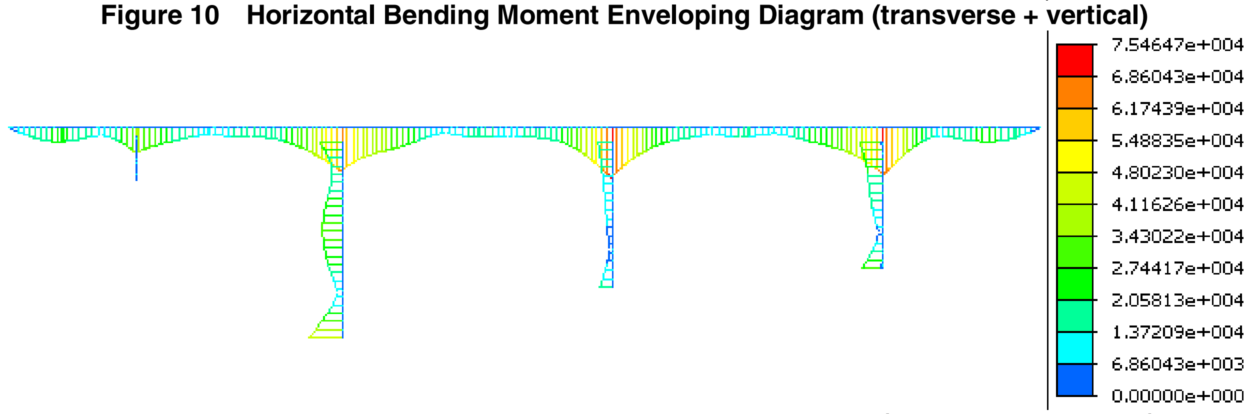

Figure 11 Longitudinal Bending Moment Enveloping Diagram (transverse + vertical)

By referring to the inner force response enveloping diagrams and structure design diagrams, we can judge that the expected parts, which will bring plastic hinge are the foundation and top of the pier column (weak parts in resisting earthquakes). These two parts' aseismic safety could be assured by correct reinforcement arrangement design, so the blue print needn't to be revised.

CONCLUSION

To see from the distribution of earthquakes, China lies in the joint of two great global earthquake belts. The west of China is always an area where earthquakes come often and strong earthquakes happen frequently. When the central government made the decision to develop the west of China, the leaders made the strategy " Traffic goes first, moderately goes before need." So the traffic line should start predictive studies of important technical problems. In the studies of disasters proof and disasters reduction, the studies of lifeline engineering's disasters proof and reduction is an important element, and the study of bridge structure is especially important among them. So it is an important study task to start studies on western bridges' anti-earthquake performance and the reinforcement of present bridges.

The earthquake response analysis of Tai Zaogou Bridge shows that continuous rigid framed structure adopted by the bridge, and the bearing set on No.1 pier top to connect with main girder, and the short No.1 pier could greatly reduce the longitudinal earthquake load, so that the longitudinal earthquake load of No.2, No.3, and No.4 pier could be evenly allotted to the structure. This kind of structure has better integrated anti-seismic performance. Through the design practice of the bridge, we got better understanding to the forcing characteristic and dynamic features and design keys of reinforced concrete continuous rigid framed structure bridge. The understanding provides a beneficial reference to similar bridges' design and construction in the future.

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