Analysis of Seismic Isolation Effects on a Reverted L-shaped Pier Bridge in High Seismic Intensity Region with Finite Element Simulation

Longfei Wang*
Gansu Province Transportation Planning, Survey & Design Institute Co. Ltd., Lanzhou, Gansu, China
*Corresponding author email: wanglongfei76@126.com

Abstract. The seismic response of urban special-shaped bridges is large, and the consequence of these bridges’ failure is very influential, therefore, the seismic response of this kind of bridges must carefully be calculated and seismic measures of isolation should be used for them. Simulation methods was studied for common used seismic isolation structures such as the rubber bearing, high damping rubber bearing, friction pendulum bearing and block. Four layouts of those seismic structures were set up for an actual reverted L-shaped pier bridge, which were correspondingly four simulation cases. The seismic responses of the bridge were analyzed and comparatively studied in all simulation cases, as a result, the seismic performance and seismic isolation effects of those structures were researched for the bridge, and the isolation design methods were gained. The results show that measures of isolation can reduce largely the seismic response of this kind of special-shaped bridge, high damping rubber bearings have remarkable effect and make the responses among piers more even, and setting reasonably blocks with clearance can make full use of the seismic performance of structures of the bridge.

Keywords: Seismic isolation; High damping; Friction pendulum; Seismic response; Simulation.

1. Introduction

Earthquakes are very widespread in China, so many cities and even large cities are in high seismic intensity regions[1]. With the continuous expansion and development of cities, more and more bridges in cities are constructed to improve their traffic conditions. Because of the limitation and influence of surrounding buildings, roads and underground pipelines, many urban bridges have to adopt special-shaped structures, such as the inverted L-shaped pier bridge, large span gantry pier bridge, large curvature curved bridge and long cantilever pier bridge. These special-shaped bridges are not only structurally complex, but also more sensitive to earthquake actions, therefore, the seismic response of these bridges is relatively large. Because the collapse of an urban bridge easily causes a large number of casualties and a heavy economic loss, it is very important to reduce the seismic response of urban bridges and improve the seismic performance of structure of these bridges.

The traditional seismic design method is always to make the structure have enough strength and rigidity, in order to achieve the resistance of structure to earthquakes of fortification target. This kind of design method, which is "resist the strong with strong force", often has to increase the geometric size and overall weight of structure of the bridges. In this case, the method not only does not reduce the seismic response of structures, but also may increase their seismic effects, as a result, sometimes it reduces the seismic safety of bridges[2]. The seismic isolation design method for a bridge is to reduce seismic response of structure by prolonging the period of natural vibration of the bridge and consuming its...
seismic energy. In this way, it not only saves materials of structure, but also reduces harm of earthquakes to the bridge, therefore, more and more attention of bridge engineers has been paid to the seismic isolation design method[3]. In urban bridges, such structures as the rubber bearing, high damping rubber bearing, friction pendulum bearing and block are often used for the seismic isolation design. However, seismic isolation effects of these structures on special-shaped bridges is rarely studied, so it is necessary to analyze and study the seismic isolation of urban special-shaped bridges in cities in high seismic intensity regions.

Taking a inverted L-shaped pier continuous small box beam bridge in actual engineering as the research object, this paper comparatively analyzes the seismic isolation effects of the rubber bearing, high damping rubber bearing, friction pendulum bearing and block on the bridge by using a nonlinear time history analysis method, finds out rules of the seismic isolation effects of these structures, and establishes seismic isolation design methods for this kind of special-shaped pier bridges.

2. Method for Analyzing Seismic Isolation Effects
Response spectrum method and time-history method are ways commonly used for analyzing seismic response of bridges. The response spectrum method whose concept is simple is convenient and quick for directly calculating the maximum values of seismic response of structure, so it's very widely used. Because this method can not reflect the whole process of an earthquake action, and it is difficult to consider geometric material nonlinearity of structure, boundary nonlinearity and traveling wave effect of earthquake, it is not very suitable for calculating complex special-shaped structures and large scale bridges. The time-history method can analyze all kinds of nonlinearities of structure and has fairly good applicability for structures, but it is more dependent on the accuracy of seismic waves, and takes a long time to calculate seismic effects, which requires computers having high performance. Because the seismic isolation analysis of a bridge involves many nonlinearities[4], the nonlinear time-history method is better to use for calculating seismic isolation effects. In this method, the corresponding nonlinear models for different damping and isolating structures are used in simulating seismic response of the reverted L-shaped pier bridge.

2.1. Rubber Bearing
The rubber bearing is a commonly used form of supporting for bridges. Because it is elastic, which allows relative displacement between the superstructure and substructure of a bridge, it has a seismic isolation effect for the bridge. In the seismic response analysis of structure, a rubber bearing can be simulated by a spring with certain stiffness. Firstly, the elastic stiffness of a rubber bearing is calculated by using its characteristics, and then the elastic stiffness is given to a spring element which is used to simulate the rubber bearing in finite element software.

2.2. High Damping Rubber Bearing
A high damping rubber bearing is made of material of high damping rubber, which can be got from natural rubber being added flexible graphite, or be made of polymer synthetic material. This synthetic high damping rubber not only has good damping performance, but also possesses excellent resistance to deterioration, so the high damping rubber bearing of polymer synthetic material shows a good development potential. The high damping rubber bearing can be simulated by the force-displacement hysteretic model, which can considering nonlinearities of material and energy dissipation under earthquake actions. Fig. 1 shows the hysteretic model of a high damping rubber bearing, where F is force, Fy is yield force, K1 is the first stiffness, K2 is the second stiffness, Ke is effective stiffness, S is displacement.
2.3. Friction Pendulum Bearing

A friction pendulum bearing under the action of static force, which then is like a fixed bearing, can better resist and distribute the forces of bridge coming from longitudinal slope, temperature and impact. When the bridge is under a highly intensive earthquake action, shear bolts of the bearings are cut, and their limit devices open. Then the bearings do not let seismic energy to be transferred from piers to beams, and consumed seismic energy through rubbing between arcs of the friction pendulum bearings. As a result, seismic energy of the bridge decreases constantly, and seismic response of the structure is relatively small. The most advantage of friction pendulum bearing is that when the highly intensive earthquake is over, bearings can automatically reset under the force of resilience of arcs in the bearings, and the structure recovers for the use of bridge. When displacement is not very large, the restoring force of a friction pendulum bearing[5] can be expressed by

$$F = \frac{W}{R} \cdot D + \mu \cdot W \cdot \text{sgn}(\dot{\theta})$$  \hspace{1cm} (1)

where $F$ is restoring force, $R$ is radius of the sliding arc, $D$ is isolation displacement in design, $\mu$ is factor of sliding friction, $W$ is vertical load of the bearing. The second stiffness of a friction pendulum bearing can be expressed as

$$K_e = \frac{W}{R}$$  \hspace{1cm} (2)

According to the mechanical characteristics of friction pendulum bearing, a hysteretic model for it can be formed as Fig. 2, where $F_y$ is yielding force. The effective stiffness and viscous damping ratio [5] can be expressed by the following Eq. 3 and Eq. 4.

$$K_e = \frac{W}{R} + \frac{\mu \cdot W}{D}$$  \hspace{1cm} (3)

$$\zeta_v = \frac{2 \mu R}{\pi D}$$  \hspace{1cm} (4)

2.4. Block with Clearance

In areas with low seismic intensity or in simple bridges, blocks are often used to limit the lateral displacement of structure of a bridge under earthquake actions. In order to reduce the impact between beams and blocks, blocks are usually affixed with a layer of rubber buffer. In this case, the block can be simulated by a spring with high stiffness got through calculating. Sometimes, a clearance can be set between the block and main beam in order to make full use of the advantage of block in seismic isolation. When the relative displacement of structures at the bearing is smaller than the reserved clearance, the blocks are not involved in interactions of the structures in the bridge. When the relative displacement is...
more than the reserved clearance, the blocks will limit some relative movement of the structures, in which blocks like springs with high stiffness. The block with reserved clearance can be simulated by a spring element with a certain clearance in finite element software. Fig. 3 shows the mechanic model of a block with clearance.

![Mechanic model of block with clearance.](image)

Figure 3. Mechanic model of block with clearance.

The force-displacement formula of this model can be expressed as

\[
F = \begin{cases} 
K(S + O), & (S + O \leq 0) \\
0, & (S + O > 0) 
\end{cases}
\]

where \( F \) is elastic force, \( K \) is elastic stiffness, \( S \) is elastic displacement, \( O \) is reserved clearance.

3. Simulation and Analysis of Seismic Isolation Effects on the Bridge

The reconstruction project of Xiaoxihu interchange in Lanzhuo in China consists of a group of overhead urban bridges. Because of complex alignment of the interchange, numerous underground pipelines and the restriction by surrounding unites and buildings in the city, many special-shaped structures are adopted for bridges in the urban interchange. One of these is the reverted L-shaped pier continuous small box beam bridge which is very sensitive to earthquake, and the project lies in VIII degree seismic intensity region. This paper selects a typical reverted L-shaped pier bridge to study, in order to find out the rules of seismic isolation effects of layout of those isolating structures previously mentioned.

![Section of the reverted L-shaped pier bridge (unit: cm).](image)

Figure 4. Section of the reverted L-shaped pier bridge (unit: cm).

3.1. Spatial Finite Element Modal of the Bridge

The bridge for analyzing is a continuous small box beam bridge with 4 spans of 30m in the project. Its substructure consists of reverted L-shaped piers and pile foundations. The size of piers is 1.8mx2.8m, and the capping beam is 10.8m long and 1.8m wide. All piers are prestressed concrete structures. The superstructure of the bridge is simple continuous small box beams. There are four beams in every span, the height of which is 1.6m and the distance between which is 2.73m. The total width of bridge is 11.8m.
All reverted L-shaped piers are built by C40 concrete, and beams are made of C50 concrete. Fig. 4 shows the section of the bridge.

Figure 5. Spatial finite element model of the reverted L-shaped pier bridge.

According to the actual bridge, the spatial finite element model is established by use of the finite element software MIDAS. Reverted L-shaped piers and capping beams of the bridge are simulated by spatial beam element, and its small box beams are simulated by beam element. Materials and main layouts of the structures in the model are consistent with the design of the actual bridge. Rubber bearing is simulated by spring element, high damping rubber bearing and friction pendulum bearing are by hysteretic model, and blocks are by use of nonlinear spring element with clearance for the finite element model. The elements for bearings and blocks have respectively the same main properties with those of the actual bridge. Fig. 5 shows the spatial finite element model of the reverted L-shaped pier continuous small box beam bridge.

3.2. Simulation Cases for Analyzing Seismic Isolation Effects

A variety of simulation cases are set up in order to study the seismic isolation effects of the structures on the reverted L-shaped pier bridge. In every case, the bridge adopts a kind of layout of bearings which have been mentioned previously. Table 1 gives characters of the bearings and block with clearance. The seismic response of the bridge in every simulation case is analyzed by use of the nonlinear time-history method, and the seismic performance of this kind bridge and seismic isolation effects of these bearing layouts are achieved through comparing the results of these cases. There are four simulation cases as following:

1. The middle pier is set with fiction pendulum bearings, the others are set with rubber bearings, and blocks limit lateral relative displacement of beams of the bridge.
2. The middle pier is set with fiction pendulum bearings, the others are set with rubber bearings, and blocks are not used.
3. The middle pier is set with fiction pendulum bearings, the others are set with high damping rubber bearings, and blocks are not used.
4. The middle pier is set with fiction pendulum bearings, the others are set with high damping rubber bearings, and blocks are used with reserved clearance.

Table 1. Characters of bearings and block with clearance.

| Structure         | Effective stiffness(KN/m) | First stiffness(KN/m) | Second stiffness(KN/m) | Damping ratio |
|-------------------|--------------------------|----------------------|-----------------------|---------------|
| Rubber bearing    | 2120                     |                      |                       |               |
| Friction pendulum bearing | 1759             | 100000               | 1172                  | 0.212         |
| High damping bearing | 2120                   | 10760                | 1660                  | 0.15          |
| Block with clearance | 100000             |                      |                       | Clearance of 7.5cm |
3.3. Time History of Ground Motion and Calculating Seismic Isolation Effects
The basic seismic intensity of the region is VII degree, its seismic peak acceleration is 0.2g, the site is II class, and its characteristic site period is 4.5s. For comparison, the analysis for seismic isolation effects adopts the EL-centro earthquake wave as time history of ground motion acceleration, which is adjusted according to E2 seismic peak acceleration. The seismic isolation effects on the bridge under E2 earthquake action are calculated to find out the characters of seismic isolation in the structure and the ways for seismic isolation design. Inputting ground motion acceleration has two types, one is simultaneously inputting vertical and longitudinal waves, the other is simultaneously inputting vertical and lateral waves. The time of inputting ground motion acceleration is 40s, and the time history of ground motion acceleration of EL-centro earthquake wave is showed as Fig. 6.

![Figure 6. Time history of ground motion acceleration of EL-centro earthquake wave.](image)

After the spatial finite element model of the reverted L-shaped pier bridge is established according to four simulation cases mentioned above, time history nonlinear analysis of the structure can began through inputting the time history of ground motion acceleration which comes from the adjusted EL-centro earthquake wave and the imputing time interval of which is 0.05s. Comparing the response of displacement and internal force of structures in key locations, which is the calculating result under only earthquake actions for analyzing more easily, the rules of seismic isolation effects and the analyzing method for the reverted L-shaped pier bridge can be find out as a result.

4. Analysis of Simulation Results

4.1. Comparing Natural Vibration Periods of Structure
The top 100 order natural vibration periods of structure are calculated in the finite element model of the bridge in four simulation cases, and the periods of structure and modes of the top six of them are shown as Table 2. Periods and modes of case3 and case4 are same, so it is clear that the clearance of block has no influence on the characteristics values of structure. Because the longitudinal character of bearings in all the cases is similar, periods and modes of the first order in four cases do not change much, which mainly reflect changes in longitudinal displacements. When elastic connections and high damping rubber bearings are set for the bridge, the periods of structure in 2-6 orders are much different. It is shown that these ways of connection have much effects on the seismic response of the bridge in corresponding orders.
Table 2. Top six periods and modes of the reverted L-shaped pier bridge.

| Order | Case1          | Case2          | Case3, Case4   |
|-------|---------------|---------------|---------------|
|       | Period(s) | Mode          | Period(s) | Mode          | Period(s) | Mode          |
| 1     | 2.046      | Longitudinal moving | 2.169     | Longitudinal moving | 2.571     | Longitudinal moving |
| 2     | 0.387      | Vertical bending | 1.555     | Lateral moving  | 1.727     | Lateral moving  |
| 3     | 0.344      | Vertical bending + lateral dumping | 1.186     | Antisymmetric lateral bending | 1.187     | Antisymmetric lateral bending |
| 4     | 0.322      | Vertical bending + twisting | 0.510     | Asymmetric lateral bending | 0.516     | Asymmetric lateral bending |
| 5     | 0.303      | Lateral dumping | 0.387     | Vertical bending | 0.387     | Vertical bending |
| 6     | 0.240      | Twisting       | 0.342     | Vertical bending | 0.344     | Vertical bending |

4.2. Comparing Seismic Isolation Effects in Longitudinal Direction
Simultaneously inputting vertical and longitudinal time histories of ground motion acceleration, the seismic response of structure are calculated for the bridge to gain their displacements and internal forces in four simulation cases.

Figure 7. Displacements under longitudinal and vertical earthquakes.

The maximum longitudinal and vertical displacements of structure in four cases are showed as Fig. 7. In longitudinal direction, the conditions of bearing in case1 and case2 are similar, therefore, their displacements approximate, so are those in case3 and case4. When high damping rubber bearings are set in the bridge, the response of displacement under earthquake actions decreases largely. For example, the maximum longitudinal displacement decreases 59%, and the maximum vertical displacement decreases 43%. It is clear that the high damping rubber bearing has remarkable seismic isolation effect on the response of displacement.

Longitudinal bending moments and shears at the bottom of piers in every simulation case are showed as Table 3 after nonlinear time history analysis. It can be seen that the longitudinal seismic responses in case1 and case2 are nearly the same, and that those in case3 and case4 are the same. When high damping rubber bearings are set in the bridge, longitudinal bending moments and shears decrease much, for example, the maximum bending moment reduces 61%, and the maximum shear reduces 60%.

It is clear that high damping rubber bearing can decrease the seismic response of structure in the bridge and lateral blocks nearly do not affect the longitudinal seismic response in the bridge.
Table 3. Internal forces of piers in four cases under longitudinal and vertical earthquakes.

| Case | Force          | Bottom of pier1 | Bottom of pier2 | Bottom of pier3 | Bottom of pier4 | Bottom of pier5 |
|------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|      | Bending moment (KN.m) | 14435.4        | 33060.4        | 26876.4        | 33047           | 5643.5         |
|      | Shear (KN)     | 700.3           | 3772.1          | 3067.6          | 3770.1          | 700.3           |
| Case2| Bending moment (KN.m) | 5643.5         | 33062.7        | 26874           | 33044.7         | 5643.5         |
|      | Shear (KN)     | 700.3           | 3772.4          | 3067.3          | 3770.2          | 700.3           |
| Case3| Bending moment (KN.m) | 4139.7         | 12854.9        | 7010.1          | 12843.2         | 4139.7         |
|      | Shear (KN)     | 516.4           | 1505.6          | 871.3           | 1503.8          | 516.3           |
| Case4| Bending moment (KN.m) | 4139.7         | 12854.9        | 7010.1          | 12843.2         | 4139.7         |
|      | Shear (KN)     | 516.4           | 1505.6          | 871.3           | 1503.8          | 516.3           |

4.3. Comparing Seismic Isolation Effects in Lateral Direction

Simultaneously inputting vertical and lateral time histories of ground motion acceleration, the seismic responses of structure are calculated for the bridge to gain their displacements and internal forces in four simulation cases.

Figure 8. Relative lateral displacements of piers under lateral and vertical earthquakes.

The lateral displacements of structure in four cases are showed as Fig. 8. When beams and piers of the bridge are laterally hinged, the relative displacements between beams and the top of pier are very small, that is to say their displacements are nearly the same. When rubber bearings are set for piers of the bridge, which represents elastic connection for the bridge, the maximum relative displacement of beam reaches 21.7 cm in all piers, which is bigger than the offering isolation displacement (10cm) of friction pendulum bearing. When block with a clearance of 7.5cm is adopted, the maximum relative lateral displacement reduces, which is smaller than the offering isolation displacement, and the displacements of piers are more even.

Under the lateral and vertical earthquake actions, responses of internal force of the bridge are shown as Table 4. When beams and piers are hinged in lateral direction, the response of internal force is the greatest. When rubber bearings and high damping rubber bearings are set, seismic response of internal force of the bridge decreases much relative to that with hinged connection. The maximum bending moment of the bridge with high damping rubber bearings is 18% of that with hinged connections, and 48% of that with rubber bearings. The maximum shear of the bridge with high damping rubber bearings is 17% and 48% respectively. When blocks with clearance of 7.5cm are set in the bridge, internal forces...
will increase in the second and fourth piers, and those in the third pier with friction pendulum bearings increase a little. The high damping bearings make internal forces among piers more even.

### Table 4. Internal forces of piers in four cases under lateral and vertical earthquakes.

| Case | Force                  | Bottom of pier1 | Bottom of pier2 | Bottom of pier3 | Bottom of pier4 | Bottom of pier5 |
|------|------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|      | Bending moment (KN.m)  | 27091.1         | 57905.3         | 65596.0         | 69959.2         | 31297.7         |
|      | Shear(KN)              | 2661.9          | 5527.2          | 5670.7          | 6177.9          | 2675.7          |
| Case2| Bending moment (KN.m)  | 19155.2         | 19616.9         | 21197.1         | 20192.7         | 19676.9         |
|      | Shear(KN)              | 2275.1          | 2038.3          | 1770.1          | 2036.7          | 2266.4          |
| Case3| Bending moment (KN.m)  | 10438.7         | 12379.3         | 12281.1         | 12379.3         | 10438.7         |
|      | Shear(KN)              | 1043.5          | 1066.3          | 1033.3          | 1066.3          | 1043.5          |
| Case4| Bending moment (KN.m)  | 10438.7         | 17306.8         | 12281.1         | 17306.8         | 10438.7         |
|      | Shear(KN)              | 1043.5          | 2311.9          | 1273.8          | 2311.9          | 1043.5          |

### 5. Summary

A reverted L-shaped pier continuous small box beam bridge is calculated and comparatively studied in four simulation cases with a finite element software. The conclusions are as following:

1. Because isolation bearings significantly prolong the top several periods of the bridge, their effects on seismic responses of the bridge in these periods are very high.
2. High damping rubber bearings make the lateral and longitudinal seismic responses of the bridge decrease much and those among piers more even.
3. Compared with no lateral blocks, blocks with clearance can remarkably reduce the maximum lateral displacement, but quickly increase the internal forces of the piers. If blocks with clearance are used reasonably, the seismic performance of structures of the bridge can be fully used.

### References

[1] J. Wang, Z. Zhao, Y. Ding, D. Li, Energy response analysis for base-isolated structures with a friction pendulum system under multi-axial ground motion, Journal of Vibration and Shock. 5(2011) 241-244.

[2] Y. Shi, J. Li, H. Qin, Z. Zhong, Y. Wang, Review on design methods and seismic performances of seismically isolated bridges, China Earthquake Engineering Journal, 5(2019) 1121-1132.

[3] C. Shen, F. Zhou, W. Heisa, Y. Ma, Test study on mechanical property of different type of isolators for bridge, China Civil Engineering Journal. 1(2012) 233-237.

[4] R. Zhao, Y. Jia, Y. Zhan, Y. Wang, P. Liao, Seismic mitigation and isolation design for multi-span and long-unit continuous girder bridge in meizoseismal area, Journal of Zhejiang University(Engineering Science), 5(2018) 886-895.

[5] W. Wang, Z. Cao, Y. Chen, J. Bo, Z. Chen, Theoretical analysis and experimental study of equivalent friction coefficient for hyperboloid spherical anti-vibration bearing, Railway Standard Design. 7(2017) 93-96.