Influence of High Damping Rubber Bearing on Seismic Performance of The Bridge

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Abstract. Based on the qingyijiang bridge of ya’an-kangding expressway in Sichuan province, the influence of high damping rubber bearing on the seismic performance of the bridge is analyzed from the aspects of structural natural vibration period, internal force at the bottom of the pier, displacement at the top of the pier, displacement at the end of the beam and shear displacement of the bearing. The results are compared with those of ordinary rubber bearing. Some suggestions are put forward for its applicability on conventional highway bridges.

1. Introduction
China is a country prone to strong earthquakes. The recent “5 •12” Sichuan Wenchuan Earthquake, the “4 • 14” Qinghai Yushu Earthquake, and the “4 • 20” Sichuan Lushan Earthquake have brought us serious disasters. As an important part of the lifeline, highway bridges, once damaged, will seriously affect rescue and post-disaster reconstruction. Seismic resistance of bridges is getting more and more attention, and it has become an essential part of bridge design.

In terms of bridge earthquake resistance, the technology that is relatively mature and widely used today is seismic isolation technology. By setting the vibration isolation support between the beam and the pier, on the one hand, it can extend the natural vibration period of the structure and reduce the seismic force, on the other hand, the damping performance of the seismic isolation bearings is used for hysteretic energy dissipation to protect the main structure of the bridge[1].

At present, the more commonly used shock absorption and isolation bearings include ordinary plate rubber bearings, friction swing bearings, lead rubber bearings, and high-damping vibration-isolating rubber bearings. High-damping vibration-isolating rubber bearings (HDR vibration-isolating bearings) have reasonable structure, simple appearance, good damping effect, stable technical performance, low maintenance cost, and good durability[2]. As a new type of seismic isolation bearings, HDR vibration-isolating bearings have been gradually accepted by the bridge engineering community after years of research and application. However, because the design engineers do not know enough about the seismic performance, applicability, and economics of high-damped rubber-isolated rubber bearings, and the HDR seismic-isolated bearings are more complicated than ordinary plate rubber bearings in seismic analysis calculation and parameter selection, to a certain extent, the popularization and application of the HDR vibration-isolating bearings have been hindered.

2. Isolation mechanism analysis of HDR vibration-isolating bearings
High-damping vibration-isolating rubber bearings are a kind of rubber bearings those are made by vulcanizing special rubber materials (such as graphite) and steel plates. Its rubber material is very
viscous and can absorb energy by itself. Under the action of strong earthquakes, the deformation of the bearing generates large damping, which consumes a large amount of energy entering the structural system, so as to achieve the purpose of controlling the internal force distribution and size of the structure.

Through experimental research on the HDR vibration-isolating bearing, it is found that the area of the hysteresis loop is relatively full. According to JT / T 842-2012 "High Damping Isolation Rubber Bearings for Highway Bridges", a bilinear restoring force model can be used to simulate [3], see Fig.1. In the figure, K₁ is the stiffness before yielding, K₂ is the stiffness after yielding, Kₕ is the horizontal equivalent stiffness, Xₚ is the yield displacement, Qₚ is the yield force, X is the allowable shear displacement under the E2 earthquake, and Q is the level corresponding to X Shear force [2].

The yield force Qₚ of the HDR vibration-isolating bearing is small. Under the action of earthquake, the bearing is easy to yield, so that elastoplastic deformation occurs. The rapid reciprocating motion consumes a large amount of vibration energy of the bridge structure, and the seismic force of the superstructure to the pier and abutment is controlled within a certain range. The post-yield stiffness K₂ is much smaller than the pre-yield stiffness K₁, so the horizontal equivalent stiffness Kₕ is small. Therefore, the flexibility of the bridge structure is increased, the natural vibration period is extended, and the seismic force response of the bridge structure is reduced.

The sliding-type bearing supporting the HDR vibration-isolating bearing is a polytetrafluoroethylene plate and a stainless steel plate added above the bearing body. The elasticity occurs before sliding friction, and the friction force is constant after sliding. The mechanical model is shown in Fig. 2[3]. In the figure, K₀ is the horizontal stiffness before sliding, Xₚ is the yield displacement, and Qₚ is the sliding friction. The sliding friction force Qₚ of the sliding bearing is small. Under the action of earthquakes, after the bearing slides, the seismic force that transmits the superstructure to the pier and abutment through the back and forth movement and friction is controlled below the sliding friction force Qₚ.

![Figure 1. Bilinear restoring force model of HDR isolation bearing.](image1)

![Figure 2. Mechanical Model of Sliding Bearing.](image2)
3. Relying on Engineering Overview

The Qingyi River Extra Large Bridge from Ya'an to Kangding Expressway in Sichuan Province is located in Yucheng District, Ya'an City. The bridge spans the Qingyi River reservoir area. The recommended bridge type of the main bridge uses $42 + 75 + 42$ meters and $42 + 70 + 42$ meters of prestressed concrete continuous beams to cross the river embankment. A $4 \times 46.5$ prestressed concrete simply supported T-beam is used in the Qingyi River. The approach bridge on both sides of the strait uses a prestressed concrete T-beam with a perforated length of 30.5 meters and 30.95 meters. The bridge is 1421.6 meters long. The bridge structure is set up in sections, with a half bridge width of 12.25 meters. This article takes one of the representative bridges for analysis and research. The hole span is $4 \times 30.95$ meters. The upper beam body is composed of 5 simply supported T beams in the transverse direction, and the bridge deck is continuous in the longitudinal direction[4]. See Fig. 3 for the bridge elevation and Fig. 4 for the cross section.

For the convenience of research, it is assumed that the bridge piers have the same height and the same geological conditions. The heights of the pier are 15m, 20m, 25m and 30m respectively. The diameter of the pier is 1.6m, and the diameter of the pile foundation is 1.8m.

According to the two-stage construction drawing design document of the project, the three bridge piers in the middle adopt high-damping isolation rubber bearings. The model is HDR (II) $320 \times 420 \times 127$-G0.8, which is type II rectangular high-damping vibration-isolating rubber bearing. The longitudinal bridge dimension is 370mm, the transverse bridge dimension is 420mm, the height is 127mm, and the shear modulus is 0.8 MPa. When the shear strain is 150%, its main mechanical parameters are: $K_1=4170kN/m$, $K_2=1190kN/m$, $K_h=1510kN/m$, $X_y=10.1mm$, $Q_y=42kN$, allowable shear displacement $X=126mm$, vertical bearing capacity $P=1360kN$, vertical compression stiffness $K_v=777000kN/m$, equivalent damping ratio $\xi=12\%$. Sliding bearings are used at the two junction pier. The model is LNR (H) $320 \times 420 \times 137$, that is, the longitudinal bridge dimension is 370mm, the transverse bridge dimension is 420mm, and the height is 137mm. Its main mechanical parameters are: $K_0=1710kN/m$, $X_y=25.1mm$, $Q_y=43kN$, vertical bearing capacity $P=1440kN$, vertical compression stiffness $K_v=735000kN/m$.

For comparative research, if the conventional static design is adopted, and according to the calculation results of the support reaction force and the bearing shear displacement, the specifications...
of the ordinary plate rubber bearing at the middle 3 bridge piers are GJZ300 × 450 × 63. Its main mechanical parameters are: vertical bearing capacity \( P = 1260 \text{kN} \), dynamic shear modulus \( G_d = 1.2 \text{MPa} \), horizontal shear stiffness \( K_h = 3600 \text{kN/m} \), vertical compression stiffness \( K_v = 1464509 \text{kN/m} \). The specification of the PTFE skateboard rubber support at the junction pier is GJZF4300 × 450 × 65. Its main mechanical parameters are: coefficient of friction \( \mu = 0.06 \), horizontal stiffness before sliding \( K_0 = 3600 \text{kN/m} \), vertical compression stiffness \( K_v = 1464509 \text{kN/m} \). Sliding friction force \( Q_y \) is calculated from the supporting force under dead load.

After the “5 • 12” Wenchuan Earthquake, according to the GB18306-2001 “China Earthquake Parameter Zoning Map” National Standard No. 1 Amendment Sheet, the peak acceleration of the ground motion of this project is 0.1g, and the characteristic period of the ground motion response spectrum is 0.40s. The type of site is II, and the basic seismic intensity is VII.

4. Analysis of Bridge Seismic Performance

According to JTG / T B02-01-2008 "Seismic Design Details for Highway Bridges", the Yakang Road Tsing Yi River Bridge is Class B and two-level fortification is adopted. That is to say, under the E1 earthquake, the bridge structure is generally not damaged or can be continued to be used without repair. The E2 earthquake should ensure that it does not collapse or cause serious structural damage, and can be used for emergency traffic maintenance after temporary reinforcement[5]. During E1 earthquake, the multi-mode inelastic response spectrum method (equivalent linearization analysis method) is used to calculate the earthquake resistance. When E2 is applied, three groups of artificial time-history waves are used for nonlinear time-history analysis and calculation, and the maximum value of the three groups of calculation results is taken. When E1 earthquake action (the probability of earthquake overtaking is 10% for 50 years), the design acceleration response spectrum of this project is shown in Fig. 5, the importance coefficient of earthquake resistance is 0.5, and the site coefficient and damping adjustment coefficient are both 1.0. The artificial time-history wave at the time of E2 earthquake action (seismic overtaking probability is 50% for 2 years) is shown in Figs. 6.1 to 6.3, and the maximum acceleration peak is 1.95 m/s².

![Figure 5. Acceleration response spectrum under earthquake action.](image1)

![Figure 6.1. Group 1 Artificial Time Wave.](image2)

![Figure 6.2. Group 2 Artificial Time Wave.](image3)
Figure 6.3. Group 3 Artificial Time Wave.

Under the E1 and E2 earthquakes, eight different working conditions were calculated according to different bearing types and different pier heights. The seismic calculation uses the space finite element program Midas Civil 2015. The main beam, piers, tie beams and pile foundations use beam elements. The calculation model is shown in Fig.7. When performing multi-mode inelastic response spectrum analysis and calculation under the E1 earthquake, ordinary plate rubber bearings, PTFE slide rubber bearings, HDR isolation bearings, and sliding bearings are all elastically connected. Among them, the horizontal shear stiffness of the PTFE slide rubber bearing and the sliding bearing is zero, and the horizontal shear stiffness of the HDR isolation bearing is taken as the horizontal equivalent stiffness. When the calculated value of the shear strain of the HDR-isolated bearing is not equal to 150%, it is necessary to determine its horizontal equivalent stiffness through iterative calculation. When performing nonlinear time-history analysis and calculation under the E2 earthquake, ordinary plate rubber bearings are elastically connected. The PTFE skateboard rubber bearing, HDR vibration-isolating bearing, and sliding bearing adopt the bilinear restoring force model of general connection[6].

Figure 7. Earthquake resistance calculation mode.

Under E1 earthquake, when ordinary plate rubber bearings (tetrafluoro slide rubber bearings at the junction piers) are respectively used, the calculation results are shown in Table 1.

Under E1 earthquake, when high damping isolation rubber bearings (sliding bearings at the junction piers) are respectively used, the calculation results are shown in Table 2.

Under the E2 earthquake, when ordinary plate rubber bearings (tetrafluoro slide rubber bearings at the junction piers) are respectively used, the calculation results are shown in Table 3.

Under E2 earthquake, when high damping isolation rubber bearings (sliding bearings at the junction piers) are respectively used, the calculation results are shown in Table 4.
Table 1. Response of Bridge Structure under E1 Earthquake with Ordinary Plate Rubber Bearing.

| bridge pier height (m) | 15      | 20      | 25      | 30      |
|------------------------|---------|---------|---------|---------|
| First Order Period of Longitudinal Bridge Vibration (s) | 2.322   | 2.914   | 3.586   | 4.323   |
| First Order Period of Transverse Bridge Vibration (s) | 1.223   | 1.374   | 1.579   | 1.835   |
| Longitudinal seismic response of bridge | | | | |
| Bending Moment at Pier Bottom (kN.m) | 1150    | 1193    | 1197    | 1194    |
| Pier top displacement (m) | 0.018   | 0.026   | 0.035   | 0.045   |
| Beam end displacement (m) | 0.028   | 0.035   | 0.043   | 0.052   |
| Bearing shear displacement (mm) | 8.2     | 6.8     | 5.8     | 5.4     |
| Transverse Seismic Response of Bridges | | | | |
| Bending Moment at Pier Bottom (kN.m) | 728     | 914     | 1045    | 1136    |
| Pier top displacement (m) | 0.004   | 0.007   | 0.011   | 0.015   |
| Beam end displacement (m) | 0.017   | 0.019   | 0.021   | 0.024   |
| Bearing shear displacement (mm) | 9.6     | 8.8     | 7.8     | 7.1     |

Table 2. Response of Bridge Structure under E1 Earthquake with High Damping Isolation Rubber Bearing.

| bridge pier height (m) | 15      | 20      | 25      | 30      |
|------------------------|---------|---------|---------|---------|
| First Order Period of Longitudinal Bridge Vibration (s) | 2.691   | 3.282   | 3.973   | 4.744   |
| First Order Period of Transverse Bridge Vibration (s) | 1.679   | 1.788   | 1.943   | 2.148   |
| Longitudinal seismic response of bridge | | | | |
| Bending Moment at Pier Bottom (kN.m) | 1085    | 1153    | 1177    | 1184    |
| Pier top displacement (m) | 0.017   | 0.026   | 0.036   | 0.046   |
| Beam end displacement (m) | 0.032   | 0.039   | 0.047   | 0.057   |
| Bearing shear displacement (mm) | 13.7    | 11.5    | 9.9     | 8.8     |
| Transverse Seismic Response of Bridges | | | | |
| Bending Moment at Pier Bottom (kN.m) | 665     | 880     | 1018    | 995     |
| Pier top displacement (m) | 0.004   | 0.006   | 0.010   | 0.013   |
| Beam end displacement (m) | 0.021   | 0.023   | 0.025   | 0.027   |
| Bearing shear displacement (mm) | 16.1    | 15.5    | 15.1    | 13.8    |

Table 3. Response of Bridge Structure under E2 Earthquake with Ordinary Plate Rubber Bearing.

| bridge pier height (m) | 15      | 20      | 25      | 30      |
|------------------------|---------|---------|---------|---------|
| Longitudinal seismic response of bridge | | | | |
| Bending Moment at Pier Bottom (kN.m) | 5080    | 5696    | 5889    | 6015    |
| Pier top displacement (m) | 0.078   | 0.124   | 0.169   | 0.224   |
| Beam end displacement (m) | 0.123   | 0.160   | 0.201   | 0.254   |
| Bearing shear displacement (mm) | 39.0    | 32.0    | 27.2    | 26.5    |
| Transverse Seismic Response of Bridges | | | | |
| Bending Moment at Pier Bottom (kN.m) | 3042    | 3831    | 4519    | 4606    |
| Pier top displacement (m) | 0.017   | 0.030   | 0.048   | 0.062   |
| Beam end displacement (m) | 0.065   | 0.075   | 0.090   | 0.092   |
| Bearing shear displacement (mm) | 42.8    | 37.1    | 31.3    | 30.0    |

Table 4. Response of Bridge Structure under E2 Earthquake with High Damping Isolation Rubber Bearing.

| bridge pier height (m) | 15      | 20      | 25      | 30      |
|------------------------|---------|---------|---------|---------|
| Longitudinal seismic response of bridge | | | | |
| Bending Moment at Pier Bottom (kN.m) | 4603    | 5438    | 5670    | 5738    |
| Pier top displacement (m) | 0.072   | 0.122   | 0.171   | 0.226   |
| Beam end displacement (m) | 0.129   | 0.164   | 0.212   | 0.260   |
| Bearing shear displacement (mm) | 52.1    | 38.6    | 31.6    | 30.0    |
| Transverse | | | | |
| Bending Moment at Pier Bottom (kN.m) | 2146    | 2855    | 3321    | 3792    |
Seismic Response of Bridges

|                     | Pier top displacement (m) | Beam end displacement (m) | Bearing shear displacement (mm) |
|---------------------|---------------------------|---------------------------|--------------------------------|
|                     | 0.012                     | 0.063                     | 49.1                           |
|                     | 0.022                     | 0.084                     | 57.6                           |
|                     | 0.033                     | 0.084                     | 51.1                           |
|                     | 0.052                     | 0.097                     | 45.6                           |

From the above analysis results, it can be seen that compared with the case of installing a normal plate rubber bearing when a high-damping vibration-isolating rubber bearing is provided:

1. It can properly extend the structure's natural vibration period of 0.3 to 0.45 seconds. Under the action of the E1 earthquake, the shear displacement of the HDR isolation support is about small, and its horizontal equivalent stiffness $K_h$ is approximately close to the elastic stiffness $K_1$, and the isolation effect is not obvious.

2. Under the E1 earthquake, the bending moment of the longitudinal bridge towards the pier bottom decreases by 0.8% to 5.7%; the bending moment of the transverse bridge towards the pier bottom decreases by 2.6% to 12.4%. The pier height is shorter, the isolation effect will be better.

3. Under the E1 earthquake, the displacement of the pier top has little effect, but the beam end displacement and bearing shear deformation slightly increase, and the bridge needs to increase the limit measures.

4. Under the E2 earthquake, the bending moment of the longitudinal bridge towards the bottom of the pier decreases by 3.7% to 9.4%; the bending moment of the transverse bridge towards the bottom of the pier decreases by 17.7% ~ 29.5%. The shorter the pier height, the better the isolation effect.

5. Under the action of the E2 earthquake, the effect of the displacement at the top of the pier and the displacement at the beam end is small, and the amount of shear deformation of the bearing increases significantly.

5. Applicability analysis of HDR isolation bearings

According to the analysis and calculation of earthquake resistance under 8 working conditions, the high damping isolation rubber bearing is favorable for prolonging the natural vibration period of the structure and reducing the internal force of the pier under earthquake action. Moreover, the isolation effect of the high damping isolation rubber bearing is different with different pier heights, as shown in Figs. 8 and 9.

Figure 8. Under E1 earthquake, Bending Moment ratio at pier bottom changes with pier height when different supports.
Figure 9. Under E2 earthquake, Bending Moment ratio at pier bottom changes with pier height when different supports

In the figure, \( M_{y11} \) refers to the bending moment of the longitudinal bridge at the bottom of the pier when a high-damping seismic isolation rubber bearing is set under the E1 earthquake. \( M_{y12} \) refers to the bending moment of the pier bottom longitudinal bridge when an ordinary plate rubber bearing is set under the E1 earthquake. \( M_{z11} \) refers to the bending moment of the transverse bridge at the bottom of the pier when the high-damping vibration-isolated rubber bearing is set under the E1 earthquake. \( M_{z12} \) refers to the bending moment at the bottom of the pier when the ordinary plate rubber bearing is set under the E1 earthquake. \( M_{y21}, M_{y22}, M_{z21}, \) and \( M_{z22} \) are the corresponding pier moments under the E2 earthquake.

It can be seen from Fig. 8 and Fig. 9 that the high-damped vibration-isolated rubber bearings are more effective for the isolation and isolation of low-pier bridges than high-pier bridges. In addition, the effect of seismic isolation on the transverse bridge is better than that of the longitudinal bridge, which indicates that the smaller the period of the structure's natural vibration and the greater the stiffness, the better the seismic performance of the bridge when the high-damping isolation rubber bearing is adopted. The deviation of individual data from the transverse bridge is due to the frame structure of the piers in the transverse bridge direction and the inconsistent vibration in the transverse direction of the piers.

See Fig.10 and Fig. 11 for the hysteresis loops of the HDR base bearing with the same bearing under the same seismic time-history wave, when the pier height is 15 meters and 30 meters, respectively. From Fig. 10 and Fig. 11, it can be seen that the smaller the height of the piers, the larger the shear displacement of the high-damping vibration-isolated rubber bearing, the larger the area of the hysteresis loop, and the greater the energy consumption.

Figure 10. 15m the pier height HDR Isolation rubber bearing , the longitudinal bearing shear force-displacement curve under the action of time-history wave
Figure 11. 30m the pier height HDR Isolation rubber bearing, the longitudinal bearing shear force-displacement curve under the action of time-history wave

Bridge spans and pier heights vary widely, and it is inconvenient to quantify the applicability of high-damping vibration-isolated rubber bearings from the structural dimensions. A more suitable indicator is the natural vibration period of the structure. From the acceleration response spectrum curve and analysis results, it is suitable to use a high-damped vibration-isolated rubber bearing when the natural vibration period corresponding to the mode shape that mainly contributes to the seismic response of the structure is less than 3 seconds and the seismic intensity is high.

6. Conclusion

High-damping vibration-isolating rubber bearings have been gradually developed and applied in recent years. Its horizontal equivalent stiffness is small, it can extend the natural vibration period of the structure, and it has the characteristics of a bilinear restoring force model. It can form a hysteresis loop to consume energy and reduce seismic force under repeated earthquake action.

For conventional simple-supported beam bridges of highways, by comparing with ordinary plate rubber bearings, when the pier height is short and the structure's natural vibration period is small, the use of high-damping vibration-isolated rubber bearings can improve the seismic performance of bridge structures. When the height of the pier is large, the natural vibration period of the structure is long, and the vibration isolation effect of the high-damping vibration-isolating rubber bearing is not obvious.

For bridges with high-damping isolation rubber bearings, the bearing shear displacement and beam end displacement are slightly larger. It needs to be equipped with vertical and horizontal limit devices, such as stoppers, steel tie rods, and shock-absorbing rubber cushions.

When the self-vibration period corresponding to the mode shape that mainly contributes to the seismic response of the structure is less than 3 seconds and the seismic intensity is high, it is suitable to use a high-damping vibration-isolating rubber bearing.

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