Seismic Design of Tied Arch Bridge in High Earthquake Region Based on Friction Pendulum Seismic Isolation Bearing

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Abstract. Taking the through-type tied arch bridge with a span of 144m as the research object, the working principle of the friction pendulum bearing is introduced; through the finite element simulation analysis, the seismic performance of the Yunnan Nujiang Dukou Bridge is studied, and the seismic safety evaluation is used to give. The three seismic wave time-acceleration time-history curves are respectively analyzed for the seismic performance of the through-type tied arch bridge when the friction pendulum vibration isolation support and the ordinary steel spherical hinge support are used. The research results show that the use of friction pendulum damping and isolation bearings can delay the vibration response of the superstructure from the seismic excitation, thereby achieving the effect of prolonging the vibration period of the structure and reducing the possibility of resonance of the structure under the action of an earthquake. At the same time, when the friction pendulum support swings back and forth, part of the seismic energy can be consumed by the friction between the wear plates. Compared with ordinary steel spherical hinge bearings, the use of friction pendulum vibration isolation bearings can make the piers of the arch bridge participate in the earthquake resistance together, and the internal force distribution of the piers is also more uniform. However, the horizontal displacement of the pier beams increases significantly, and corresponding protection needs to be taken.

1. Introduction

The Yunnan Nujiang Dukou Bridge Project is located in Liuku Town, Lushui City, Nuijiang Prefecture, and is a poverty alleviation project for China Communications Construction. The total length of the project road is 310m, with a main span of 144m through steel box tied arch bridge across the Nu River, which is composed of 2 arch ribs laterally, the lateral width of the bridge is 22.8m, and the lateral layout is 1.95m (suspender area) + 2.95m (Sidewalk) + 13.0m (carriageway) + 2.95m (sidewalk)+1.95m (boom area), stop at the intersection of Dukou Road and Renmin Road, with a design speed of 40km/h. The upper structure of the main span is a steel box tied arch, the length of the tied box is 143.76m, and the vertical ride-span ratio is 1/6.09; the main axis of the box arch is a multi-parabola form. A total of 64 booms are installed on the Nujiang Dukou Bridge, symmetrically arranged on both sides, with 32 booms on each side. The horizontal projection distance of the mesh suspenders in the longitudinal bridge direction is 7.5m, and the horizontal bridges are arranged obliquely to the inside.

The design of this bridge has a safety level of Class I, and is designed as a Type B bridge. Seen
from the preliminary design documents, works Bridge bit area type field II category, located in zone 8 of fortification, designed acceleration 0.2g, earthquake response spectrum characteristic period of 0.45s, the Nu bridge crossing elevation view shown in Figure 1.

![Figure 1 Yunnan Nujiang Dukou Bridge](image)

2. Working principle of friction pendulum support
The friction pendulum vibration isolation bearing is a device that can effectively reduce the natural vibration period of the structure. It uses the pendulum principle to delay the vibration response of the superstructure from the seismic excitation, so as to achieve the effect of extending the vibration period of the structure. It not only avoids the resonance of the structure under the action of earthquake, but also reduces the input of seismic capacity. The friction pendulum bearing has the characteristics of high load-bearing capacity, large damping ratio, and strong resetting ability. Therefore, in recent years, it has become a kind of bearing with more applications for seismic isolation bearings [1,2].

After the bridge structure adopts the friction pendulum support, the structure period basically depends on the sliding spherical radius of the support, and has nothing to do with the upper bridge structure being supported. The equivalent stiffness of the friction pendulum support and the maximum sliding displacement of the support and the restoring force of the support determines the size of the hysteresis loop area, that is, the seismic energy consumed by the friction pendulum support swinging back and forth for a week. In general engineering applications, it is only necessary to adjust the sliding spherical radius of the bearing and the sliding friction coefficient of the contact surface to predict and control the seismic response of the bridge structure [3].

When a severe earthquake occurs, the limit device of the friction pendulum vibration isolation support will fail [4], the upper and lower parts of the support can slide on the contact surface, and energy is dissipated through the friction of the sliding interface, and the pendulum ball drives the beam to swing back and forth, so that the vibration response of the superstructure and the seismic excitation have a delay hysteresis, so as to achieve the effect of prolonging the vibration period of the structure and reduce the possibility of resonance of the structure under the action of earthquake. The friction pendulum vibration isolation bearing is to consume seismic energy through the back and forth swing of the bearing friction plate under the action of seismic force, and by changing the sliding radius of the bearing to change the structure vibration period and self-restoring force, reduce the input of seismic energy, and at the same time By changing the radius of curvature of the friction pendulum damping and isolating support to adjust the maximum sliding distance of the support, the energy consumption of the support can be effectively adjusted. The hysteretic energy consumption model of the friction pendulum support is shown in Figure 2.
Figure 2 Hysteresis curve of friction pendulum vibration isolation support

The basic mechanical characteristics of the friction pendulum damping and isolating bearing are as follows:

Vibration period of friction pendulum vibration isolation system: \( T = 2\pi \sqrt{\frac{R}{g}} \)

Initial friction stiffness: \( K_p = \frac{uW}{d_y} \)

Stiffness after yielding: \( K = \frac{W}{R} \)

Equivalent stiffness: \( K_{eff} = \frac{W}{R} + \frac{uW}{D} \)

Support restoring force: \( F = \frac{WD}{R} + uW \)

In the formula, \( u \): friction factor, \( R \): radius of the sliding surface of the bearing, \( d_y \): yield displacement of the bearing, \( W \): reaction force of the bearing, \( D \): maximum sliding displacement of the bearing.

3. Seismic performance analysis

3.1. Finite element model

The anti-seismic model of the through arch bridge of Nujiang Dukou Bridge uses the finite element software MIDAS CIVIL to establish the finite element model of the whole bridge anti-seismic time history analysis. The force form of the suspension rod is a two-force rod, which is simulated by truss elements, and the rest are simulated by beam elements. The bridge structure adopts ordinary steel spherical hinge bearings and friction pendulum seismic isolation bearings to conduct a comparative analysis of dynamic characteristics and seismic response conditions. Considering the site characteristics and bridge types, the design parameters of the support selected are \( R=3.5 \) m, \( \mu=0.02 \), and the finite element calculation model of the Nujiang Dukou Bridge is shown in Figure 3.
3.2. Seismic wave input
The "Highway Bridge Seismic Rules" stipulates that the seismic design of arch bridges requires the use of seismic time-history acceleration calculation methods. Therefore, this seismic check calculation uses three seismic wave time-acceleration time-history curves given by the seismic safety evaluation at the bridge location for seismic analysis. The three seismic wave acceleration peaks are 2.034 m/s², 2.596 m/s², and 2.632 m/s², and the duration is 40s. The seismic calculation result of the arch bridge is the most unfavorable effect value generated by the input seismic wave as the E2 seismic calculation result. One of the seismic wave time-acceleration curves obtained from the performance evaluation is shown in Figure 4 below.

3.3. Dynamic characteristics analysis
The natural vibration period of the bridge structure and the corresponding formation characteristics are important parameters for evaluating the dynamic characteristics of the bridge structure. This calculation uses the multiple Ritz method to analyze the dynamic characteristics [5]. From the calculation, it can be obtained that the first-order formation of the arch bridge structure is transversely bent, the second-order formation is longitudinal displacement, the third-order formation is transversely S-curved for the main girder, the fourth-order formation is transversely bent for the main girder, and the fifth-order formation is The arch rib and the main beam are bent transversely.

It can be seen from Table 1 that the setting of the friction pendulum ball bearing has little effect on extending the first-order period. The basic period is extended from 5.176s to 6.069s, which is extended by 0.893s, and the extension rate is 17.25%, indicating that the friction pendulum is installed. The support can extend the lateral natural vibration period of the down-ride arch bridge, but the impact is small, and the improvement of the lateral seismic resistance of the bridge is small. The setting of the friction pendulum ball bearing has a significant effect on extending the second-order period. The basic period is extended from 1.994s to 3.582s, which is 1.588s, and the extension rate is 79.64%. The natural vibration period of the lower-mounted arch bridge is far away from the characteristic period of the bridge site and avoids the frequency range where the seismic force is concentrated, which can effectively improve the longitudinal seismic performance of the structure and make a greater contribution to the overall longitudinal seismic resistance of the bridge.
Table 1 Dynamic characteristics of bridge before and after seismic isolation

| Mode order | Cycle/s | Cycle change/% |
|------------|---------|----------------|
|            | Ordinary bearing | Friction pendulum vibration isolation bearing |            |
| 1          | 5.176   | 6.069          | 17.25       |
| 2          | 1.994   | 3.582          | 79.64       |
| 3          | 1.684   | 2.621          | 55.64       |
| 4          | 1.476   | 2.003          | 35.70       |
| 5          | 0.967   | 1.175          | 21.51       |

3.4. Time history analysis results

The time history analysis considers two load combinations: longitudinal action + vertical action combination, lateral action + vertical action combination, and seismic time history of arch bridges under two modes of friction pendulum seismic isolation bearings and ordinary steel spherical hinge bearings. The analysis results are compared, and the results are the maximum effect values produced by the three seismic waves. The internal force of the non-fixed pier, the fixed pier bottom and the displacement of the pier beam before and after the reduction and isolation are shown in Tables 2 and 3, where the isolation rate = (friction pendulum Seismic isolation support - steel ball hinge support) / steel ball hinge support × 100%.

Table 2 Seismic response before and after seismic mitigation and isolation (along bridge direction + vertical direction)

| Bridge pier | Time history analysis results | Steel ball hinge bearing | Friction pendulum vibration isolation bearing | Vibration isolation rate/% |
|-------------|------------------------------|--------------------------|---------------------------------------------|---------------------------|
| 1#          | Beam bottom displacement /mm  | 60.3                     | 162.5                                      | -169.49                   |
|             | Pier top displacement /mm     | 58.2                     | 10.9                                       | 81.27                     |
|             | Shear force at pier bottom /kN | 18635.2                 | 16995.3                                   | 8.80                      |
|             | Pier bottom bending moment /kN*m | 21430.5                | 19374.6                                   | 9.59                      |
| 2#          | Beam bottom displacement /mm  | 63.2                     | 178.3                                      | -182.12                   |
|             | Pier top displacement /mm     | 60.8                     | 12.5                                       | 79.44                     |
|             | Shear force at pier bottom /kN | 80468.1                 | 17489.5                                   | 78.27                     |
|             | Pier bottom bending moment /kN*m | 584198.4               | 125924.4                                  | 79.20                     |

Table 3 Seismic response before and after seismic mitigation and isolation (transverse direction + vertical direction)

| Bridge pier | Time history analysis results | Steel ball hinge bearing | Friction pendulum vibration isolation bearing | Vibration isolation rate/% |
|-------------|------------------------------|--------------------------|---------------------------------------------|---------------------------|
| 1#          | Beam bottom displacement /mm  | 63.4                     | 180.6                                      | -184.86                   |
|             | Pier top displacement /mm     | 61.8                     | 23.2                                       | 62.46                     |
|             | Shear force at pier bottom /kN | 56394.6                 | 14389.6                                   | 74.48                     |
|             | Pier bottom bending moment /kN*m | 64853.8                | 17267.5                                   | 73.37                     |
| 2#          | Beam bottom displacement /mm  | 65.3                     | 186.4                                      | -185.45                   |
|             | Pier top displacement /mm     | 62.8                     | 25.7                                       | 59.08                     |
|             | Shear force at pier bottom /kN | 57925.6                 | 15236.2                                   | 73.70                     |
|             | Pier bottom bending moment /kN*m | 424015.4               | 109700.6                                  | 74.13                     |

According to the results of seismic response (in the direction of the bridge + vertical) before and after the earthquake reduction and isolation in Table 2, the horizontal shear force of the two main piers of the arch bridge will The total is 99103.3kN, of which the shear force of fixed pier No. 1 is 18635.2kN, which bears the proportion of 20%, and the shear force of fixed pier No. 2 is 80468.1kN,
which bears the proportion of 80%. The seismic horizontal force is mainly borne by the fixed pier No. 2 of the arch bridge, and the sliding pier No. 1 bears a smaller proportion; when the friction pendulum seismic isolation support is used, the two main piers bear the same magnitude of the seismic force in the direction of the bridge, of which Pier No. 1 is reduced 8.8%, pier 2 decreased by 78.27%, and the shear value of pier 2 decreased significantly. With the friction pendulum damping support, the horizontal displacement of the pier top is relatively reduced, but the longitudinal displacement of the main girder in the longitudinal direction of the bridge increases, and the horizontal displacement of the support between the piers and beams increases significantly.

It can be seen from Table 3 that under the combined action of horizontal and vertical seismic waves at the bridge site, when ordinary steel spherical hinge bearings are used, the sum of the horizontal shear forces of the two main piers of the arch bridge is 11,4320.2 kN, of which the shear force of the fixed pier No. 1 is 56394.6 kN. The shear force of No. 2 fixed pier is 57925.6kN, which bears the same proportion of 50%; when the friction pendulum isolation support is adopted, the two main piers bear the same magnitude of seismic force in the transverse direction, but the internal force value is relatively reduced. Among them, Pier No. 1 decreased by 74.48%, Pier No. 2 decreased by 73.70%, which was a significant decrease. With the friction pendulum damping support, the horizontal displacement of the pier top is relatively reduced, but the horizontal displacement of the main girder in the transverse direction increases, and the horizontal displacement of the support between the piers and beams increases significantly.

In summary, the seismic response of the structure is significantly reduced after the friction pendulum isolation support is adopted. Under the action of the E2 earthquake, the No. 1 and No. 2 piers jointly participate in the force, and the internal force distribution is relatively uniform. The main girder support The vertical and horizontal displacements are significantly increased, and measures to prevent the main beam from falling must be considered.

4. Conclusion
Through the comparative analysis of ordinary steel ball hinge bearings and friction pendulum vibration isolation supports, it can be seen that the use of friction pendulum vibration isolation supports can delay the vibration response of the superstructure and the seismic excitation, so as to extend the vibration period of the structure. The effect of this reduces the possibility of the structure resonating under the action of an earthquake. At the same time, when the friction pendulum support swings back and forth, relying on the friction between the wear plates can consume a part of the seismic energy. Compared with ordinary steel spherical hinged bearings, the use of friction pendulum vibration isolation bearings can make the piers of the arch bridge participate in the earthquake resistance, and the internal force distribution of each pier is also more uniform, and the damping effect is significant. However, the horizontal displacement of the pier beams increases significantly, and corresponding protection needs to be taken.

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