Energy Response and Parameter Optimization of Continuous Girder Bridge with Friction Pendulum Bearing

Chong Fu
Institute of Mechanical Metrology, Henan Institute of Metrology, Zhengzhou, China

Abstract: Taking 4-span continuous beam bridge of high speed railway as the research object, the nonlinear dynamic model of isolation bridge with friction pendulum bearing (FPB) was established, and the energy response curves of isolation bridge under the earthquake wave of EI Centro were obtained. The friction coefficient and sliding radius of FPB were optimized based on the amplitude of response energy. The results showed that FPB had good energy dissipation capacity, which can effectively improve the seismic performance of bridge; when the seismic intensities were 7 and 8, the optimal friction coefficients were 0.03-0.04 and 0.05-0.06, and the optimal sliding radius were 2m and 2.5m. The friction coefficient needed to be increased properly with the increase of seismic intensity, and the isolation effect was basically unchanged when a certain value of sliding radius was reached.

Keywords: Friction Pendulum Bearing; Continuous Girder Bridge; Dynamic Model; Energy Response; Friction Coefficient; Sliding Radius

1. Introduction

The seismic energy response can comprehensively reflect the damage degree of bridge structure induced by seismic excitation. Therefore, the energy response analysis is widely used in the bridge aseismic designs [1]. Seismic isolation design is to set a specific seismic isolation device between the upper and lower structures of the bridge. The energy dissipation capacity of the seismic isolation device is utilized under the earthquake action to reduce the transmission of seismic energy to the upper structure, and meanwhile, the dynamic response of the structure under the earthquake can be reduced [2-4]. Friction pendulum bearing (FPB) has the advantages of strong energy dissipation capability and wide application scope, which has been widely studied and applied in bridge aseismic designs [5-7]. Taking a continuous bridge as the research object, Zhao Renda [8] et al. studied and compared the seismic isolation effect of hyperboloid friction pendulum bearing, adhesive tape damper and velocity locking device. The results shown that the hyperbolic friction pendulum support has the optimal isolation capability. Zhang Changyong [1] et al. used MIDAS/CIVIL to analyze the energy response of a three-span concrete continuous beam bridge under different isolation design conditions. The results shown that the increase of sliding radius and friction coefficient within a certain range can improve the damping effect. Jia Yi [9], Liao Ping [10] et al. respectively used ANSYS for parameter optimization and research on the damping effect of a specific bridge hyperbolic friction pendulum bearing. Taking the internal force and displacement of the pier as the optimization objective, the selection basis and optimal value of the sliding radius and friction coefficient were respectively obtained. However, in the study of energy response of bridge with friction pendulum bearings so far, the effect of seismic fortification intensity on the optimization results of friction pendulum bearings has not fully considered.

Taking 4-span continuous beam bridge of high speed railway as an example, the seismic energy response and energy dissipation effect of the bridge structure adopting a friction pendulum bearing isolation design are analyzed, and the influence of the sliding radius of the friction pendulum support and the friction coefficient on the seismic energy response and distribution is analyzed by taking the control of the bridge response energy amplitude as an optimization target. The research can provide a technical support for the isolation design of friction pendulum bearings in high-speed railway bridges.

The energy response equation of the isolation bridge system under seismic excitation is shown in formula (1) [1, 11]. $E_K(t)$ is the kinetic energy of the bridge system, $E_D(t)$ is the self-damping energy dissipation of the bridge system, $E_F(t)$ is the energy consumption of the isolation device, $E_P(t)$ is the potential energy of the bridge system, and $E_O(t)$ is the seismic input energy.

$$E_K(t)+E_D(t)+E_F(t)+E_P(t)=E_O(t) \quad (1)$$

The structural response energy is defined as the sum of kinetic energy and potential energy of the isolation bridge system. The structural response energy can fully reflect the cumulative damage effect of earthquake excitation on the isolation bridge. The calculation method of structural response energy amplitude is shown in Formula (2). At the same time, the energy consumption ratio λ of the friction pendulum bearing is defined as the ratio of the energy consumption of the isolation device to the seismic input energy.

$$E_R = MAX(E_K(t)+E_p(t)) \quad (2)$$

2. Structural Calculation and Analysis Model

2.1 Project Overview

Taking a four-span high-speed railway continuous bridge of as an example, the main beam is a double-line full-span box girder with a span of 24 meters, and the pier is a double-column pier with a height of 6 meters. The cross-sectional shape of main beam and pier are shown in Figure 1, the structural parameters are shown in Table 1.

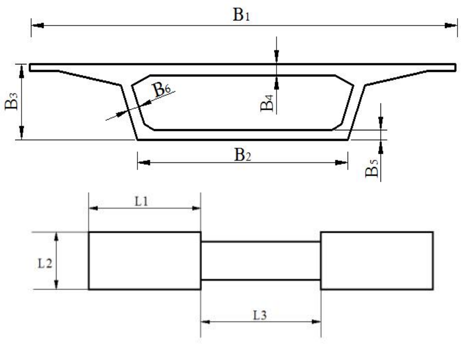

Figure 1. Cross Section of Main Beam and Pier

Table 1. Structure Parameters of Bridges for High-Speed Railway

Parameter	B_1	B_2	B_3	B_4	B_5	B_6	L_1	L_2	L_3
Dimensions	12.4 m	6.12 m	2.00 m	0.30 m	0.25 m	0.45 m	3m	1.5 m	3m

2.2 Finite Element Modeling

SAP2000 was chosen to establish dynamic numerical simulation model of high-speed railway Isolation Bridge, as shown in Figure 2. The main beam and pier model unit are thick plate unit and 3D beam unit respectively. The pier and main beam are connected by friction pendulum bearing. The friction pendulum bearing is simulated by the friction element in LINK unit. The damping ratio of bridge structure is 0.05. The model does not consider the energy dissipation caused by pile-soil interaction, and the piers are consolidated to the ground.

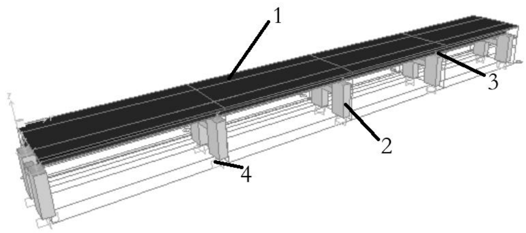

Figure 2. Three-Dimensional Finite Element Model of Continuous Bridge with Friction Pendulum Bearing

1. Main beam 2. Pier 3. Friction pendulum bearing 4. Constraint

2.3 Seismic Dynamic Input

During calculation and analysis, EI Centro wave is adopted as seismic excitation, and the acceleration amplitude of seismic wave is adjusted to 0.22 g and 0.4 g respectively according to the fortification requirements of seismic basic intensity of 7 degree and 8 degree. The acceleration time-history curve of EI Centro wave at basic seismic intensity of 7 degree is shown in Figure 3. The direction of seismic excitation action is the lengthwise direction of the bridge. The influence of seismic excitation in other directions is not considered.

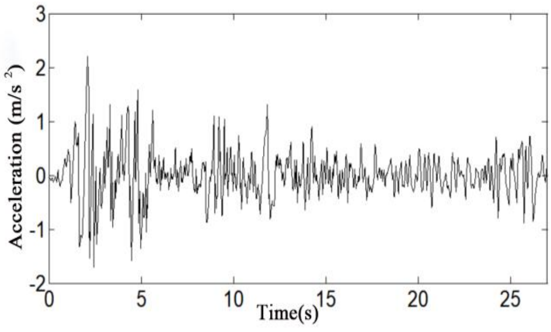

Figure. 3 Acceleration Time History Curve of EI Centro Wave

3. Influence of Design Parameters for The Friction Pendulum Bearing on Seismic Energy Response

Friction coefficient and sliding radius of friction pendulum bearing are the main parameters which affect the isolation performance of bridge. Therefore, the friction coefficient and sliding radius of the bearing are optimized.

3.1 Optimization of Friction Coefficient and Parameters

The energy response of isolated bridge system with friction coefficient of 0.01-0.1 is studied by selecting the sliding radius of friction pendulum bearing as 2 meters. When the friction coefficient is 0.05, the energy response curve of the structure and the hysteresis curve of the bearing are shown in Fig. 4 and Fig. 5 respectively. The energy response of the bridge structure under different friction coefficient is shown in Table 2. From Fig.4 and Table 2, it can be found that seismic input energy, hysteretic energy consumption and damping energy consumption increase cumulatively with time, and kinetic energy and potential energy reach amplitude at a certain moment. From Fig. 5 and Table 2 ,it can be found that the friction pendulum bearing has strong hysteretic energy dissipation capacity, and simultaneously, the hysteretic energy dissipation is relatively high, which can effectively dissipate the seismic input energy. Therefore, the friction pendulum bearing has better energy dissipation and isolation capability.

Taking the response energy amplitude of the isolation bridge structure as the optimization target, the influence of the friction factor on the response energy amplitude of the bridge structure at seismic fortification intensity of 7 and 8 degrees is shown in Figure 6 and Figure 7 respectively. From Fig. 6 and Fig. 7, it can be found that the optimum friction coefficients are 0.03-0.04 and 0.05-0.06 respectively when the seismic fortification intensity is 7 and 8 degrees, which indicates that the friction coefficient needs to be increased appropriately with the increase of seismic fortification intensity.

3.2 Optimization of Sliding Radius Parameters

The effect of different sliding radii R on the energy response amplitude of the bridge structure is studied by selecting the friction coefficient of 0.03, and the results are shown in Table 3. As shown in Table 3, the energy dissipation ratio of the friction pendulum bearing reaches more than 80%, and the energy response amplitude of the isolation bridge decreases with the increase of the sliding radius. However, when the sliding radius reaches a certain value, the energy response amplitude of each energy response remains basically unchanged after the sliding radius is continuously increased.

When the seismic fortification intensity is 7 and 8 degrees, the influence of the sliding radius on the response energy of the bridge structure is shown in Fig. 8 and Fig. 9 respectively. From Fig. 8 and Fig. 9,it can be found that the optimal sliding radius is 2 m and 2.5 m respectively when the seismic fortification intensity is 7 degree and 8 degree, while the response energy amplitude of the structure remains basically unchanged when the sliding radius is further increased.

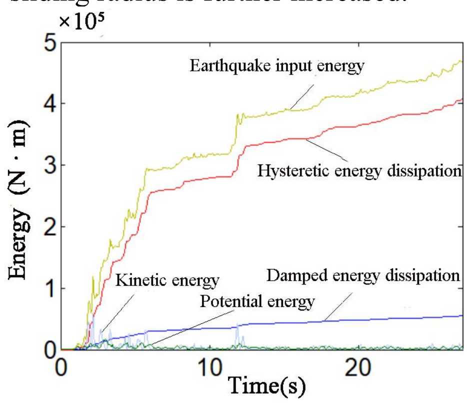

Figure.4 Energy response curve

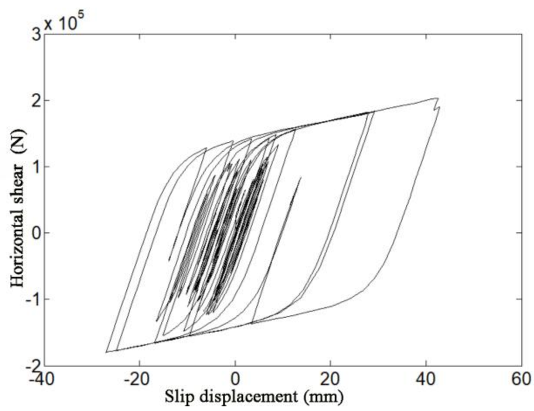

Figure. 5 Hysteresis Curve

Table. 2. Energy Response Amplitudes With Different Friction Coefficients

Friction coefficient μ	Seismic input energy E_O (kN·m)	Hysteretic energy dissipation E_F (kN·m)	Kinetic energy amplitude E_K (kN·m)	Potential energy amplitude E_P (kN·m)	Damping energy dissipation E_D (kN·m)	Hysteretic energy dissipation ratio λ (%)
0.01	312.6	216.7	144.0	55.7	94.3	69.3
0.02	322.2	262.4	64.7	24.5	57.0	81.4
0.03	349.5	297.0	49.5	18.0	48.7	85.0
0.04	406.0	350.0	49.4	17.1	50.8	86.2
0.05	469.0	408.0	59.0	16.2	55.2	87.0
0.06	522.4	455.6	67.3	16.0	60.3	87.2
0.07	570.4	497.9	75.2	17.7	65.1	87.3
0.08	617.9	540.1	82.6	19.0	69.7	87.4
0.09	669.9	584.6	89.4	20.6	76.0	87.3
0.1	724.0	629.3	95.9	23.4	84.3	86.9

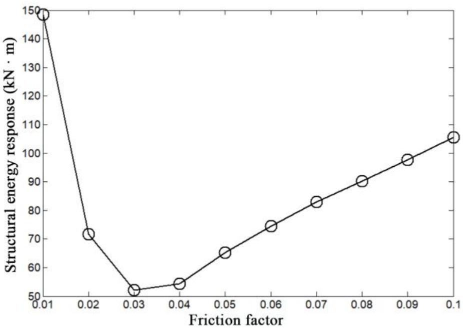

Figure. 6 Response Energy Amplitudes with Different Friction Coefficients (Seismic Fortification Intensity: 7)

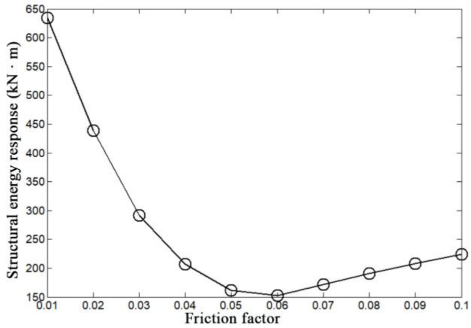

Figure. 7 Response Energy Amplitudes with Different Friction Coefficients (Seismic Fortification Intensity: 8)

Table. 3. Energy response amplitudes with different sliding radius

Friction coefficient μ	Seismic input energy E_O (kN·m)	Hysteretic energy dissipation E_F (kN·m)	Kinetic energy amplitude E_K (kN·m)	Potential energy amplitude E_P (kN·m)	Damping energy dissipation E_D (kN·m)	Hysteretic energy dissipation ratio λ(%)
0.5	434.9	353.1	86.3	42.4	75.1	81.2
1	379.4	317.2	54.8	24.7	56.6	83.6
1.5	359.6	303.8	52.0	19.7	51.0	84.5
2	349.5	297.0	49.5	18.0	48.7	85.0
2.5	347.1	295.2	47.6	16.6	48.2	85.0
3	346.1	294.7	46.0	14.9	48.0	85.1

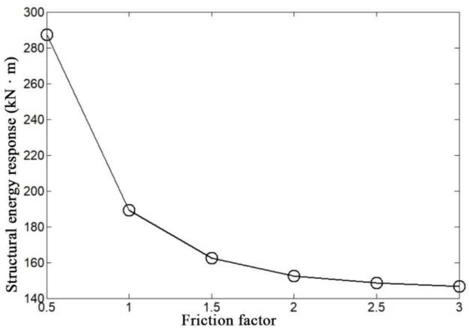

Figure. 8 Response Energy Amplitudes with Different Sliding Radius (Seismic Fortification Intensity: 7)

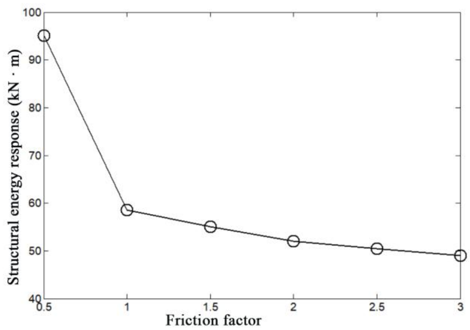

Figure. 9 Response Energy Amplitudes with Different Sliding Radius (Seismic Fortification Intensity: 8)

4. Conclusions

Based on the dynamic analysis of the nonlinear numerical simulation model of continuous beam Isolation Bridge, it is found that the friction pendulum bearing has good isolation energy consumption capability. In the energy response, it is found that the reasonable friction coefficient of the bearing can minimize the response energy amplitude of the isolation bridge structure. With the increase of seismic fortification intensity, the friction coefficient needs to be increased appropriately. At the same time, the energy response amplitude of the high-speed railway isolation bridge also decreases with the increase of the sliding radius. However, when the sliding radius reaches a certain value, the amplitude of the response energy remains unchanged when the sliding radius is increased, and the effect of isolation and energy dissipation cannot be further improved.

References

[1] Matsuzaki H. Time-dependent seismic reliability of isolated bridges considering ageing deterioration of lead rubber bearings. Structure and Infrastructure Engineering, 2022, 18(10-11): 1526-1541.

[2] Hassan A L, Billah A M. Influence of ground motion duration and isolation bearings on the seismic response of base-isolated bridges. Engineering Structures, 2020, 222:111129.F

[3] Zhang H, Li J, Peng T. Development and mechanical performance of a new kind of bridge seismic isolator for low seismic regions. Shock and Vibration, 2013, 20(4): 725-735.

[4] Khoshnoudian F, Hemmati T A. Impact of structures with double concave friction pendulum bearings on adjacent structures. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 2014, 167(1): 41-53.

[5] He W, Jiang L, Wei B, et al. The influence of pier height on the seismic isolation effectiveness of friction pendulum bearing for Double-Track railway bridges//Structures. Elsevier, 2020, 28: 1870-1884.

[6] Li Zhongxian, Zhang Haipiing, Luo Yunbia. Influence of vertical component of ground motion on seismic isolating performance of friction pendulum bearings isolated viaduct. Earthquake Engineering and Engineering Dynamic, 2018, 38(6): 8-17.

[7] Ivan Delgado, Roberto Aguiar, Pablo Caiza. Bilinear model proposal for seismic analysis using triple friction pendulum (TFP) bearings. Open Journal of Civil Engineering, 2017, 7: 14-31.

[8] Zhao Renda, Jia Yi, Zhan Yulin, et al. Seismic mitigation and isolation design for multi-span and long-unit continuous girder bridge inmeizoseismal area. Journal of Zhejiang University, 2018, 52(5):886-895.

[9] Jia Yi, Zhao Renda, Liao Ping, et al. Parameter optimization and damping effect of hyperbolic surface friction pendulum bearing for continuous girder bridge under rare earthquake. China Railway Science, 2018, 39(3): 31-40.

[10] Liao Ping, Zhao Renda, Jia Yi, et al. Effects of hyperbolic surface friction pendulum bearings' parameters on seismic response of the bridge. Journal of Southeast University, 2016, 46(6):1251-1256.

[11] Zhong Tieyi, Yang Fengli, Xia He. The design method of the seismically isolated bridge by lead rubber bearing based on energy method. China Railway Science, 2009, 30(2): 43-47.

