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Research Article

Seismic Fragility Analysis of Self-Anchored Suspension Bridge Considering Damping Effect

Xiangong Zhou ,[1] Lei Cao,[2] Heng Han,[1] Xiaobo Zheng ,[1] Hanhao Zhang ,[1] and Zhiqing Zhang[1]

[1]*School of Highway, Chang'an University, Xi'an 710064, China*
[2]*Shenzhen General Integrated Transportation and Municipal Engineering Design & Research Institute Co. Ltd., Shenzhen 518131, China*

Correspondence should be addressed to Xiaobo Zheng; zhengxiaobo0721@outlook.com

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The self-anchored suspension bridge is a kind of the flexible and redundant structural system. For this type of bridge, the current code only gives the overall seismic design principle, and there is little research on seismic fragility in the existing literature. Taking the three-tower self-anchored suspension bridge as the research object, the finite-element dynamic models with and without damping are established, respectively. Based on the strong earthquake database of PEER (Pacific Earthquake Engineering Research), 10 ground motion records are selected, and the seismic fragility curves of piers, bearings, towers, and slings are established by using the incremental dynamic analysis (IDA) method. The fragility curves of the bridge system were established by first-order reliability theory. In this study, the damage probability of bridge components under a seismic wave is studied. The results show that the damage exceedance probability of the damped connection system is reduced compared with the undamped fully floating structure system under the action of seismic waves. The damper device makes the seismic performance of the structure significantly improved, and the reduction effect of the damper device on high-intensity earthquakes is more obvious than that on low-intensity earthquakes.

1. Introduction

Multitower self-anchored suspension bridge has been widely used as a landscape bridge with its beautiful shape, superior mechanical properties, and good spanning ability. At present, seismic disasters seriously threaten the safety performance of bridge structures. The academic research on seismic fragility of bridge types such as girder bridges, long-span rigid frame bridges, and cable-stayed bridges have become increasingly mature.

Han Xing et al. [1] conducted research on the possibility of failure of high-speed railway continuous RC bridge under earthquake damage and obtained the probability density function of bridge seismic fragility based on the failure probability method and reliability function. Ramanathan et al. [2] analyzed the fragility of highway bridges with or without seismic detail design in the central and southeast of the United States, selected four multispan bridge structural models for fragility and failure probability analysis, established fragility curve models, and compared and analyzed the differences in bridge fragility between nonseismic design and seismic design. Kotoky et al. [3] analyzed the fragility of local components of highway bridges, conducted mixed tests on piers made of mixed fiber concrete, steel fiber, and polypropylene fiber, gave the limit state capacity and numerical model response curve of local components of the bridge structure, and obtained the conclusion that the exceedance probability of mixed fiber piers increases with the increase in intensity level. Wei et al. [4] selected a continuous girder bridge and analyzed its seismic response by using the incremental dynamic method, and came to the conclusion that the damage probability of the bridge and track increases with the increase in ground motion component. Calvi et al. [5] preliminarily evaluated the seismic capacity of RC bridge, analyzed its collapse mode and mechanism in combination with the application of hollow pier in practical engineering, classified and discussed the influencing factors such as lack of fortification, insufficient shear capacity, displacement of key section, and insufficient lap length, and gave the prediction and evaluation model of this kind of bridge. Nielson et al. [6] evaluated the seismic response and seismic risk of common steel girder and reinforced concrete bridges in the central and southeast of the United States, selected typical multispan bridges, conducted approximate risk test research on them by using the nonlinear three-dimensional model method, and proposed the setting method of model parameters such as load input direction and damping ratio. Padgett et al. [7]proposed a curve model for improving the fragility of bridge system, selected a typical multispan continuous-beam bridge to verify the model, and gave some measures and suggestions for improving bridge reinforcement. Sun et al. [8] established a 1 : 1 three-span RC continuous-beam bridge model, analyzed its seismic fragility by using the incremental dynamic analysis method, and put forward the method of reducing structural seismic loss. Baiben et al. [9] took the 926 m Erdong Yangtze River Bridge in Hubei Province as an example, studied the influence of nonlinear viscous damper on the seismic response of long-span bridge structures under the action of different periodic seismic waves, and analyzed the displacement and internal force response of bridge structures with different velocity parameters and damping coefficients under the input of long-period and general periodic seismic waves. Dong et al. [10] constructed the three-dimensional seismic damage index function of the dangerous parts of the bridge, calculated the probability of bridge damage under the three-dimensional earthquake by using the probability theory and structural reliability theory, verified it theoretically by taking a typical continuous-beam bridge as an example, and established the spatial fragility diagram. Wu [11–13] summarized the seismic fragility analysis methods of bridges at home and abroad, divided the theoretical seismic fragility function into four categories according to the probability parameter estimation method, established the model of typical bridges by using OpenSees finite-element software, analyzed the seismic response and parameter sensitivity of different local components by using strip analysis method, and selected 100 vibrations, considering the theory of probabilistic demand model, the dynamic response of the model is analyzed, and a probabilistic analysis model suitable for multispan continuous-beam bridge is proposed. Considering the uncertainty of site, ground motion, and bridge parameters, Hwang and Liu [14] analyzed the fragility of concrete continuous beams in expressway systems in the middle east of the United States. Considering the near-site vibration parameters, Liu et al. [15] selected a steel-concrete composite bridge as an example, selected the near-site and far-site vibration records from the Pacific seismic database of the United States, and gave the overall and local fragility curves of the bridge. Lan et al. [16] put forward the earthquake damage prediction model based on bridge fragility, predicted the fragility of the distribution of traffic trunk bridges in Taiyuan, and gave the prediction distribution map of the urban area. Zhuang et al. [17] summarized the seismic damage investigation data of 1657 bridges on highway sections in Sichuan Province during the Wenchuan earthquake, analyzed the seismic damage characteristics of beam bridges and arch bridges, respectively, and gave relevant seismic countermeasures. Li [18] analyzed the seismic damage characteristics of typical bridge structures, collected and sorted out the seismic damage investigation data of bridge structures in typical earthquakes, evaluated their fragility level by using different intensity standards and lifeline engineering specifications, established the bridge seismic damage fragility matrix model, and evaluated their intensity level.

Gaudio et al. [19, 20] used the simplified mechanical method of structural seismic fragility assessment (pushover shear model) to verify the RC building structures that suffered different degrees of damage in the 2009 L'Aquila earthquake in southern Italy, and obtained the fragility curve through the locking closed nonlinear static response, used ems-98 to classify the damage degree of the structure, and made data statistics considering geometric characteristics, the correlation between different parameters was obtained by fitting. Buratti et al. [21] analyzed the seismic fragility of prefabricated RC buildings in combination with the actual observed damage data after the Emilia earthquake in northern Italy in 2012. Taking RC building structure as the research object, Vargas et al. [22] proposed a content econometric nonlinear analysis method to analyze the fragility of the structure, considering the random factors of probability conditions, material strength, and ground motion. Song [23] analyzed the fragility of 17000 RC building structures in the high seismic active area of California, studied six seismic fragility parameters, and took 18 building structures from Erjinkan, Turkey, in 1992 and Kathmandu, Nepal, in 2015 as examples for damage assessment and deviation analysis. Ramamoorthy [24] conducted an in-depth study on the seismic fragility of RC building structures considering GLD design in the Americas. Combined with the impact of floors on fragility, five different story heights (1, 2, 3, 6, and 10 floors) were selected as representatives, and the Bayesian probabilistic demand model was used to predict the maximum interstory displacement. Zhong et al. established the probability seismic demand model (PSDM) under pulse-like ground motions in the near-fault earthquake [25], explored different damage states of pier columns in seismic fragility analysis [26], and studied the selection of appropriate IM for long-span bridges [27].

However, for self-anchored suspension bridges, the seismic design scheme given by the current seismic design theory [28] is not detailed, and there are few relevant seismic fragility studies. Therefore, it is particularly necessary to analyze the seismic performance of such bridges.

Seismic fragility analysis is an evaluation method based on probability to evaluate the seismic performance of structures. The fragility curve can describe the conditional probability that the structural demand exceeds the structural capacity under certain ground motion intensity (I_M) [7]. The probability of failure of a structure under a certain damage state can be expressed by

$$P_f = P[D \geqslant C \mid I_M], \quad (1)$$

where P_f is the structural damage probability; D is the structural requirement; C is the structural capacity; and I_M is the ground motion intensity parameter.

Based on formula (1), the structural fragility curve is established by solving the damage exceeding probability, and the seismic performance of the structure is evaluated.

Taking a three-tower self-anchored suspension bridge as an example, structural seismic fragility analysis is carried out based on the incremental dynamic method. The component fragility curves and the overall structural fragility curves under four different damage states are established and compared with the results considering the damping effect.

2. Seismic Fragility Analysis Based on IDA

At present, there are three main methods for theoretical fragility curve analysis: frequency statistical method of exceeding failure state based on numerical simulation; direct regression linear fitting method considering capacity, demand, and seismic uncertainty; and curve fitting method on the ratio of capacity demand based on damage index.

However, method 1 has poor accuracy and a large amount of calculation. About method 2, the statistical parameters in American specification HAZUS99 need to be used, which cannot be directly used for bridges in China. Therefore, method 3 combined with incremental dynamic analysis (IDA) is used to fit the structural fragility function based on the structural performance damage index. The exceedance probabilities of the structure in different damage states are calculated, and the structural fragility curves are established [29].

The establishment processes of fragility curves based on incremental dynamic analysis (IDA) are as follows [30]:

(1) According to the site conditions of the real bridge, select a number of appropriate ground motion records to determine the ground motion intensity parameter I_M

(2) Set a set of amplitude modulation coefficients to adjust the ground motion intensity

(3) The adjusted seismic waves are used and the nonlinear time history analysis of the established bridge dynamic model is carried out to solve the seismic response of the structure

(4) The response calculation results are sorted out and regressed by the least square method to obtain the regression mean μ and standard deviation σ, as shown in formulas (2) and (3). The damage exceedance probability of the structure under different levels of earthquake can be calculated by using (4).

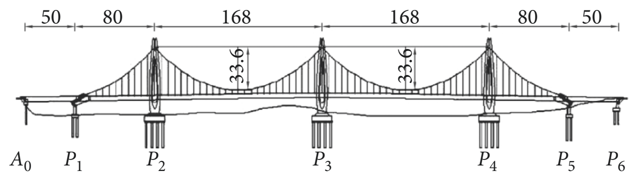

Figure 1: General layout of the bridge (m).

$$\mu = a[\ln(Sa)]^2 + b\ln(Sa) + c, \quad (2)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}[\ln(D_i) - \mu]^2}{N-2}}, \quad (3)$$

$$P_f = P\left[\frac{S_d}{S_c} \geqslant 1\right] = 1 - \Phi\left[\frac{\ln(1) - \mu}{\sigma}\right] = \Phi\left[\frac{\mu}{\sigma}\right]. \quad (4)$$

Where a, b, and c are regression coefficients, respectively; D_i is the peak seismic demand of the bridge structure under the number i earthquake. N is the number of ground motions. S_c and S_d refer to the structural capacity and structural requirement, respectively.

(5) The seismic fragility curve of each component is drawn according to the fragility function obtained by regression. The first-order boundary method is used to establish the fragility curve of the bridge system.

3. Example Background and Dynamic Analysis Model

3.1. Example Background. Taking the self-anchored suspension bridge under construction in Linfen, Shanxi Province, as an example, the bridge structure is a three-tower self-anchored full-floating suspension bridge system, and the seismic fortification intensity of the real bridge site is 8 degrees. The span arrangement is $50 + 80 + 168 + 168 + 80 + 50$ m and the sag of the main cable is 33.6 m. The bridge adopts a steel-concrete composite beam with a beam width of 50.5 m. The bridge towers adopt C50 concrete, and the height of the tower is 60 m. The slings adopt parallel steel wire with a nominal tensile strength of 1670 MPa, and there are 142 slings in total for the whole bridge. The layout of the whole bridge is shown in Figure 1.

3.2. Finite-Element Dynamic Analysis Model. The nonlinear dynamic model of the structure is established by Midas finite-element software. The beam, towers, and piers adopt spatial beam elements. Spatial cable units are adopted for the main cable and slings. The P-Δ analysis method is adopted to consider the geometric nonlinear effect of the structure. The bearing is simulated by a double broken line hysteretic model. The six-spring model is used to simulate pile-soil interaction and stiffness is calculated by the M method according to the specification. Figure 2 shows the structural

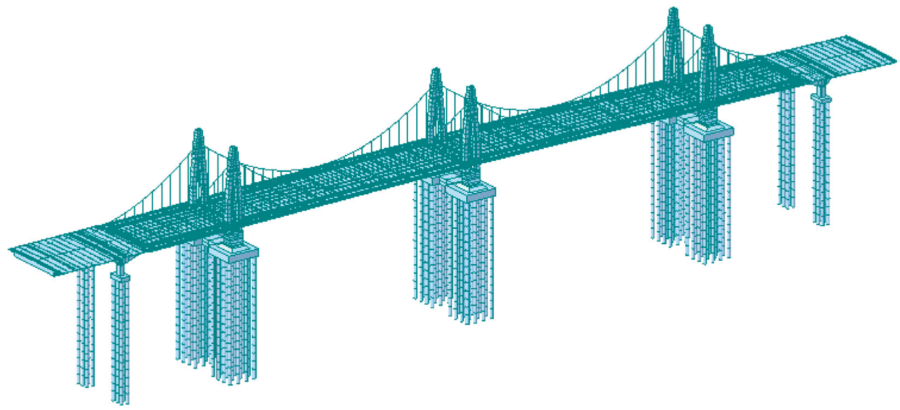

Figure 2: The structural finite-element model.

finite-element model, and Table 1 lists the first five dynamic characteristics of the bridge.

4. Seismic Fragility Analysis of Three-Tower Self-Anchored Suspension Bridge along the Bridge Direction

4.1. Selection of Ground Motion Parameters. Using 10–20 seismic records in IDA analysis can achieve a certain accuracy [31]. According to the class III site type of the real bridge and aiming at the response spectrum in JTG/T 2231-01-2020 for Seismic Design of Highway Bridges, the author selects 10 seismic waves from the strong earthquake database of Pacific earthquake engineering research center (PEER) to calculate the seismic fragility of the bridge. The comparison between the selected seismic wave response spectrum and the target response spectrum is shown in Figure 3.

Peak ground acceleration (*PGA*), peak ground velocity (*PGV*), and spectral acceleration corresponding to the basic period of the structure ($Sa\ (T_1)$) are commonly used to describe the seismic intensity index parameters. The research shows that because the first-order vibration mode plays a major role, when the spectral acceleration corresponding to the basic period of the structure is used as the strength index parameter, the regression analysis result is good [32]. Therefore, the authors take the spectral acceleration corresponding to the basic period of the structure ($Sa\ (T_1)$) as the seismic intensity index, and the amplitude modulation range is 0 ~ 0.7 G, 0.05 g per level. A total of 140 amplitude modulated seismic waves are input into the structural nonlinear dynamic model along the bridge direction.

4.2. Definition of Damage Index. The bridge seismic damage is mainly the damage to the pier and bearing, and the damage to the superstructure itself is relatively rare. According to the calculation, the response of the main beam under an earthquake does not play a key role, so it is judged to be a member that is not easy to damage. The auxiliary pier, bearing, main tower, and sling of the bridge are selected as the vulnerable components of the structure, which can be divided into four damage levels: slight damage, moderate damage, serious damage, and complete damage. At present, there are few studies on sling damage indicators. Wang Jingquan et al. [33] used strain ratio as an indicator for fragility analysis. Referring to this method and combined with the design code, it is determined that the safety factor of

Table 1: Dynamic characteristics of a self-anchored suspension bridge.

Number	Period T/s	Mode description
1	2.334	Antisymmetric vertical bending of main beam
2	1.658	Longitudinal drift of main beam and towers
3	1.616	Antisymmetric vertical bending of main beam
4	1.589	Symmetrical vertical bending of main beam
5	1.443	Symmetrical vertical bending of main beam

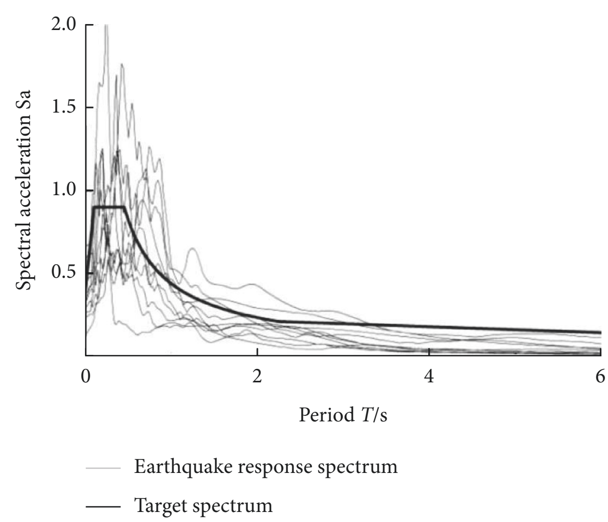

Figure 3: Seismic response spectrum and target response spectrum.

the sling under conventional load is 2.2 [34]. The four-grade damage indexes of sling defined by stress ratio are 0.45, 0.60, 0.75, and 0.90, respectively. The safety factors of corresponding slings are 2.2, 1.6, 1.3, and 1.1, respectively.

Fiber models of sections in the side and middle tower and pier bottom are established. And the first yield curvature is calculated. The curvature ductility factor μ_φ is defined as the ratio of sectional curvature to initial yield curvature. The curvature ductility coefficient is used as the evaluation index of pier and tower [35], as shown in formula:

$$\mu_\varphi = \frac{\varphi}{\varphi_y}. \tag{5}$$

Here, μ_φ is curvature ductility factor; φ is the sectional curvature of the component; and φ_y is the first yield curvature of the section.

The fragility of the bearing is analyzed, and the horizontal shear deformation is used as the performance index. The calculation of bearing shear strain γ is shown in the following formula:

$$\gamma = \frac{\mu_{\max}}{t}, \tag{6}$$

where $\mu_{\max}$ is the maximum displacement response of bearing under earthquake and t is the thickness of the rubber layer of the bearing. Table 2 provides the specific parameters of damage indexes of each component.

4.3. Establishment of Fragility Curve

4.3.1. Component Fragility Curve. The amplitude-modulated seismic waves are input into the nonlinear dynamic model of the structure for analysis. Collect the structural target response and conduct quadratic polynomial regression analysis. Establish the fragility curves of pier, bearing, tower, and sling. Figures 4–8 show the specific curves. Figure 4 shows that P1 and P5 piers are prone to slight and moderate damage under the action of seismic waves along the bridge. When Sa = 0.2 g, the probability of slight damage to P1 and P5 piers is 65.2%. Figure 5 shows that under the action of seismic waves along the bridge, the sling cable is prone to slight and moderate damage. When Sa = 0.2 g, the probability of slight damage to the sling is 66.1%, the probability of moderate damage is 29.2%, and the probability of serious damage is 9.8%. Figure 6 shows that the bearing components are prone to slight damage under the action of seismic waves along the bridge. When Sa = 0.2 g, the probability of slight damage to the bearing is 92.1%. Compared with Figures 7 and 8, it can be seen that the bridge tower is relatively difficult to be damaged. When Sa = 0.2 g, the slight damage probability of the side tower is 55.3%, and that of the middle tower is 23.6%. It can be seen from the whole fragility curve that the side tower of the three-tower self-anchored suspension bridge is more likely to be damaged than the middle tower under the action of seismic waves along the bridge direction.

In Figure 4, the seismic fragility of each component of the suspension bridge increases with the increase in Sa, and the probability of slight damage and moderate damage is large. Compared with other components, the probability of damage to P1 and P5 pier and bearing is relatively high, while the tower is relatively more difficult to damage. This is consistent with the relevant requirements in the seismic rules. The damage probability of components from easy to difficult is bearing, pier, sling, side tower, and middle tower.

4.3.2. System Fragility Curve. Each component in the structure has a great influence on the overall seismic performance of the structure. Based on the above calculation results of seismic fragility of components, the first-order boundary method based on structural reliability theory is used to analyze the fragility curve of the structural system and solve the system damage exceedance probability. The first-order boundary method is a method based on a series of parallel systems and ignoring the correlation between components. Its lower bound is the component with the largest failure probability in the system. The upper limit is the probability of failure of all components, which can be expressed by the following formula:

$$\max_{i=1}^{n}[P(F_i)] \leqslant P_s \leqslant 1 - \prod_{i=1}^{n}[1 - P(F_i)], \tag{7}$$

where $P(F_i)$ is the damage exceedance probability of the i^{th} structural member and P_s is the damage exceedance probability of the structural system.

Because the lower limit of the first-order limit method will underestimate the damage exceedance probability of the structural system, the upper limit value is used to evaluate the fragility of the structural system. Figure 9 shows the fragility curve of the structural system under these four damage states.

It can be seen from Figure 9 that under the action of seismic wave along the bridge, when Sa = 0.1 g, the overall slight damage probability of the structure is 54.1%, the moderate damage probability is 28.3%, and the serious damage and complete damage probability are basically 0. Compared with Figure 4, it can be seen that the overall damage probability of the structure is significantly higher than that of each component under each damage level.

5. Seismic Fragility Analysis along the Bridge considering the Damper Connection System

5.1. Summary. The full-floating suspension bridge is a suspension bridge structure with a separated tower and beam. This structure connects the main tower and the main beam through a sling at the position of the tower. The main beam will not be constrained by the tower. This system can offset part of the seismic force through the displacement along the bridge direction of the main beam under the action of the earthquake, which is beneficial to the seismic resistance of the structure. However, for a fully floating structure, the main beam that can move freely along the bridge may have excessive displacement in an earthquake. In order to

Table 2: Component fragility index.

Bridge components	Evaluating indicator	Damage level			
		Slight damage	Moderate damage	Serious damage	Complete damage
Pier	μ_φ	1	2	4	8
Tower	μ_φ	1	2	4	8
Bearing	γ	1.0	1.5	2.0	2.5
Sling	s/s_y	0.45	0.60	0.75	0.90

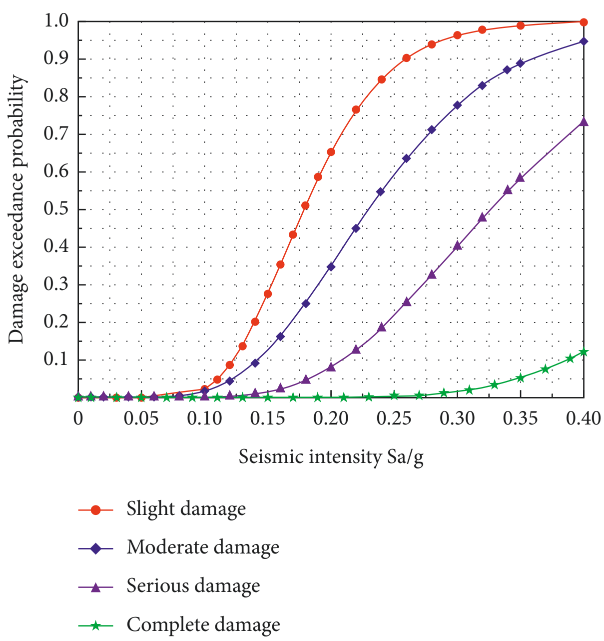

Figure 4: Fragility curves of pier.

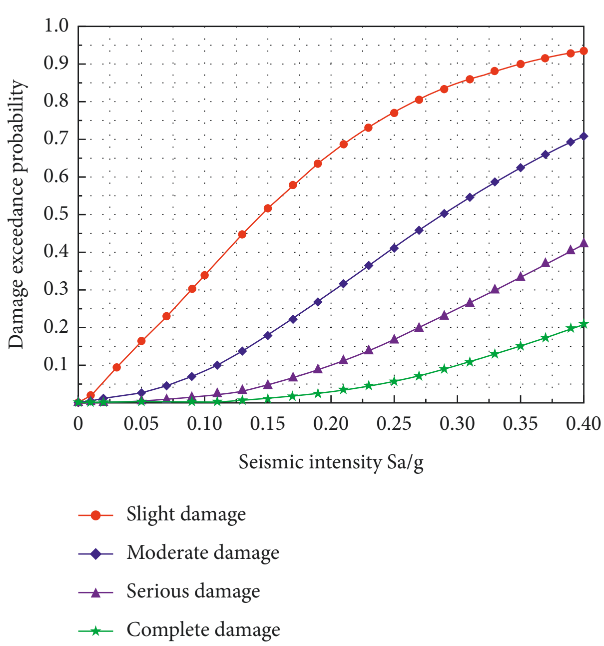

Figure 5: Fragility curves of sling.

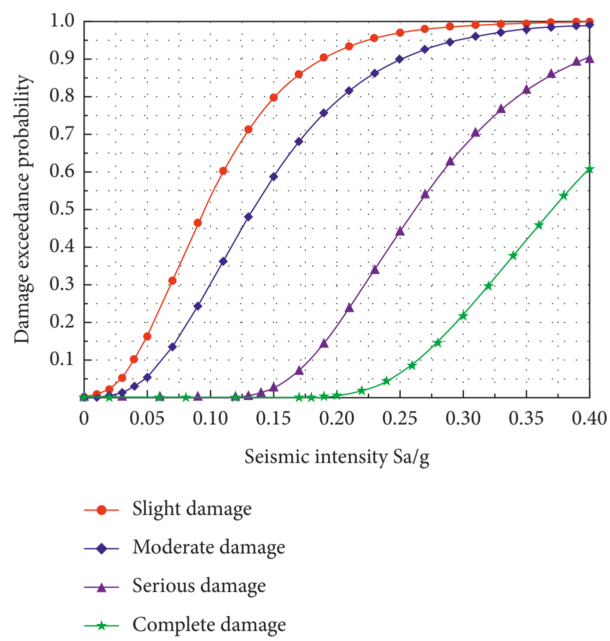

Figure 6: Fragility curves of bearing.

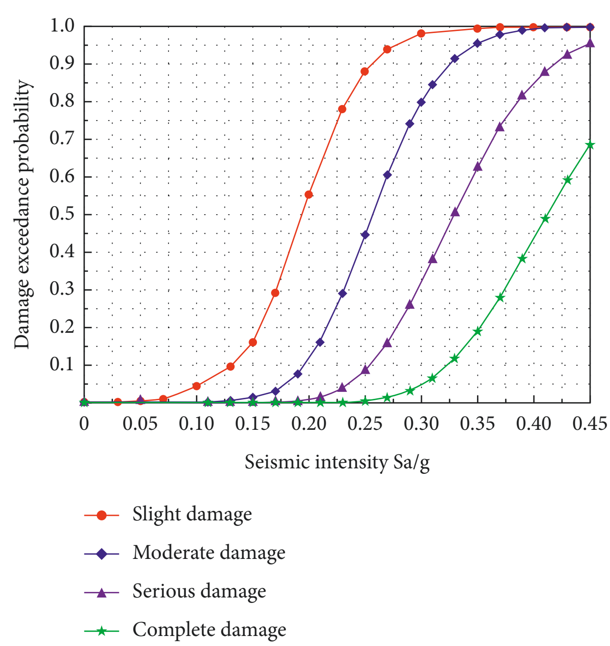

Figure 7: Fragility curves of side tower.

avoid this problem, various vibration reduction and isolation devices such as elastic connection devices and viscous dampers are gradually adopted. The viscous damper can effectively reduce seismic displacement. Many long-span bridges at home and abroad use viscous dampers as a damping device. In this section, the fragility analysis is

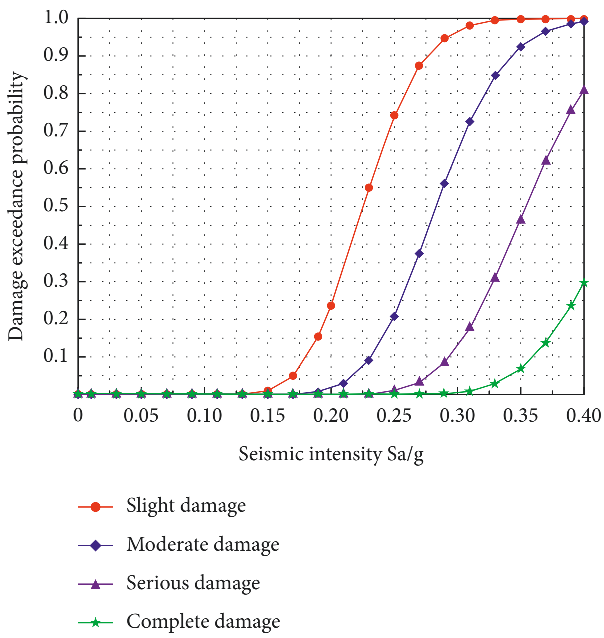

Figure 8: Fragility curves of middle tower.

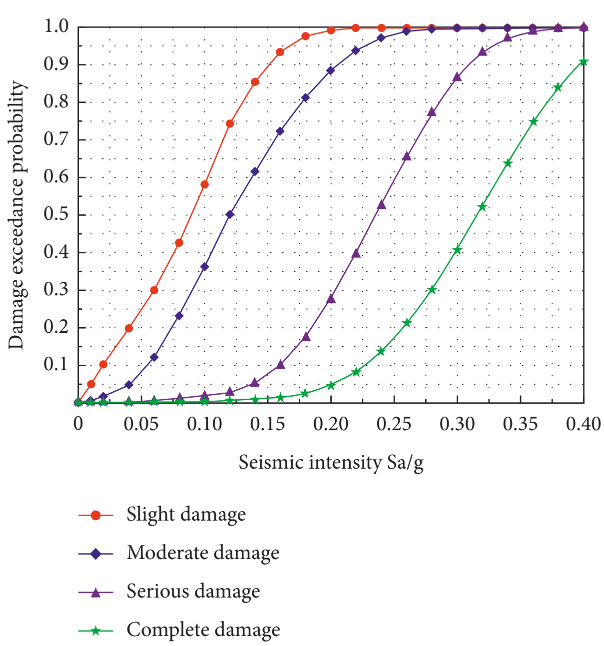

Figure 9: Structure system fragility curves.

carried out for the structure equipped with a liquid viscous damper, and the fragility is compared with the floating system structure.

5.2. Model Establishment. Adjust the structural fragility model of the self-anchored suspension bridge established in Section 4 and add a liquid viscous damper device. In this paper, Maxwell model is used to simulate a viscous damper. In the constitutive model, the liquid viscous damper is a

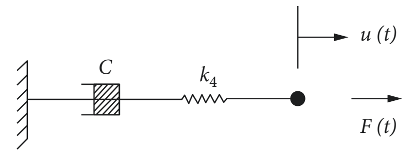

Figure 10: Schematic diagram of the Maxwell constitutive model.

series model of damping element and spring element, as shown in Figure 10. When the damping force is not proportional to the deformation speed of the liquid viscous damper, the whole is nonlinear. At this time, the expression is shown in formula (8):

$$F = Cv^{\xi}. \quad (8)$$

In the above formula, F represents the maximum damping force; C is the damping coefficient; v represents speed; and ξ represents the damping index.

Two liquid viscous dampers for the side tower and four for the middle tower are settled along the bridge direction. Table 3 provides the specific parameters of the liquid viscous damper along the bridge.

5.3. Fragility Analysis of Members of the Damper Connected System. For the above structures with dampers, the fragility of the member is analyzed. The selection method of vulnerable components and damage indicators is the same as in section 3. The fragility of components is calculated and analyzed. Figures 11 and 12 show the fragility curve of the bottom section of the main tower.

It can be seen from Figure 11 that when Sa = 0.2 g, the probability of slight damage to the bottom section of the side tower equipped with a damper is 35.4%. The probability of moderate damage is 1.7%. The probability of serious damage and complete damage is basically zero. Compared with the fragility curve of the bottom section of the side tower of the floating system in section 3, the installation of damper reduces the probability of slight damage and moderate damage by about 20% and 10%. It can be seen from Figure 12 that when Sa = 0.2 g, the probability of slight damage to the bottom section of the middle tower with a damper is 3.3%, and the probability of damage above moderate damage is basically zero. Compared with the fragility curve of the bottom section of the tower in the above floating system, the installation of a damper reduces the probability of slight damage at the bottom of the middle tower by about 20%. According to the fragility curves of the two towers at various levels, the use of dampers significantly reduces the damage probability of the components of the three-tower self-anchored suspension bridge. In addition, the damage to the tower bottom section is significantly delayed and the damage growth rate is significantly slowed down. It shows that the damping device has an obvious change in the internal force of the floating structure under the earthquake, prolongs the process of the main tower components from elasticity to elastoplasticity, reduces the damage probability of the main tower, and significantly improves the seismic performance of the structure.

Table 3: Damper parameters along the bridge.

Position	Damper parameters			
	Maximum damping force/kN	Maximum displacement/mm	Damping index/kN/$(m/s)^{\alpha}$	Speed index α
Middle tower	1250	350	1250	0.3
Side tower	1250	350	1250	0.3

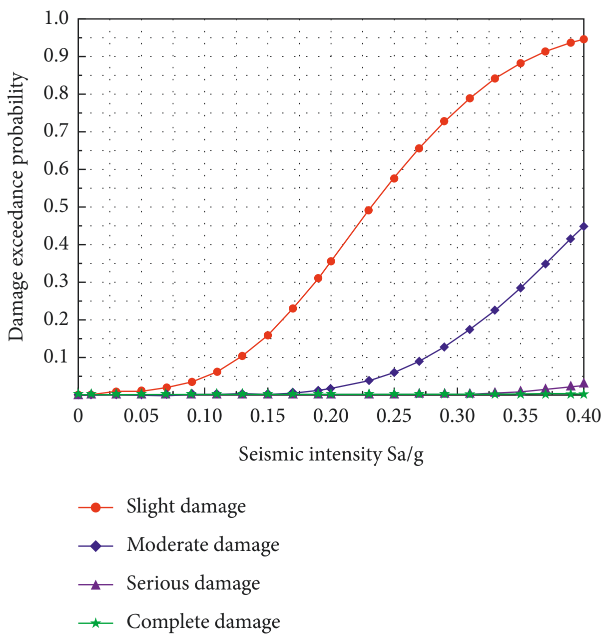

Figure 11: Fragility curves of side tower in the damper connected system.

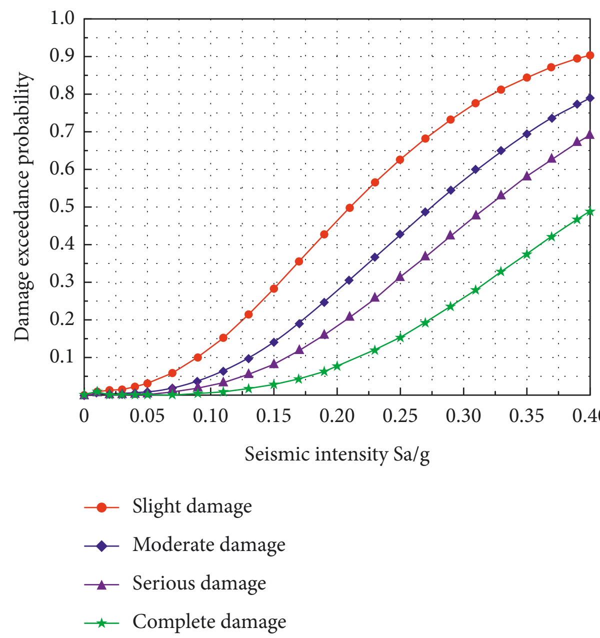

Figure 13: Fragility curves of pier in the damper connected system.

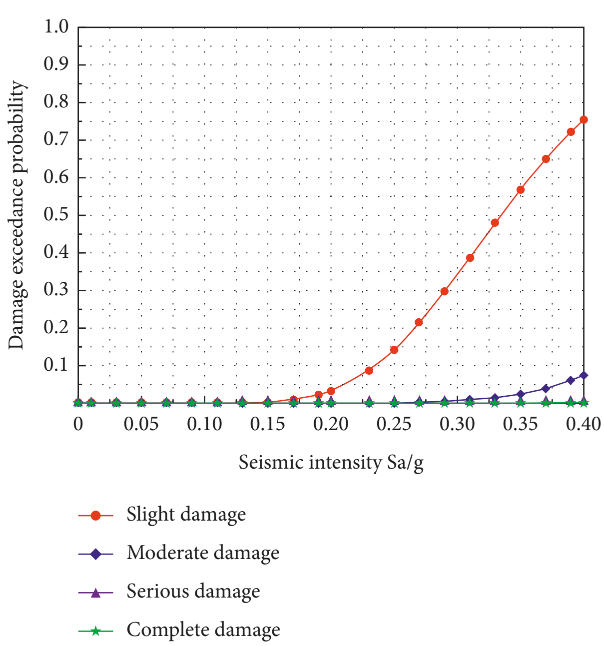

Figure 12: Fragility curves of the middle tower in the damper connected system.

Figures 13–15, respectively, show the fragility curves of the side pier, bearing, and sling under different damage levels. According to Figure 13, when the ground motion intensity Sa = 0.2 g, the probability of slight damage to the bearing is 18.4%, the probability of moderate damage is 5.4%, the probability of serious damage is 2%, and the probability of complete damage is basically zero. According to Figure 14, when the ground motion intensity Sa = 0.2 g, the probability of slight damage to the side pier is 46.5%, the probability of moderate damage is 27.7%, the probability of serious damage is 18.3%, and the probability of complete damage is 7.7%. According to Figure 15, when the ground motion intensity Sa = 0.2 g, the probability of slight damage to the sling is 36.2%, the probability of moderate damage is 6%, and the probability of serious damage and complete damage is basically zero.

According to the above component fragility curve, it can be seen that after the installation of the damper device, the exceedance probability of each component of the structure under different damage levels is reduced compared with the corresponding components of the previous floating system. The damage probability of bearing decreases most obviously. The reason is that the damper limits the longitudinal displacement of the beam and the stress of the bearing is significantly changed. The fragility curve of each component still shows the above "Three-stage" growth trend, but the seismic action intensity required for each component to have a damage point increases, and the growth rate of damage probability slows down. The reason is that the seismic performance of the structure is improved, which

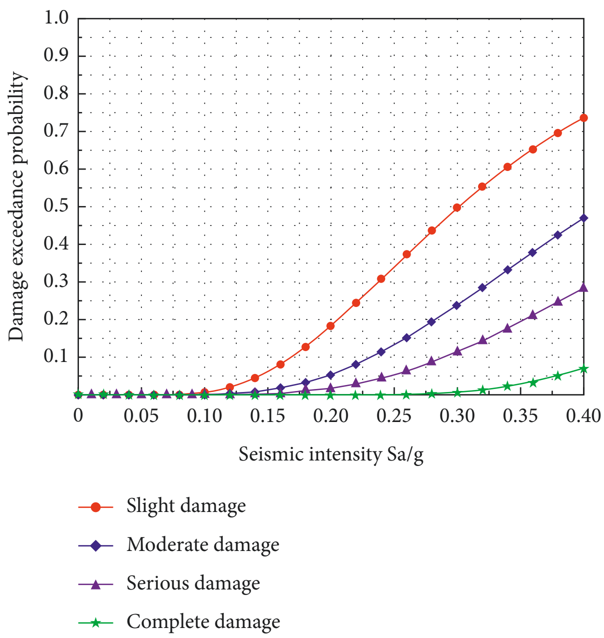

Figure 14: Fragility curves of bearing in the damper connected system.

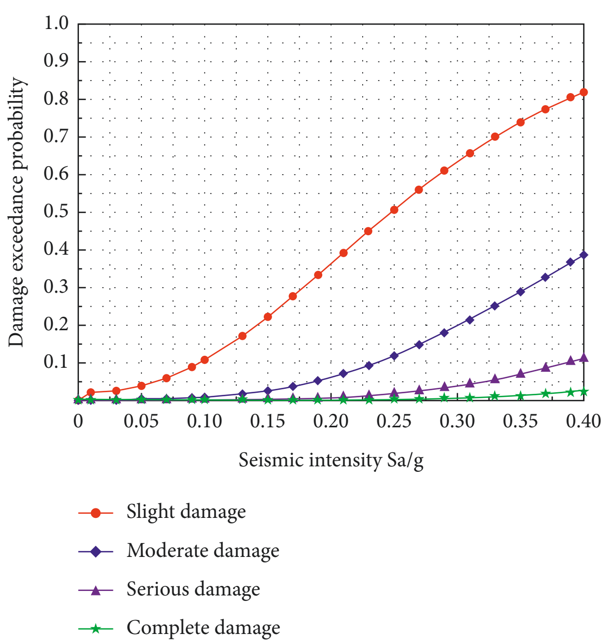

Figure 15: Fragility curves of sling in the damper connected system.

prolongs the ground motion intensity threshold of damage to each component.

5.4. Fragility Analysis of the Damper Connected System. The first-order limit method based on reliability theory is also used to analyze the overall fragility of the system. The research in the previous section shows that the fragility analysis of the structure using the parallel system is better for

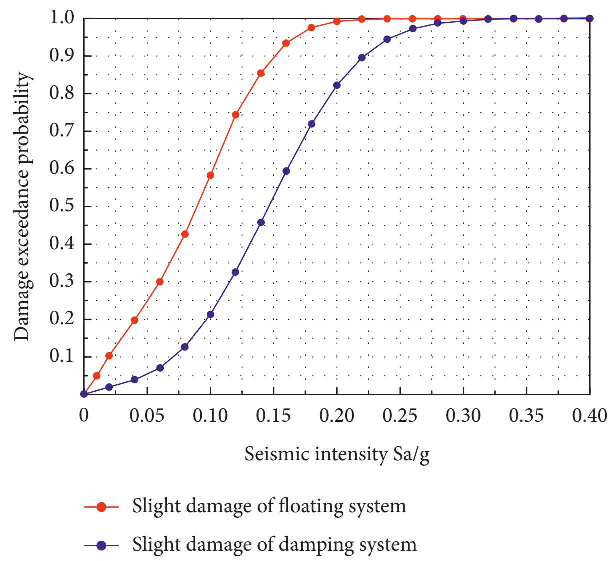

Figure 16: Structure system of slight damage fragility curves.

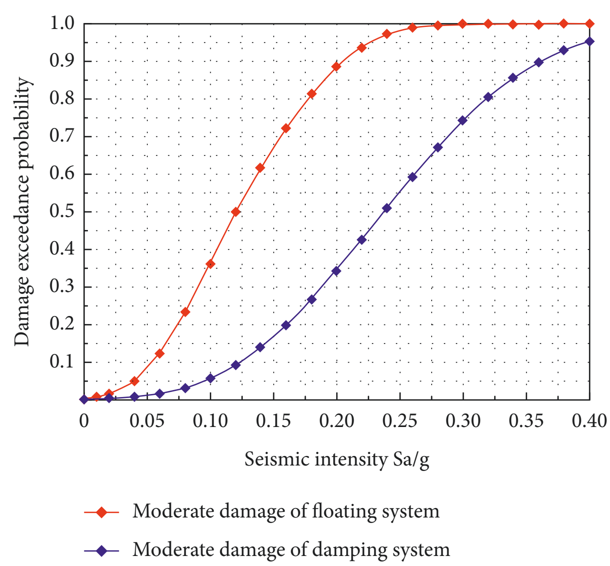

Figure 17: Structure system of moderate damage fragility curves.

the simulation of the damage exceedance probability of the system. This section only gives the structural fragility curve of the parallel system and compares it with the fragility curve of the full-floating system under the same damage level, as shown in Figures 16–19.

It can be seen from Figures 16–19 that taking the ground motion intensity Sa = 0.2 g as an example, the probability of slight damage to the damper connection system is 82.2%, the probability of moderate damage is 34.4%, the probability of serious damage is 20.3%, and the probability of complete damage is 3.6%. The damage probability of the floating system under the same ground motion intensity is 99%, 88.6%, 27.5%, and 4.5%. The probability of minor damage is reduced by 16.8%, the probability of moderate damage is reduced by 54.4%, the probability of serious damage is

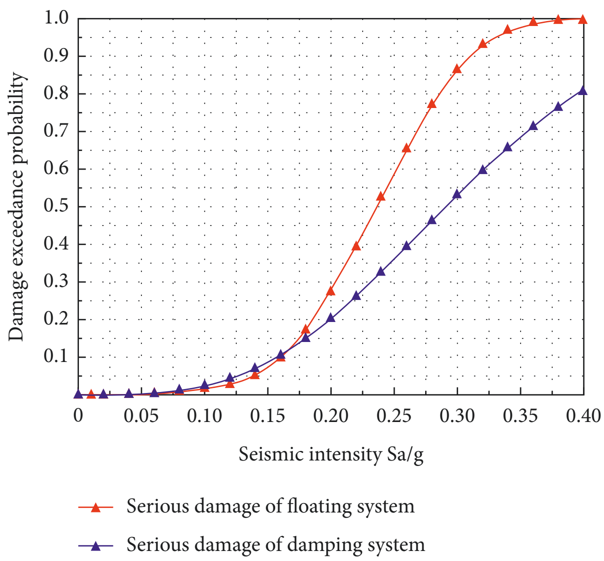

Figure 18: Structure system of serious damage fragility curves.

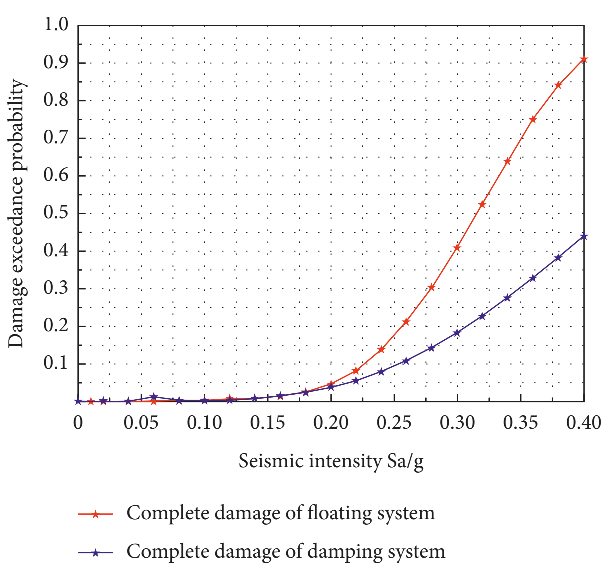

Figure 19: Structure system of complete damage fragility curves.

reduced by 7.2%, and the probability of complete damage is reduced by 0.9%. Comparing the fragility curves of two different systems under each damage level, it can be obtained that the damage exceedance probability of each damage level of the damper connected system is less than that of the floating system, and the overall fragility of the damper connected system is greater than that of each component. The starting point of damage in the system fragility curve is significantly delayed compared with the floating system. At the same time, the growth rate of damage exceedance probability at each damage level of the structure slows down, and the growth process of damage exceedance probability prolongs. With the increase in ground motion intensity, the damage exceedance probability difference between the system and the floating system gradually expands, indicating that the damper device can significantly improve the seismic performance of the structure, and the reduction effect for a high-intensity earthquake is more obvious than that for low-intensity earthquake.

6. Conclusion

In this study, the research and analysis method of structural fragility of three-tower self-anchored suspension bridge is given in detail based on practical engineering cases. The structural finite-element simulation is carried out. Finally, the structural fragility curve is drawn through regression analysis. First, the fragility curves of bearings, side piers, slings, side towers, and middle towers of fully floating bridges under different damage levels are given. Then, combined with the first-order limit method in reliability theory, the fragility curve of the structural system is calculated. Then, the fragility curves of each component under different damage levels and the fragility curves of the structural system are calculated, respectively. Finally, two different connection systems are compared. The following are the conclusions obtained from the calculation and analysis:

(1) The exceedance probability of side pier, bearing, sling, side tower, and middle tower components of floating system structure under each damage level is positively correlated with the seismic intensity. The damage probability of components under the action of seismic waves along the bridge is bearing, side pier, sling, side tower, and middle tower from easy to difficult.

(2) The probability of slight and moderate damage to the piers and bearings of the floating system of the three-tower self-anchored suspension bridge is high, while the probability of damage to the bridge tower is relatively small. This design is in line with the design idea of taking the easily repaired components as secondary components in the seismic design

(3) Under the action of seismic waves along the bridge, the damage exceedance probability of the whole floating structure system is higher than that of each component. The overall system is prone to slight and moderate damage, that is, the overall structure is prone to cracking and partial reinforcement yielding under earthquake, which is consistent with the design principle of local repairable damage of structure under E2 earthquake in seismic rules.

(4) Under the action of along bridge seismic wave, each component of the damping connection system structure is prone to slight and moderate damage. Compared with the floating system, the damage exceedance probability of each component under each earthquake level is reduced. The component with the most reduction in damage exceedance probability is the bearing and the least reduction in damage exceedance probability is the bridge tower component. Under the action of along bridge seismic

wave, the damage probability of each component in the damper connection system from easy to difficult is the side pier, sling, bearing, side tower, and middle tower, which still conforms to the design idea that the bridge tower has a lower damage probability as a component that is not easy to maintain.

(5) Under the action of seismic waves along the bridge, the damage exceedance probability of the damped connection system is lower than that of the fully floating structure system. At the same time, the difference in damage exceedance probability of the two systems under the same damage level continues to expand. It shows that the addition of a damper device can significantly improve the seismic performance of the structure, and the reduction effect of a damper device for a high-intensity earthquake is more obvious than that for a low-intensity earthquake.

In view of the above conclusions, the following engineering suggestions are given in this section:

(1) The analysis shows that the viscous damper device can significantly reduce the structural damage probability, especially the moderate damage probability, and can sufficiently decrease the seismic effect of inelastic deformation of the structure. As a self-anchored floating system suspension bridge, the damping device has a good effect. It is recommended that similar bridges use this kind of equipment as the damping device.

(2) It is suggested to prioritize the structural members according to the fragility degree obtained from the analysis. For small earthquakes, priority shall be given to the inspection of structural bearings, side piers, and other parts with high fragility probability, and problems shall be found and maintained in time. For large earthquakes, it is recommended to check one by one according to the sequence of bearings, side piers, slings, and bridge towers, and repair the damaged positions in time.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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