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Seismic Vulnerability Analysis of Long Span Prestressed Concrete Continuous Rigid Frame Bridge

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Abstract

Bridges are critical links in a transportation network that are susceptible to seismic actions, their vulnerability assessment is essential for seismic risk assessment and mitigation. In order to explore the damage probability of long span prestressed concrete continuous rigid frame bridge in the event of earthquake, this study took the Longxi Jialing River Bridge as an example and presents seismic vulnerability assessment based on the incremental dynamic analysis method. Taking the curvature of the pier's most unfavorable section as the damage index, the seismic vulnerability curve of the pier was established with peak acceleration(PGA) as the independent variable and the probability of the structure exceeding a specific damage state as the dependent variable. Results demonstrate that under the action of a near-field earthquake, when PGA =0.5 g, the failure probabilities of slight damage is 0.02926, the failure probabilities of moderate damage is 0.01823, and the failure probabilities of severe damage is 0.00075. When PGA = 1.0 g, the failure probabilities of slight damage is 0.672 and 0.597 for moderate damage, 0.20109 for severe damage, and 0.00484 for complete damage. Under the action of a far-field earthquake, when PGA = 0.5 g, the failure probability of slight damage is 0.00194, and the failure probability of moderate damage is 0.00101 along the span direction. When PGA = 1.0 g, the failure probability of slight damage is 0.04358, 0.02802 for moderate damage, and 0.00138 for serious damage along the span direction. The complete damage of the bridge hardly occurs. With the increase of intensity of an earthquake, the failure probability of the pier gradually increases. After entering the moderate damage stage, the pier has relatively good ductility. This study provides a good reference for the seismic design of similar bridges.

Keywords: Continuous rigid frame bridge, Log-normal distribution, Section curvature, Incremental dynamic analysis, Seismic vulnerability analysis

1. Introduction

In recent years, strong earthquakes in Southwest China have brought severe potential safety hazards to transportation infrastructure. As a safe passage of escape during an earthquake and a key passage of rescue and disaster relief after such disaster, the safety of bridges is particularly important in earthquake. Seismic vulnerability analysis is an effective tool for the seismic safety assessment of structures. Notably, Chongqing has special terrain conditions; the bridge span in this area is large, the pier is high, the height difference between adjacent piers is large, and the bridge is irregular. At present, the research on the seismic vulnerability of bridges in this area remains insufficient. Given the lack of seismic damage data on bridges, the theoretical analysis method is widely used by scholars. However, traditional methods often need a large number of time-history analysis to ensure the accuracy of vulnerability analysis. Therefore, improving the theoretical vulnerability analysis method without having to increase the number of time-history analysis is a key problem in theoretical vulnerability analysis at present.

In the existing literature, scholars have carried out a large number of studies on evaluating the seismic performance of common highway and railway simply-supported beam bridges and continuous beam bridges with medium and small spans on highways. Meanwhile, the research on the seismic vulnerability of long span prestressed concrete continuous rigid frame bridges is insufficient. Therefore, a method to analyze the seismic vulnerability for long span prestressed concrete continuous rigid frame bridges with high analysis efficiency and reliable analysis results must be sought.

In this study, the Longxi Jialing River Bridge was taken as an example to explore the damage probability of long span prestressed concrete continuous rigid frame bridges in the event of earthquake based on the incremental dynamic analysis method. The seismic vulnerability curve of the pier is established with peak acceleration (PGA) as the independent variable and the probability of the structure exceeding a specific damage state as the dependent variable. The study is expected to provide a theoretical reference for the seismic design of bridges in the future.

2. State of the art

Scholars have done substantial research on the seismic vulnerability of bridges. He, H.X. et al. [1] indicated that a bridge can be regarded as a ternary system composed of a pier, an abutment bearing, and a pier bearing. In addition, they introduced the multivariate copula function to establish the method for solving the seismic fragility of the ternary

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component system. A sample analysis showed that the bridge system fragility based on the multivariate copula function can more truly represent the damage characteristics and fragility of the whole bridge, thus significantly improving the calculation accuracy and efficiency. Furthermore, Bai, Y.L. et al. [2] proposed a simplified LRS FRP-confined concrete model under cyclic axial compression. According to the simplified model, the seismic fragility of the continuous girder bridge before and after LRS FRP strengthening was analyzed on the basis of seismic fragility analysis theory and incremental dynamic analysis (IDA) method using OpenSees platform. Li, S.Q. et al. [3] established an empirical seismic-damage vulnerability function based on the survey data for 2,134 bridges in 22 highway sections affected by the Wenchuan earthquake on May 12, 2008. Thapa Sunil et al. [4] carried out a comparative seismic vulnerability analysis of a representative RC bridge from Nepal Himalaya. The results depicted that the horizontal response parameters, such as displacement and displacement ductility, are not considerably affected by the vertical ground motion; however, the effect is found to be increasingly significant for higher damage states. Dizaj Ebrahim Afsar et al. [5] investigated the influence of bridge layout on the seismic vulnerability of piers of varying heights. Their results showed that the unbalanced seismic displacement demand and failure probability of different bents of a multi-span irregular RC bridge significantly depend on the height of piers and their arrangement. Saygili Ozden et al. [6] performed a seismic assessment study of two historical masonry arch bridges, with different geometries and spans. The study showed that rigid block models have the ability to represent the dynamic elastic response of the bridges effectively; the scholars also found that these models can be calibrated by ambient vibration measurements. Dong, J. et al. [7] introduced the Bayesian estimation method (BEM) to analyze the seismic vulnerability of a typical four-span railway simply-supported beam bridge. Meanwhile, Zhang, P.H. et al. [8] proposed a new vulnerability analysis method by combining BOX-COX transformation and Monte Carlo sampling technique. Hu, D.Y. [9] evaluated the seismic performance of a typical three-span continuous girder bridge of the Chongqing-Kunming high-speed railway and compared the seismic vulnerability curves of the bridge structure with ordinary spherical steel bearing and hyperboloid spherical seismic isolation bearing. Li, P. et al. [10] established a theoretical seismic vulnerability model of a typical long span bridge with high pier in a southwest mountainous area. Results showed that the damage probability of each key part of a typical long span continuous rigid frame bridge with high pier under near-field earthquake is much higher than that of far-field earthquake. Wu, W.P. et al. [11] built a finite element analysis model for a certain high-pier long span continuous rigid frame bridge in deep water based on OpenSees source code analysis platform considering the effects of pile-soil interaction (PSI).

As noted above, scholars have adopted the traditional analysis method to establish the bridge vulnerability curve. However, these traditional methods often need a large number of time-history analysis to ensure the accuracy of vulnerability analysis, and the calculation results of bridges with different pier heights and different spans cannot provide a reference for each other. Furthermore, if the commonly used methods are employed to evaluate the seismic vulnerability of typical bridges with various pier heights and spans in the Chongqing area, the computational complexity will be huge. Hence, it will occupy a large number of computational resources. To improve the efficiency of bridge seismic vulnerability analysis and reduce the computational work to obtain real and reliable analysis results, the incremental dynamic analysis method is employed to establish the seismic vulnerability curves of bridges with different pier heights under far and near site vibrations in this study. This investigation is expected to provide a theoretical reference for similar practical projects in the future.

The remainder of this study is organized as follows: Section 3 describes the basic engineering situation of the Longxi Jialing River Bridge and constructs the bridge seismic vulnerability analysis process based on incremental dynamic analysis and the damage state and damage index of piers. Then, Section 4 derives the vulnerability curves of piers under far-field and near-field earthquakes. Lastly, Section 5 summarizes the conclusions.

3. Methodology

3.1 Study Bridge

The Longxi Jialing River Bridge is the controlling project of the Hechuan Changshou Section of the Chongqing Third Ring Expressway. It is located in the Longdongtuo River section at the downstream of Hechuan District, crossing the Jialing River. Its span layout is 3 × 30 m + 4 × 30 m prestressed concrete T-beam + (108+200+108) m prestressed concrete continuous rigid frame + 5 × 30 m + 5 × 30 m + 4 × 30m prestressed concrete T-beam. The total length of the bridge is 1,053 m, and the main bridge is (108 + 200 + 108) m prestressed concrete continuous rigid frame bridge, as shown in Fig. 1. The main beam is a single box with two chambers. The top width of the box beam is 21.5 m, and the bottom width is 13.5 m. The height of the beam section at the main pier is 12.5 m, and the height of the beam section in mid span is 4 m. The beam height changes according to the quadratic parabola, as shown in Fig. 2. The main beam is made of C55 high-performance concrete, and the second phase dead load is 76.1 kN/m. The basic information of main piers is shown in Tab. 1. The seismic peak acceleration in the bridge site area is 0.05 g, the basic seismic intensity is VI, and the seismic fortification intensity is VII.

At present, the expert opinion method, test method, experience method, and numerical analysis method are widely used for the seismic vulnerability analysis of structures. The expert opinion method is simple but subjective; the empirical method can reflect the true vulnerability of bridges, but the regional and structural particularity is relatively strong. In addition, the test method is greatly influenced by the number of test model samples. Meanwhile, the numerical analysis method has strong reliability and can consider various uncertain factors. In particular, the numerical analysis methods adopted by scholars mainly include elastic response spectrum analysis method [12], static elastoplastic analysis method [13], nonlinear time history analysis method [14, 15], probabilistic seismic model analysis method based on Bayesian analysis [16, 17], incremental dynamic analysis method (IDA), and so on [18-19]. Notably, the incremental dynamic analysis method is a kind of method that establishes vulnerability curves through modulating the amplitude of ground motion and analyzing the nonlinear dynamic behavior of structure or member under different ground motion intensity levels. The method can accurately show the whole process from damage to complete failure of bridges. In this study, the incremental dynamic analysis method is employed to establish the seismic vulnerability curve of the bridge based on the uncertainty of bridge structure parameters and ground motion parameters. The flow is shown in Fig. 3.

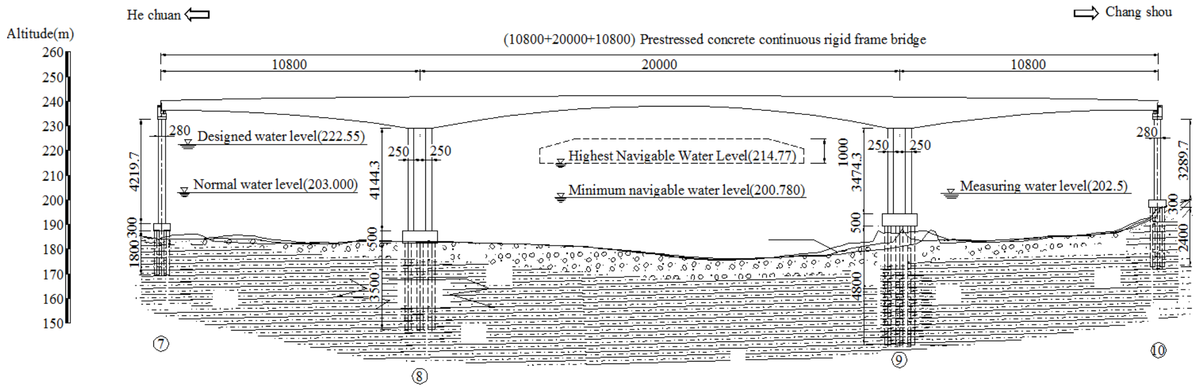


Fig. 1. Layout of Main Bridge of Jialing River Bridge in Longxi

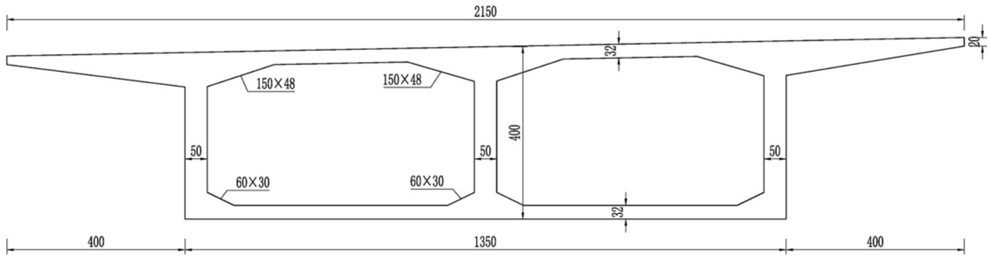


Fig. 2. Mid-span section (Unit: mm)

Table 1. Basic information of main pier

Pier number	Type	Section size of single limb/m	Strength grade of concrete	Height/m	Reinforcement type
Pier No. 8	Double-limb thin-walled pier	2.5 m × 13.5 m	C45	4.1	HRB500
Pier No.9	Double-limb thin-walled pier	2.5 m × 13.5 m	C45	3.5	HRB500

3.2 Process of seismic vulnerability analysis

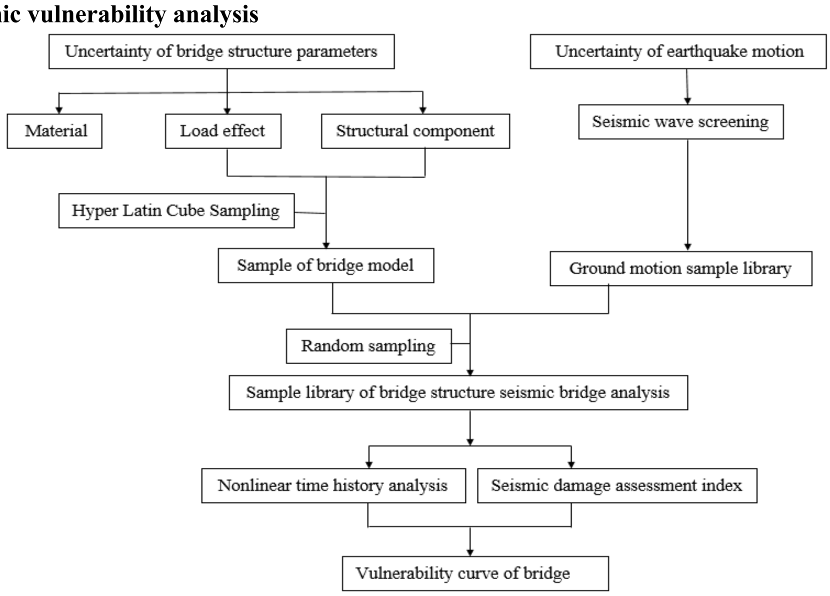


Fig. 3. Flowchart for seismic fragility analysis of Jialing River Bridge

3.3 Seismic vulnerability analysis

3.3.1 Ground-motion simulation

The uncertainty of ground motion has a great influence on the seismic vulnerability analysis of bridges. Research [20] showed that seismic vulnerability analysis based on incremental dynamic analysis requires at least 10-20 seismic records to meet the accuracy requirements. The ground motion response spectrum selected in this study is shown in Fig. 4.

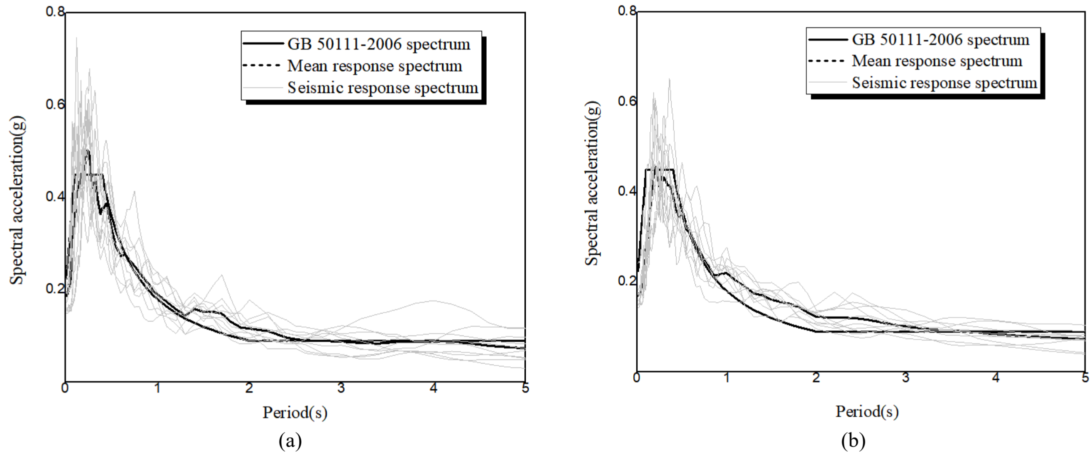


Fig. 4. Response spectrum of selected ground motions (ξ=0.05). **(a)**Far-field earthquake. **(b)** Near-field earthquake

3.3.2 Definition of damage state

Taking the curvature of the pier's most unfavorable section as the damage index, the degree of damage is divided into five grades: no damage, slight damage, moderate damage, serious damage, and complete damage, as shown in Tab. 2. $\phi_y^{'}$ is the curvature when the outermost longitudinal reinforcement of pier yields, ϕ_y is the curvature corresponding to equivalent yield point, ϕ_d is the curvature when the unconfined concrete in the compression zone is crushed, and ϕ_u is the ultimate curvature.

The moment-curvature analysis of the pier section is carried out by using UCFyber software. The Mander model is adopted for concrete, and the bilinear model is adopted for steel bar. The moment-curvature curves of the pier section are shown in Fig. 5, and the calculation results of control points of pier bottom section are shown in Tab. 3.

Table 2. Damage status and damage index of pier

Damage degree	**Damage characteristics**	**Damage index**
No damage	Slight cracks appear in concrete and steel bars do not yield	$\phi \le \phi_y^{'}$
Slight damage	Concrete has obvious cracks; the first steel bar yields	$\phi_y^{'} < \phi \le \phi_y$
Moderate damage	The protective layer begins to peel off and cracks develop; local plastic hinge begins to form and nonlinear deformation occurs	$\phi_y < \phi \le \phi_d$
Severe damage	The plastic hinge completely forms and concrete spalls in the whole plastic hinge area; cracks with a large width appear	$\phi_d < \phi \le \phi_u$
Complete destruction	Core concrete crushes; main steel bars yield; stirrups fracture	$\phi > \phi_u$

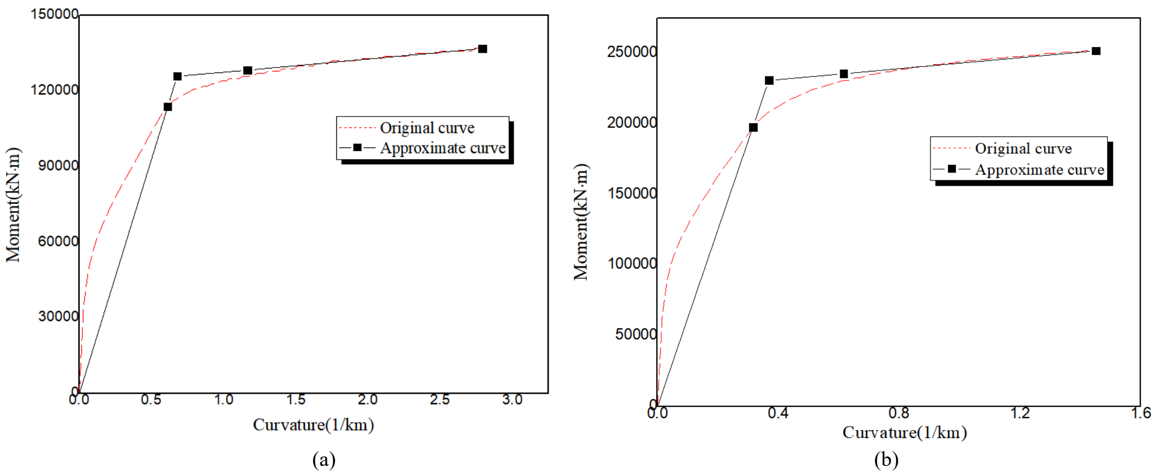


Fig. 5. Moment-curvature relationship of pier. (a) Along span. (b) Along transverse

Table 3. Data of moment-curvature of pier

Direction	$\phi_y^{'}$ **/(1/km)**	ϕ_y **/(1/km)**	ϕ_d **/(1/km)**	ϕ_u **/(1/km)**
Along span	0.61	0.68	1.16	2.79
Along transverse	0.32	0.37	0.62	1.45

4 Result Analysis and Discussion

Seismic vulnerability refers to the probability of structural response exceeding failure state under different intensity earthquakes, which can be expressed by the following formula:

$$P_f = P[DI \geq C|IM] = P[DI/C \geq 1|IM] \tag{1}$$

where

P_f——Failure probability of structure or member;

IM——Ground motion parameters, including peak acceleration (PGA), peak velocity (PGV), peak displacement (PGD), spectral acceleration (SA) of basic period of structure, and so on;

C——Seismic capacity of structure;

DI——Damage index.

Assuming that *DI* follows the lognormal distribution and satisfies the power exponential regression relationship with *IM*, the mean value of *DI* can be expressed as Eq. (2):

$$\hat{DI} = \alpha (IM)^{\beta_1} \tag{2}$$

where

α and β_1——Regression coefficient.

If logarithms are taken on both sides of Equation (2), the following formula can be obtained:

$$\ln(\hat{DI}) = \ln\alpha + \beta_1 \ln(IM) = \beta_0 + \beta_1 \ln(IM) \tag{3}$$

Then, the logarithmic mean value of *DI* can be expressed as Eq. (4):

$$\lambda_d = \ln(\hat{DI}) \tag{4}$$

Logarithmic standard deviation of *DI* can be expressed as Eq. (5)

$$\beta_d = \sqrt{\frac{1}{N-2}\sum_{i=1}^{N}\left[\ln(DI) - \ln(\hat{DI})\right]} \tag{5}$$

The failure probability can be expressed as Eq. (6)

$$P_f = P\left[\ln(C) - \ln(DI) \leq 0\right] = P(Z \leq 0) \tag{6}$$

Assuming that *C* follows the lognormal distribution, then ln(*C*) and ln(*DI*) are independent and obey normal distribution. *Z* also follows normal distribution. The logarithmic mean of *C* is λ_c, and the logarithmic standard deviation is β_c Therefore, the average value of *Z* can be expressed as Eq. (7)

$$\lambda_Z = \lambda_c - \lambda_d \tag{7}$$

Standard deviation of *Z* can be expressed as Eq. (8):

$$\beta_Z = \sqrt{\beta_c^2 + \beta_d^2} \tag{8}$$

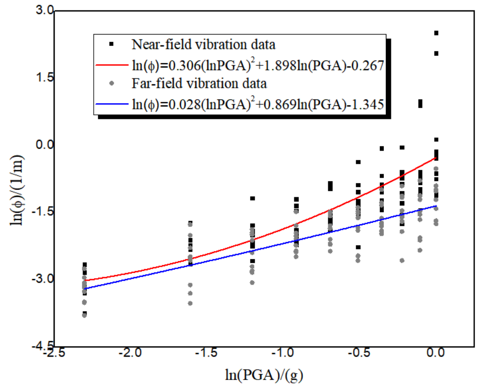
Equation (6) can be expressed as Eq. (9):

$$P_f = P(Z \leq 0) = \int_{-\infty}^{0} f(Z)dZ = \int_{-\infty}^{0} \frac{1}{\beta_Z\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{Z-\lambda_Z}{\beta_Z}\right)^2\right]dZ \tag{9}$$

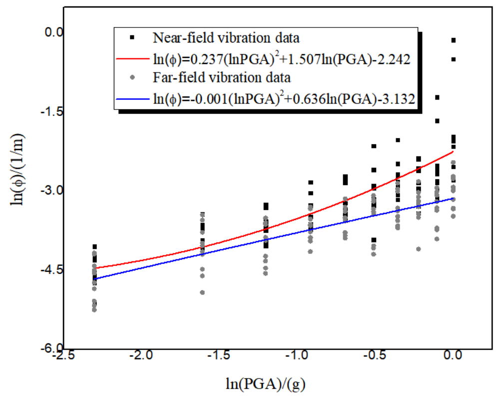
$$P_f = \Phi\left(-\frac{\lambda_Z}{\beta_Z}\right) = \Phi\left(\frac{\lambda_d - \lambda_c}{\sqrt{\beta_c^2 + \beta_d^2}}\right) \tag{10}$$

where $\Phi(x)$ is the probability function of standard normal distribution.

As the seismic demand of the main piers of this bridge is relatively similar, this study only shows the calculation results of No. 8 pier. The logarithmic IDA curve of the pier bottom section of No. 8 pier is shown in Fig. 6.



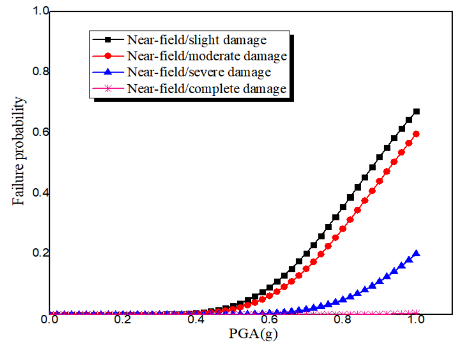
(a)



(b)

Fig. 6. Logarithmic IDA curves of bridge members. (a) Along span. (b) Along transverse

The logarithmic IDA curves of bridge members under far-field/near-field ground motion are shown in Fig. 6, where PGA is adopted as the seismic strength parameter, and the combined standard deviation is taken as 0.5. Results show that the seismic demand of bridge piers under far-field seismic action is smaller than that under near-field seismic action, and the seismic demand is discrete. In the seismic design of bridges, the influence of near-field seismic action shall be considered



(a)

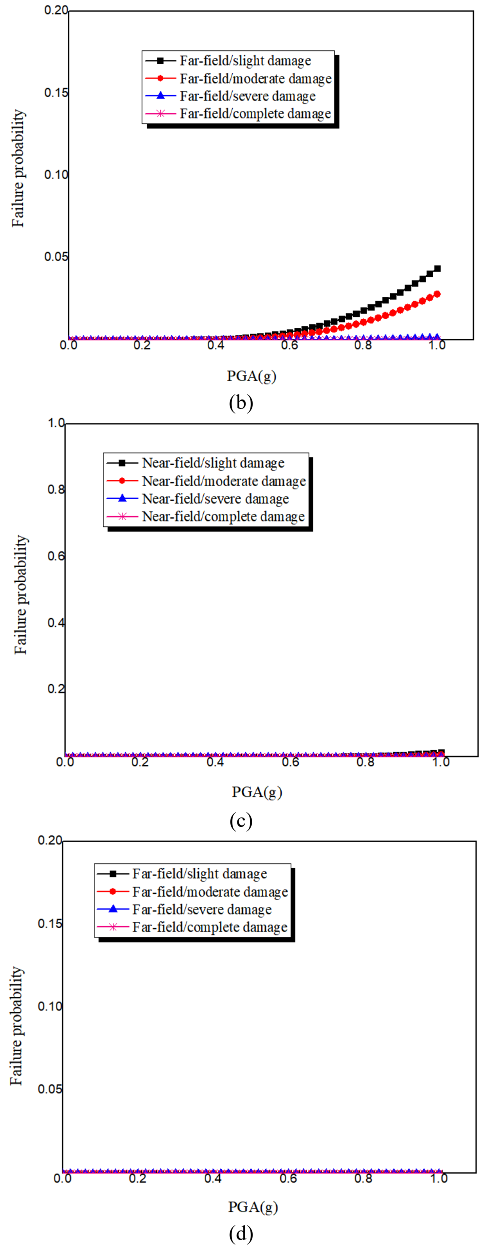


Fig. 7. Fragility curves of bridge members. (a) vulnerability curves along span direction under near-field ground motion. (b) vulnerability curves along span direction under far-field ground motion. (c) vulnerability curves along transverse direction under near-field ground motion. (d) vulnerability curves along transverse direction under far-field ground motion.

The vulnerability curves of bridge pier are shown in Fig. 7. The results show that the vulnerability curve of slight damage and medium damage is relatively steep under the action of earthquakes. Under near-field earthquake action, when PGA = 0.5 g, the failure probability of slight damage, medium damage, and severe damage along the span direction of the pier are 0.02926, 0.01823, and 0.00075, respectively. In addition, the failure probability of complete damage is close to 0. When PGA = 1.0 g, the failure probabilities of slight, moderate, severe, and complete damage along the span direction of the pier are 0.672, 0.597, 0.20109, and 0.00484, respectively. Moreover, complete damage rarely occurs. Under near-field earthquake, bridges are prone to slight and moderate damage. The bridges are not seriously and completely damaged easily, and its probability of exceedance is small.

As can be seen from Fig. 7(a) and Fig. 7(b), the vulnerability curves of slight and medium damage are relatively steep under earthquake action. The results show that under near-field earthquake action, when PGA = 0.5 g, the failure probability of slight damage, medium damage, and severe damage along the span direction of the pier are 0.02926, 0.01823, and 0.00075, respectively. Furthermore, the failure probability of complete damage is close to 0. When PGA = 1.0 g, the failure probabilities of slight, moderate, severe, and complete damage along the span direction of the pier are 0.672, 0.597, 0.20109, and 0.00484, respectively. In addition, complete damage rarely occurs. This result indicates that the bridge is easily damaged slightly and moderately under near-field earthquakes. The bridge is not easily damaged seriously and completely, and its probability of exceedance is small. Under the action of far-field earthquakes, when PGA = 0.5 g, the failure probability of slight damage and moderate damage along the span direction of the pier are 0.00194 and 0.00101, respectively, and the failure probability of severe damage and complete damage is close to 0. When PGA = 1.0 g, the failure probability of slight, moderate, and severe damage along the span direction of the pier are 0.04358, 0.02802, and 0.00138 respectively. Moreover, complete damage almost does not occur. This outcome indicates that the bridge has almost no damage under the action of far-field earthquakes.

As can be seen from Fig. 7(c) and Fig. 7(d), the failure probability of the pier along the transverse direction under each damage state is very small, almost 0. When PGA = 1.0 g, the failure probability of slight damage is 0.014, the failure probability of medium damage is 0.006, and the failure probability of severe damage and complete damage are close to 0. These outcomes indicate that the pier is not easily damaged along the transverse direction.

Briefly, with the increase of earthquake strength, the failure probability of the pier increases gradually, and the curve of medium damage and complete damage is far away, thus indicating that the pier has relatively good ductility after entering the medium damage stage.

5. Conclusions

To investigate long span prestressed concrete continuous rigid frame bridge, the seismic vulnerability analysis of No. 8 and No. 9 piers of Longxi Jialing River Bridge was carried out on the basis of the incremental dynamic analysis method. The following conclusions could be drawn:

(1) The seismic demand of the main bridge of the Longxi Jialing River Bridge under the action of far-field vibration is relatively small, and the demand of near-field vibration is relatively discrete. Therefore, the influence of near-field earthquakes should be considered in the seismic design of bridges.

(2) The vulnerability curves are steep for slight and moderate damage of piers under earthquake action, and the vulnerability curves tend to be flat for severe and complete damage. This observation shows that the bridge is prone to slight and moderate damage under near-field earthquake action, while the bridge structure is not prone to serious and complete damage.

(3) With the increase of intensity of an earthquake, the failure probability of the pier increases gradually, and the distance between the curves of moderate damage and complete damage is far away. This observation indicates that the pier has relatively good ductility after entering moderate damage.

The adopted method in this study can improve the efficiency of the seismic vulnerability analysis of bridges, reduce the calculation work, and help to obtain real and reliable analysis results. However, the area where the bridge is located is short of measured near-fault seismic records. Furthermore, although the lack of near-fault seismic samples needed for vulnerability analysis can only be compensated by artificial seismic waves, these artificial waves sometimes cannot reflect the actual situation. In the future, the near-fault seismic vulnerability curves of the bridge can be established through the measured near-fault seismic samples in the bridge site area. Doing so can increase the accuracy of the evaluation of the seismic performance of the bridge. This study is expected to provide a theoretical reference for similar practical projects in the future.

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