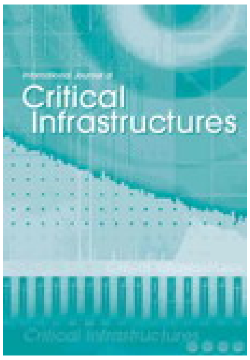

International Journal of Critical Infrastructures

ISSN online: 1741-8038 - ISSN print: 1475-3219
https://www.inderscience.com/ijcis

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DOI: 10.1504/IJCIS.2024.10056761

Article History:

Received:	07 April 2022
Last revised:	02 May 2022
Accepted:	04 May 2022
Published online:	26 January 2024

Seismic economic loss assessment of highway girder bridges using Wenchuan earthquake as a sample

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Abstract: To study the seismic economic loss of highway girder bridges, taking 596 highway girder bridges in the Wenchuan earthquake as examples, the seismic damage phenomenon of highway girder bridges was statistically analysed, the vulnerability of highway girder bridges was studied and analysed, and the vulnerability matrix and vulnerability curve of highway girder bridges were obtained. Two seismic economic loss calculation models for highway girder bridges are proposed – the probability-based seismic economic loss assessment model and the loss rate-based seismic economic loss assessment model. Then, the seismic loss of highway girder bridges is predicted. The seismic loss prediction results cannot only provide a reference range for the bridge seismic design level, but the evaluation results can also be used as a reference for the seismic capacity of highway girder bridges and as the basis for measures for earthquake prevention and disaster reduction.

Keywords: historical earthquake damage data; highway girder bridge; seismic vulnerability matrix; seismic vulnerability curve; seismic economic loss assessment.

Reference to this paper should be made as follows: Fan, Y., Zhang, H. and Li, Z. (2024) 'Seismic economic loss assessment of highway girder bridges using Wenchuan earthquake as a sample', *Int. J. Critical Infrastructures*, Vol. 20, No. 1, pp.33–55.

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1 Introduction

In recent years, high-intensity earthquakes have occurred frequently at home and abroad, and earthquake disasters are instantaneous, and the direct natural disasters and secondary disasters caused will cause huge economic losses to human production and life. As an important component of lifeline engineering, the traffic system after the earthquake has the greatest impact on the disaster relief work. As the throat of the traffic system, bridges play a key role in emergency rescue. Therefore, it is of great practical significance to predict the seismic economic losses of bridge and use the analysis results as a reference for seismic economic losses of bridge and making the measures for earthquake prevention and disaster reduction.

At present, there are many studies on seismic economic losses. The Federal Emergency Management Agency (FEMA) had developed an earthquake damage assessment software-HAZUS-MH (Hazards US multi-hazard) on the platform of GIS basic software (FEMA, 2003). The HAZUS seismic module could calculate seismic hazards, assess the likelihood of various damage states, and estimate the resulting direct and indirect damage. Chang and Shinozuka (2004) used the Monte Carlo mathematical and statistical simulation method and combined the computer programming language with GIS to obtain the resilience of the disaster area. Whittaker et al. (2020) established a conceptual model of disaster management through the analysis of the earthquake in Japan to achieve the purpose of disaster prevention. Emrich (2005) used the hazards-of-place model to quantitatively evaluate the natural disaster vulnerability of major cities in the US through the weighted average method. Fan and Li (2022) took urban disaster-bearing bodies as the main research body, based on the pressure-state-response model, and used the RAGA-PPE method to evaluate the seismic vulnerability of major cities in Gansu Province. Li et al. (2020) solved the problem of bridge damping and isolation by establishing a finite element model of continuous beams of large-span railways in high-intensity areas and analysing the nonlinear seismic response of them. Shi et al. (2021) took a continuous rigid frame bridge with long-span and high piers as the background, adopted incremental dynamic analysis method, and obtained the seismic vulnerability curves of the pier bottom, pier top and main beam root of the main pier by theoretical vulnerability method. Martinez et al. (2017) performed incremental dynamic analysis through a two-dimensional bridge model, and obtained the vulnerability curve of a typical non-inclined highway bridge in Chile to study the seismic performance of the bridge and use it for seismic risk assessment. Feng et al. (2020, 2019) used the finite element analysis software to establish a high-speed railway concrete-filled steel tube tied arch bridge model on the performance-based seismic risk assessment theory, and used the IDA method to analyse the seismic vulnerability, combining the seismic risk and loss ratio, the annual expected loss is selected as the seismic economic risk index to quantitatively analyse the seismic economic risk of bridges. Afterwards, a seismic economic risk assessment method of bridge system combining fuzzy theory and probabilistic finite element was established to conduct a comprehensive assessment of the seismic direct economy of high-speed railway continuous girder bridges. Lu (2018) proposed and verified a direct earthquake economic loss assessment method based on seismic damage loss decomposition for concrete bridges. Through vulnerability analysis and seismic demand analysis, the direct economic loss analysis under the action of main aftershocks was calculated. So far, most of the bridge seismic economic research at home and abroad mainly analyses the seismic loss of the main stress-bearing components of the bridge by establishing a finite element model. This method is mainly used to analyse the vulnerability of a single bridge, the calculation process is complex and time-consuming, which is not suitable for rapid post-earthquake assessment. Using the existing earthquake damage data and related literature research, quantitatively describe the possible earthquake economic risks of bridge structures in a probabilistic sense, which can achieve the effect of rapid assessment of post-earthquake economic losses. Therefore, based on the earthquake damage dates of 596 highway girder bridges collected in the Wenchuan earthquake, the paper evaluates the seismic economic loss of highway girder bridges through the probability-based seismic economic loss calculation model and the loss rate-based seismic economic loss calculation model.

2 Selection of historical earthquake damage data

The Wenchuan earthquake reached a magnitude of 8.0. Not only was it strong in intensity and had a wide range of effects, but also aftershocks lasted for a long time and had huge destructive power. Since the 1990s, the Wenchuan earthquake was the most destructive and the largest in scope. Its survey data was relatively comprehensive and complete, which is suitable for statistical analysis. Therefore, this paper takes 596 damaged bridges collected in the Wenchuan earthquake as samples, according to classification of earthquake damage levels for lifeline engineering (GB/T 24336, 2009) and reference (Lin et al., 2018), the damage status of bridges is divided into five levels: basically intact, minor damage, moderate damage, major damage and destruction, to analysis the vulnerability of highway girder bridges. Due to space limitations, only some bridge earthquake damage data are listed as shown in Table 1.

Table 1 Statistical table of earthquake damage of highway girder bridges in Wenchuan earthquake

No.	*Bridge name*	*Intensity*	*Damage state*	*PGA /g*
1	Guanyin Bridge	VI	Minor damage	0.074
2	Banqiao River Bridge	VI	Minor damage	0.073
3	Fushanba Bridge	VI	Minor damage	0.072
		…		
596	Shiziping Bridge	X	Major damage	0.698

Table 2 The number of bridges with a certain level of damage under different intensity (seats)

Intensity	*Damage state*					
	Basically intact	*Minor damage*	*Moderate damage*	*Major damage*	*Destruction*	*Total*
VI	91	34	16	0	0	141
VII	59	92	19	1	0	171
VIII	40	58	18	2	1	119
IX	15	12	39	17	5	88
X	2	5	38	22	9	77
Total	207	201	130	42	16	596

In Table 1, PGA is the ground motion acceleration peak value, which is a kind of ground motion parameter and represents the ground motion intensity level experienced by the bridge.

Statistical analysis is made on the bridges damaged by the Wenchuan earthquake, and the specific damage situation of bridges under different intensities is shown in Table 2.

3 Seismic economic loss assessment model for highway girder bridges

3.1 Loss rate-based seismic economic loss assessment model

3.1.1 Bridge vulnerability analysis

Seismic fragility refers to the possibility that the structure will be damaged in different degrees under the earthquake action of different intensity, or the probability that the structure will reach or exceed a certain limit state (performance level) (Li et al., 2018). It quantitatively describes the seismic performance of engineering structures from a probabilistic point of view, and macroscopically reflects the relationship between the intensity of ground motion and the degree of structural damage. It provides a certain reference for studying and determining the weak links of the structure, seismic reinforcement, and risk assessment (Muntasir and Shahria, 2015; Jia et al., 2019).

According to Table 2, the empirical vulnerability matrix of highway girder bridges is obtained through statistical analysis, and the calculation results are shown in Table 3.

Table 3 Vulnerability matrix of highway girder bridges based on Wenchuan earthquake samples (%)

Intensity	*Damage state*				
	Basically intact	*Minor damage*	*Moderate damage*	*Major damage*	*Destruction*
VI	64.5	24.1	11.3	0	0
VII	34.5	53.8	11.1	0.6	0
VIII	33.6	48.7	15.1	1.7	0.8
IX	17.0	13.6	44.3	19.3	5.7
X	2.6	6.5	49.4	28.6	11.7

In general, the standard vulnerability matrix has a probability peak in each of the five intensity zones, and the probability values on both sides of the peak decrease in turn. With the change of seismic intensity, the peak is generally located in the basically intact state in the low-intensity zone, and gradually turns to a higher damage state in the high-intensity zone. And as the seismic intensity increases, the peak position moves to a higher damage level. It can be seen from Table 3 that the bridge vulnerability matrix has two probability peaks in the IX-degree region, which is inconsistent with previous theoretical experience and research results. In addition, the vulnerability matrix based on the survey data usually needs to be improved according to earthquake damage experience or mathematical statistics, so that it can be transformed into a standard vulnerability matrix for earthquake damage prediction and loss assessment in the future. Referring to the relevant literature (Lin et al., 2018), the beta empirical distribution function is selected to further improve the pre-established vulnerability matrix. The damage state of girder bridges under each seismic intensity in the vulnerability matrix is divided into five damage grades – basically intact, minor damage, moderate damage, major damage and destruction, correspondingly divided into five subsections. Using PGA as a continuous independent variable, the histogram of PGA is made by combining with the relevant data in the preliminary vulnerability matrix, so that the continuous random variable PGA obeys the beta empirical distribution function. Then the probability density curve is used to fit the histogram contour, so that the mathematical statistics distribution of bridges in each damage state under each intensity can be obtained.

The beta distribution, also referred to as the distribution, refers to a set of continuous probability distributions defined in the (0, 1) interval. Its probability density function is:

$$f(x) = \begin{cases} \dfrac{1}{B(\alpha, \beta)} x^{\alpha-1}(1-x)^{\beta-1}, & 0 < x < 1 \\ 0, & \text{other} \end{cases} \tag{1}$$

In the formula (1), $B(\alpha, \beta) = \int_0^1 x^{\alpha-1}(1-x)^{\beta-1}dx$, α, β are all constants greater than 0, and the value of the variable should be in the same range as the earthquake damage index, between 0 and 1. Its distribution function is as follows:

$$F(x) = \begin{cases} 0, & x \le 0 \\ \dfrac{1}{B(\alpha, \beta)} \displaystyle\int_0^x u^{\alpha-1}(1-u)^{\beta-1}du, & 0 < x < 1 \\ 1, & x \ge 1 \end{cases} \tag{2}$$

The corresponding expectation and variance are:

$$E(x) = \frac{\alpha}{\alpha + \beta} \tag{3}$$

$$V = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \tag{4}$$

Table 4 Unknown parameter values of probability density functions of Beta empirical distribution in different seismic intensities

Distribution function	*Parameter*	*Seismic intensity*				
		VI	*VII*	*VIII*	*IX*	*X*
Beta distribution	α	5.7456	7.8284	4.5600	5.7552	8.1448
	β	56.0337	31.0801	11.4002	5.9963	3.8815

Taking the PGA under each seismic intensity as the independent variable *x*, the expectation and standard deviation are obtained through parameter estimation, and the formula (3) and formula (4) can be used to calculate the unknown parameters α and β of the corresponding beta empirical distribution function expression in a certain seismic intensity, so as to determine the probability density function expression. The calculated values of unknown parameters in the probability density function of the Beta empirical distribution function under different seismic intensities are shown in Table 4.

A histogram was fitted to it using MATLAB, as shown in Figure 1–Figure 5.

Figure 1 Fitting histogram of beta distribution in degrees VI (see online version for colours)

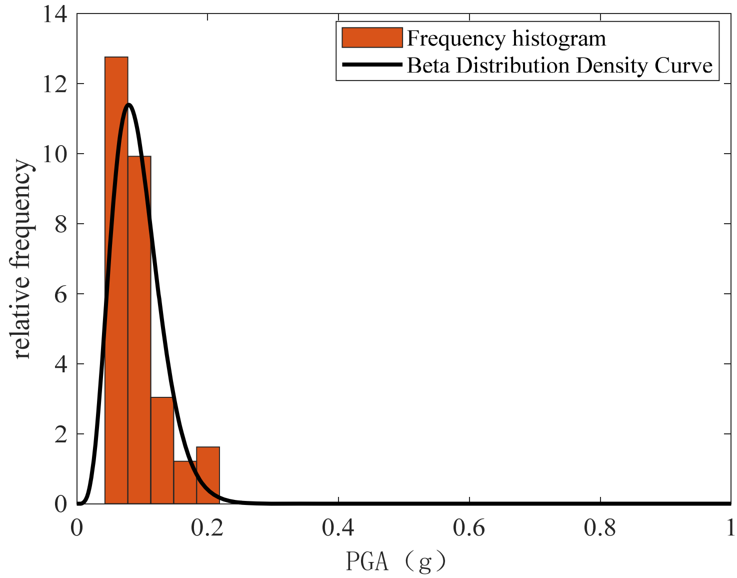


Figure 2 Fitting histogram of beta distribution in degrees VII (see online version for colours)

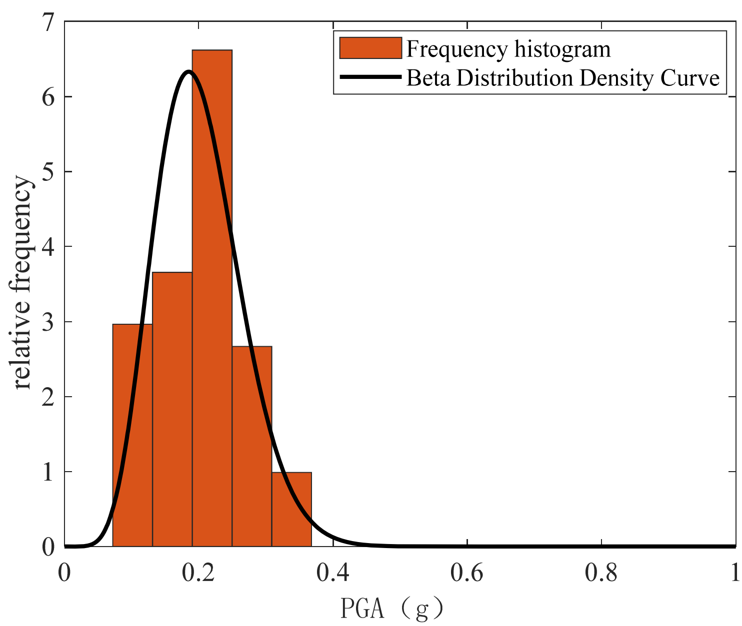


Figure 3 Fitting histogram of beta distribution in degrees VIII (see online version for colours)

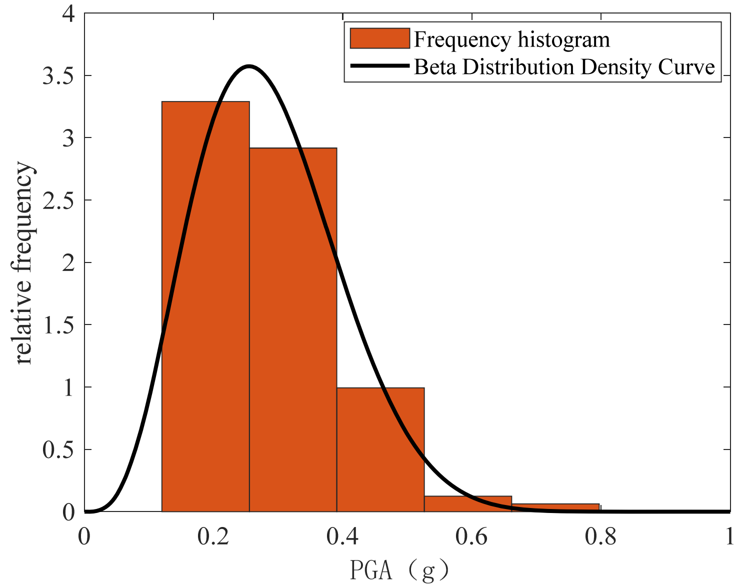


Figure 4 Fitting histogram of beta distribution in degree IX (see online version for colours)

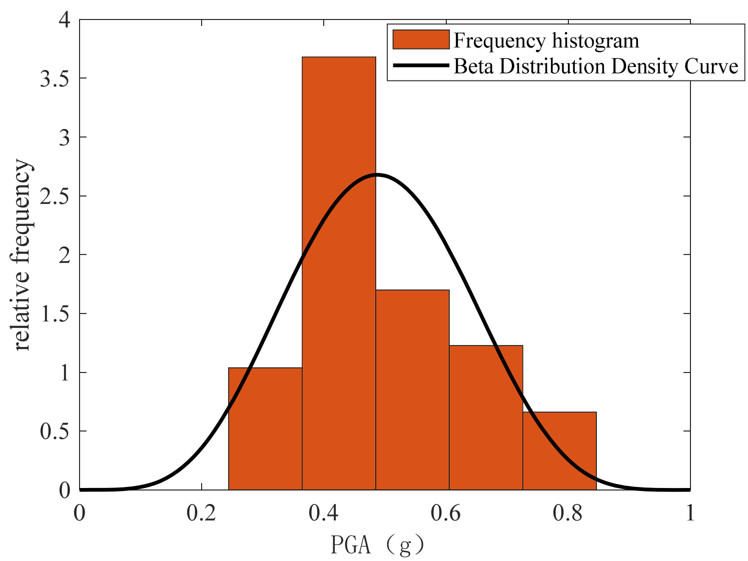


Figure 5 Fitting histogram of beta distribution in degree X (see online version for colours)

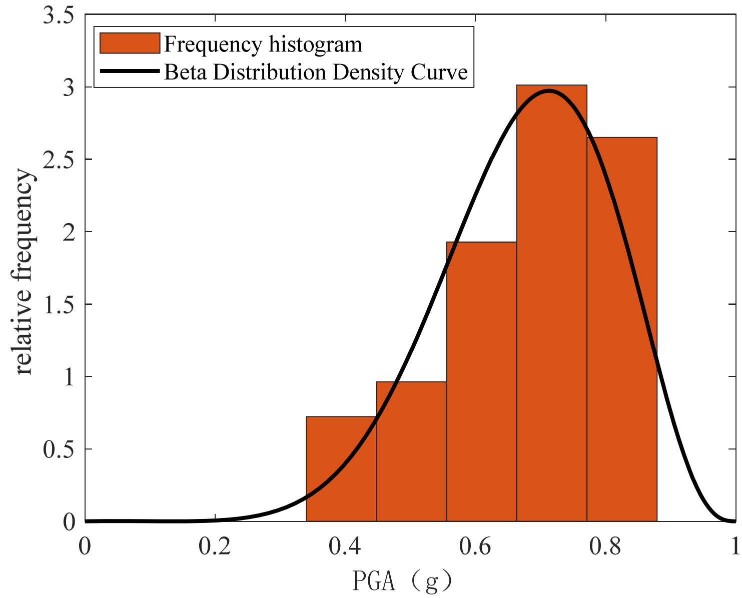


Table 5 Vulnerability matrix of improved highway girder bridges (%)

Intensity	*Damage state*				
	Basically intact	*Minor damage*	*Moderate damage*	*Major damage*	*Destruction*
VI	68.3	30.36	1.07	0	0
VII	30.4	61.5	8.10	0	0
VIII	31.3	46.9	17.2	2.8	1.8
IX	9.70	36.6	38.2	12.8	2.7
X	2.8	6.2	52.5	25.3	13.2

3.1.2 The basic concept of loss rate

Earthquake loss can be expressed in terms of currency loss ratio and building damage ratio. Currency loss ratio is abbreviated as loss rate. Its concept firstly appeared in the vulnerability classification list. Initially, it was mostly used in housing construction, and later it was widely used in bridge seismic economic loss assessment. The loss rate is mainly related to the failure probability of the bridge and the median loss rate. The median loss rate can refer to the research results of other scholars. Therefore, the value of the loss rate can be calculated by obtaining the failure probability of the bridge according to the vulnerability matrix, and then the economic loss of the bridge structure is obtained.

Structural economic losses can be expressed in terms of loss rates. It is easiest to express the direct economic losses of earthquakes by currency loss ratios. The loss rate is defined as follows:

$$Damage\ factor\ (DF) = \frac{Economic\ losses\ (L)}{\mathrm{Re}construction\ cost\ (RC)} \tag{5}$$

Among them, the reconstruction cost is the total cost of building a new structure that is functionally equivalent to the original structure.

Under the same seismic intensity, the average loss rate of the same type of structure is defined as follows:

$$Mean\ damage\ factor\ (MDF) = \frac{1}{n}\sum_{i=1}^{n}\frac{(L)_i}{(RC)_i} \tag{6}$$

In formula (6): n is the number of samples of the same type of structure. Damage rates and average loss rates can be calculated based on statistical sample data within the designated study area.

3.1.3 Earthquake loss analysis

The degree of structural damage can be expressed by the probability of damage, which can be obtained from the previous vulnerability matrix. Then the average loss rate of a certain type of structure in a given seismic intensity is shown in formula (7):

$$MDF_I = \sum_{DS=1}^{5}\left(P_{DSI}\right)\cdot\left(CDF_{DS}\right) \tag{7}$$

where MDF_I is the average loss rate of similar structures; PDS_I is the damage state; is the occurrence probability of a certain damage state in a given intensity; CDF_{DS} is the median loss rate in a certain damage state.

Table 6 gives the corresponding loss rate variation ranges in the five types of damage states (GB/T 24336, 2009).

Table 6 Five types of damage states and corresponding loss rate variation range (%)

Category	*Damage state*				
	Basically intact	*Minor damage*	*Moderate damage*	*Major damage*	*Destruction*
Range of loss rate	0	1–10	10–40	40–80	80–100
Median loss rate	0	5	25	60	90

The seismic peak acceleration corresponding to each seismic intensity is relatively discrete, it is not one-to-one correspondence. Therefore, the conversion formula of seismic peak acceleration PGA and seismic intensity I proposed in reference (Xia and Liu, 2018) is used to convert the intensity and peak acceleration:

$$PGA = 10^{[I\cdot \lg(2)-0.01]} \tag{8}$$

In formula (8), the unit of seismic peak acceleration PGA is cm/s^2.

After converting the corresponding seismic intensities according to the PGA of different bridges, combined with the vulnerability matrix in Table 5, the linear interpolation method is used to calculate the probability of the damage in basically intact, minor damaged, moderate damaged, major damaged, and destruction. The probability is represented by P_1, P_2, P_3, P_4 and P_5 respectively. Combining formula (7), the relationship between ground motion intensity and loss rate can be obtained. The calculated formula is shown in formula (9):

$$MDF_I = 0.00 \times P_1 + 0.05 \times P_2 + 0.25 \times P_3 + 0.60 \times P_4 + 0.90 \times P_5 \tag{9}$$

According to formula (5), get:

$$L = MDF \times RC \tag{10}$$

In formula (10), L is the seismic economic loss of the bridge, and RC is the bridge reconstruction cost, which can be expressed by formula (11):

$$RC = W_b \times M_b \times P_b \tag{11}$$

In formula (11), W_b is the bridge cost per unit area, which can be selected by referring to (Chen et al., 2013). M_b is the width of the bridge, and P_b is the total length of the bridge.

3.2 Probability-based seismic economic loss assessment model

3.2.1 Probabilistic seismic hazard analysis

Seismic hazard refers to the maximum degree of earthquake damage that the area or site where the structure is located may encounter within the specified service life (Chen et al., 2013). Seismic hazard analysis methods include deterministic and probabilistic method. The deterministic method can predict the magnitude and focal depth of future earthquakes, but it has limitations because it ignores the randomness of earthquakes; while the probabilistic method comprehensively considers factors such as the magnitude and return period of possible earthquakes. In this paper, the probabilistic method is used to analyse the seismic hazard with the seismic intensity as the evaluation index.

The probabilistic seismic hazard analysis is mainly based on the Poisson model, and the extreme value type III distribution model is used (Xu et al., 2014). Its distribution function is:

$$F_{III}(i) = \exp\left[-\left(\frac{\omega - i}{\omega - \varepsilon}\right)^k\right] \tag{12}$$

In formula (12): ω is the upper limit of the seismic intensity, which is taken as 12; ε is the mode of the seismic intensity, $\varepsilon = I_0$, I_0 is the fortification intensity; k is the shape parameter. The shape parameter k is determined by using the fortification intensity I_0 with a probability of 50-year transcendence of 10%, which can meet the needs of engineering applications. The value of the shape parameter k in different intensity (Zhang and Weng, 2013) is shown in Table 7.

Table 7 Values of shape parameter k

Basic intensity	*VI*	*VII*	*VIII*	*IX*
k	9.7932	8.3339	6.8713	5.4028

Referring to the literature (Feng and Yuan, 2010), the probability distribution function of the seismic intensity of the site within the design service life t years can be obtained as:

$$F_t(i) = \exp\left[-\frac{t}{50}\left(\frac{\omega - i}{\omega - \varepsilon} \right)^k \right] \tag{13}$$

Figure 6 The 100-year transcendence probability of each intensity in degree VI (see online version for colours)

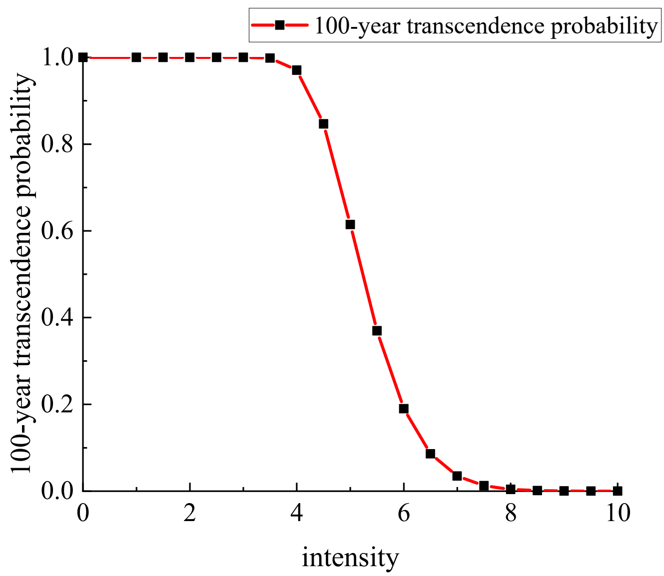


Figure 7 The 100-year transcendence probability of each intensity in degree VII

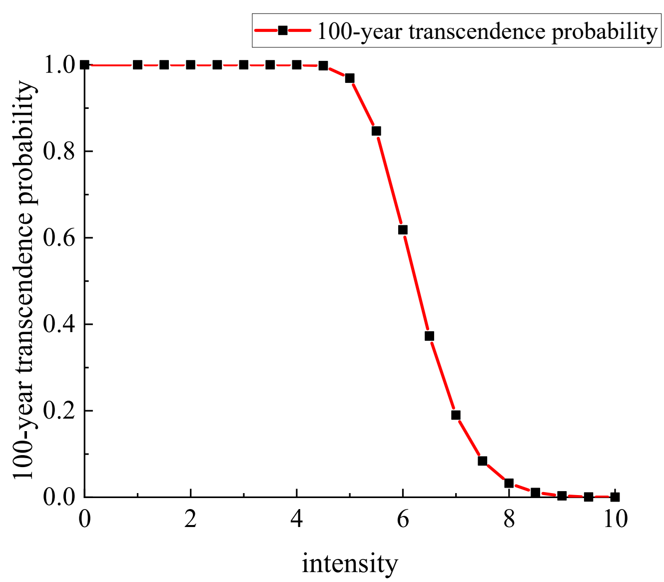


Figure 8 The 100-year transcendence probability of each intensity in degree VIII (see online version for colours)

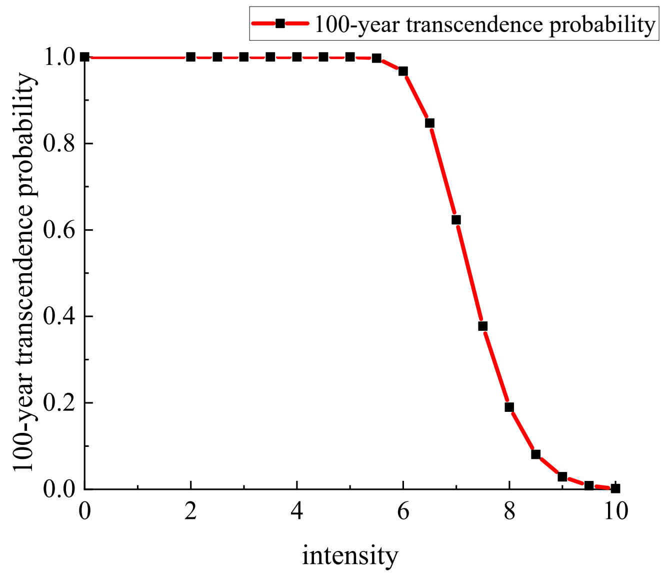
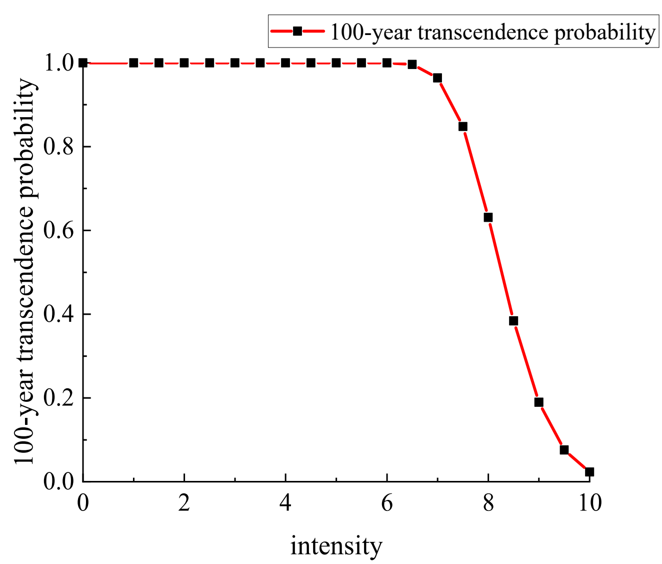


Figure 9 The 100-year transcendence probability of each intensity in degree IX (see online version for colours)



Assuming that the design service life of the bridge is 100 years, the transcendence probability of the corresponding seismic intensity within the design service life in each fortification intensity can be calculated from the formula (13). The specific results are shown in Figure 6–Figure 9.

3.2.2 Seismic vulnerability analysis

The two-parameter log-normal distribution function is very convenient in mathematical calculation; it estimates the actual strength and design strength of the structure by summarising the safety influencing factors. The sum of these safety impact factors can be decomposed into a product of a series of safety impact factors, each of which is associated with a specific source of uncertainty. Assuming that each safety impact factor obeys a log-normal distribution, as the product of these safety impact factors, the total safety impact factor also obeys a log-normal distribution (Li et al., 2021). Therefore, this paper adopts the two-parameter log-normal distribution function as the vulnerability function to construct the empirical vulnerability curve of the bridge.

The expression of the vulnerability function is shown in formula (14):

$$F(a) = \Phi\left[\frac{\ln(a/c)}{\zeta}\right] \tag{14}$$

In formula (14), $F(a)$ is the vulnerability function in a certain damage state; a is the PGA value; $\Phi(\cdot)$ is the standard normal distribution function; c and ζ are the median and logarithmic standard deviation of the vulnerability function, respectively.

It can be seen from formula (14) that if the parameters c and ζ can be estimated, then the vulnerability curve can be generated. At present, the most commonly used method is to use the maximum likelihood estimation method to estimate and solve the two parameters c and ζ (Zhuang, 2021).

To make the vulnerability curves in different damage states disjoint, the simultaneous estimation method in the maximum likelihood method is used to respectively estimate the two parameters c and ζ of the function. Set the logarithmic standard deviation as a constant, and estimate the median value of each vulnerability curve synchronously. Assume that events E_1, E_2, E_3, E_4, E_5 represent five damage status: basically intact, minor damaged, moderate damaged, major damaged, and destruction, where 'basically intact' as the initial state is satisfied for all bridge samples. $P_{ik} = P(a_i, E_k)$ is defined as the probability of occurrence of damage level E_k for randomly selected bridge samples when the ground motion intensity PGA = a_i The corresponding vulnerability function at this time is:

$$F_j\left(a_i, c_j, \zeta_j\right) = \Phi\left[\frac{\ln\left(a_i / c_j\right)}{\zeta_j}\right] \tag{15}$$

where c_j and ζ_j are the median and log standard deviation of the corresponding vulnerability functions in the states of minor damage, moderate damage, major damage and destruction (definition j = 1, 2, 3, 4). According to the assumption that the same constant ζ is taken for all vulnerability functions, it can be obtained:

$$P_{i1} = P\left(a_i, E_1\right) = 1 - F_1\left(a_i, c_1, \zeta\right) \tag{16}$$

$$P_{i2} = P\left(a_i, E_2\right) = F_1\left(a_i, c_1, \zeta\right) - F_2\left(a_i, c_2, \zeta\right) \tag{17}$$

$$P_{i3} = P\left(a_i, E_3\right) = F_2\left(a_i, c_2, \zeta\right) - F_3\left(a_i, c_3, \zeta\right) \tag{18}$$

$$P_{i4} = P\left(a_i, E_4\right) = F_3\left(a_i, c_3, \zeta\right) - F_4\left(a_i, c_4, \zeta\right) \tag{19}$$

$$P_{i5} = P\left(a_i, E_5\right) = F_4\left(a_i, c_4, \zeta\right) \tag{20}$$

The expression of the likelihood function is:

$$L\left(c_1, c_2, c_3, c_4, \zeta\right) = \prod_{i=1}^{n} \prod_{k=1}^{5} P_k\left(a_i, E_k\right)^{x_{ik}} \tag{21}$$

When PGA = a_i at the bridge site of the i^{th} bridge sample, if the bridge earthquake damage reaches the damage level E_k, then $x_{ik} = 1$, otherwise $x_{ik} = 0$.

Based on the optimisation algorithm, the extreme value of the above likelihood function is obtained, so that ln L (or L) is maximised, and the corresponding c_{0j} and ζ_0 values at this time are used as the estimated values of c_j and ζ in the vulnerability function, namely:

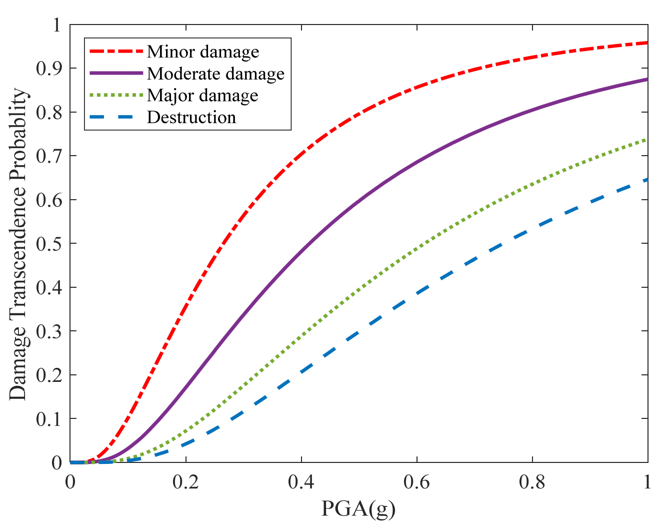
$$\frac{\partial L\left(c_1, c_2, c_3, c_4, \zeta\right)}{\partial c_j} = \frac{\partial L\left(c_1, c_2, c_3, c_4, \zeta\right)}{\partial \zeta} = 0, \quad \left(j = 1, 2, 3, 4\right) \tag{22}$$

According to formulas (15) to (22), PGA in each damage state is taken as the independent variable, and MATLAB software is used to carry out synchronous maximum likelihood estimation for c and ζ The calculation results are shown in Table 8.

Table 8 Parameter estimation of vulnerability function

Bridge type	*Unknown parameters*	*Damage state*			
		Minor damage	*Moderate damage*	*Major damage*	*Destruction*
Highway girder bridge	c/g	0.2508	0.4022	0.5963	0.7410
	ζ	0.7872	0.7872	0.7872	0.7872

Figure 10 Vulnerability curve of highway girder bridge (see online version for colours)



Taking PGA as the independent variable into the fragility function formula (15), the fragility curve of the highway girder bridge is obtained by fitting, as shown in Figure 10.

3.2.3 Seismic loss analysis

The probabilistic damage is determined by the seismic hazard in a certain area and the structural vulnerability in this area. The expression for calculating the damage probability of bridge structures in different damage states is as follows:

$$P[D_j] = \sum_i P[D_j | I_i] \times P[I_i] \tag{23}$$

In formula (23): $P[D_j \mid I_i]$ is the vulnerability of the bridge, which can be obtained from the formula (24); $P[I_i]$ is the seismic hazard of the area.

Under the same PGA, the probability calculation formula of each bridge damage is as follows:

$$\left(D = D_j \middle| PGA = pga\right) = \begin{cases} 1 - P\left(D \geq D_j \middle| PGA = pga\right) & j = 1 \\ P\left(D \geq D_j \middle| PGA = pga\right) - P\left(D \geq D_{j+1} \middle| PGA = pga\right) & 1 < j < m \\ P\left(D \geq D_j \middle| PGA = pga\right) & j = m \end{cases} \tag{24}$$

In formula (24): $P(D = D_j \mid PGA = pga)$ is the probability function of the D_j-level damage state of the component under the action of PGA, which can be obtained from the vulnerability curve; D_j is the damage level of the bridge; m is the number of five damage states corresponding to the component.

Therefore, the direct economic loss of the structure damage when the bridge structure is subjected to earthquakes of various possible intensity within the design service life can be expressed by formula (25):

$$L\left(I_d \middle| I_i\right) = \sum_{j=1}^{5} P\left(D_j \middle| I_d, I_i\right) \cdot l\left(D_j\right) \cdot RC \tag{25}$$

Among them: $L(I_d \mid I_i)$ refers to the direct economic loss of the structure with the basic intensity during the service period when the seismic intensity is I_i; $P(D_j \mid I_d, I_i)$ refers to the probability of D_j-level damage of the bridge when the fortification intensity is I_d, and the seismic intensity is I_i ; $l(D_j)$ refers to the direct economic loss ratio corresponding to each damage state of the studied structure, which is valued according to literature (Yang, 2019); D_j refers to the seismic damage level of the structure, which is divided into five levels in this paper; RC refers to the cost of highway girder bridges.

3.3 Validation of model results

To verify the rationality of the two-assessment model, six highway girder bridges are selected, including continuous girder bridges, 20 m/span simply-supported girder bridges and 30 m/span simply-supported girder bridges. The model is used to calculate and results are compared. The construction of each bridge is shown in Table 9.

Table 9 Construction of highway girder bridges

No.	*Intensity*	*Bridge name*	*Bridge type*	*Length/m*	*Width/m*	*Span/m*	*Damage state*	*PGA/g*
1	VII	Liujiahe Bridge	Continuous girder	120	8.5	20	Minor damage	0.156
2	X	Wuxin Road Mawei River Bridge	Simply-supported girder	60	12	20	Moderate damage	0.737
3	X	Gangou 3# Bridge	Simply-supported girder	48	7	20	Moderate damage	0.764
4	X	Qifu Bridge	Simply-supported girder	72	7	30	Moderate damage	0.437
5	IX	Jushuiguan Bridge	Simply-supported girder	71.2	18	30	Major damage	0.632
6	IX	Baisha River Bridge	Simply-supported girder	111	7	30	Major damage	0.780

Table 10 Comparison of seismic economic loss model results

Bridge name	*Bridge type*	*Span/m*	*Loss rate-based seismic economic loss/ten thousand yuan*	*Probability-based seismic economic loss/ten thousand yuan*	*Actual seismic economic loss/ten thousand yuan*	*Differences in results based on loss rate/%*	*Differences in results based on probability/%*
Liujiahe Bridge	Continuous girder	20	97.4	111.8	120.0	18.83	6.83
Wuxin Road Mawei River Bridge	Simply-supported girder	20	374.8	248.0	298.7	20.30	16.97
Gangou 3# Bridge	Simply-supported girder	20	117.4	90.3	103.0	12.27	12.33
Qifu Bridge	Simply-supported girder	30	141.6	189.8	154.5	8.35	18.60
Jushuiguan Bridge	Simply-supported girder	30	388.1	504.6	522.3	25.69	3.39
Baisha River Bridge	Simply-supported girder	30	343.2	369.8	401.1	14.44	7.80

According to the post-disaster reconstruction data of Wenchuan earthquake and sample bridge post-earthquake reconstruction bidding and other information, the actual reconstruction cost of the selected sample bridges was obtained, which was used as the benchmark for the seismic loss amount of the sample bridges. The actual seismic economic loss is compared with the calculation results of probability-based seismic economic loss assessment model and the loss rate-based seismic economic loss assessment model. The comparison is shown in Table 10.

As can be seen from Table 10, the difference between the calculation results of the loss rate-based seismic economic loss model and the actual seismic economic loss is within the range of between 8.35% and 25.69%, and the difference between the calculation results of the probability-based seismic economic loss model and the actual seismic economic loss is within the range of between 3.39% and 18.60%, They are within the acceptable range (Yang, 2019). Therefore, both seismic economic loss models are feasible to evaluate seismic economic loss of high girder bridges.

4 Examples

4.1 Project overview

Most areas of Northwest China, such as Gansu, Qinghai, etc., are located in relatively active seismic belts, and earthquakes occur all year round. It is necessary to predict the seismic economic losses of those newly built highway girder bridges. When the earthquake comes, we can use the emergency plan prepared in advance for earthquake rescue according to the prediction results, so as to save the time and money spent by the rescue commander. Therefore, this paper selects three highway girder bridges to predict the seismic economic loss. Two are located in Dingxi City, Gansu Province, and one is located in Xining City, Qinghai Province.

Bridge 1 K49+200 Ningyuan East River 2# Bridge

The bridge is located in Ningyuan Town, Dingxi City, Gansu Province, with a span of 30, a total of 13 spans, and a total length of 397. The net width of the bridge deck is 2 × 11.5, the upper structures adopt prestressed concrete continuous box girders, the lower structures adopt column piers and column platforms, and the foundations are all friction pile foundations. The basic earthquake intensity in this area is in the VIII-degree area, the characteristic period of the ground motion response spectrum is 0.45, the ground motion peak acceleration value is 0.20, and the design service life is 100 years.

Bridge 2 K9+055 Laowan Middle Bridge

The bridge is located in Pingxiang Town, Tongwei County, Dingxi City, Gansu Province, with a span of 20, a total of 3 spans, and a total length of 67. The net width of the bridge deck is 2×11.5, the upper structures adopt prestressed concrete continuous box girders, the lower structures adopt column piers and column platforms, and the foundations are all rock-socketed pile foundations. The basic earthquake intensity in this area is in the VIII-degree area, the characteristic period of the ground motion response spectrum is 0.45, the ground motion peak acceleration value is 0.20, and the design service life is 100 years.

Bridge 3 Jinyi Road Inner River Bridge

The bridge is located on the east side of Ningzhang Highway in Shilipu, Chengbei District, Xining City, Qinghai Province. The bridge has three spans, the spans are 40m, 60m, 42m respectively, and the total length of the bridge is 154.2. The net width of the bridge deck is 40, the upper structures adopt prestressed concrete continuous box girders, the lower structures adopt column piers and column platforms, and the foundations are all friction pile foundations. The basic seismic intensity of this area is in the VII-degree area, the characteristic period of the ground motion response spectrum is 0.45, the ground motion peak acceleration value is 0.10, and the design service life is 100 years.

4.2 Calculation of loss rate-based seismic economic loss assessment model

According to the seismic fortification classification of bridges in Specifications for Seismic Design of Highway Bridges (JTG-T 2231-01, 2020), Ningyuan East River 2# Bridge and Jinyi Road Inner River Bridge belong to Class B seismic fortification, Laowan Middle Bridge belongs to class C seismic fortification. It is stipulated in the specification that bridges belonging to class B and C should be fortified with two levels of seismic fortification, that is, under the E1 seismic action (the seismic action with a short return period of the engineering site, used in the seismic design of the first stage), the bridge should have no basic damage after the earthquake, and can be use normally; under the E2 seismic action (the seismic action with a long return period of the engineering site, used in the seismic design of the second stage), the bridge can be used for emergency traffic after temporary reinforcement after the earthquake, and will not collapse or cause serious damage to the structure. That is to say, the E1 and E2 seismic actions correspond to the two damage states of the bridge, which are basically intact and major damage, respectively. According to the ‘three levels’ of structural seismic resistance, that is, the principle of ‘no damage in small earthquake, repairable in moderate earthquake, and no collapse in large earthquake’, the bridges should also be assessed in accordance with the ‘three levels’ of seismic fortification when evaluating the economic losses of bridges, in which ‘no damage in small earthquake’ corresponds to the basically intact state under the E1 seismic action, ‘repairable in moderate earthquake’ corresponds to the moderate damage state under the action of seismic fortification, and ‘no collapse in large earthquake’ corresponds to the major damage state under the E2 seismic action.

Assuming that the earthquake damage intensity of the three bridges is identified as VIII after the earthquake, the estimated economic losses of the bridges are shown in Table 11 and Table 12.

Table 11 Results of the loss rate-based seismic economic loss model

Bridge name	*Intensity*	*Bridge length/m*	*Bridge width/m*	*Loss rate*			*Restruction cost/ten thousand yuan*	*Economic loss /ten thousand yuan*		
				Basically intact	*Moderate damage*	*Major damage*		*Basically intact*	*Moderate damage*	*Major damage*
Ningyuan East River 2# Bridge	VIII	397	23	0	0.0730	0.0916	3194.45	0	233.195	292.452
Laowan Middle Bridge	VIII	67	23	0	0.0728	0.1912	539.114	0	39.247	142.326
Jinyi Road Inner River Bridge	VIII	154.2	40	0	0.0655	0.1821	2,157.856	0	141.291	534.237

Table 12 Results of the probability-based seismic economic loss model

Bridge name	*Intensity*	*Bridge length/m*	*Bridge width/m*	*Damage probability*	*Restruction cost/ten thousand yuan*	*Economic loss /ten thousand yuan*		
						Basically intact	*Moderate damage*	*Major damage*
Ningyuan East River 2# Bridge	VIII	397	23	0.2076	3,194.45	19.895	165.792	371.374
Laowan Middle Bridge	VIII	67	23	0.4262	539.114	6.893	57.443	128.671
Jinyi Road Inner River Bridge	VIII	154.2	40	0.3902	2,157.856	25.260	210.499	470.957

It can be seen from Table 11 and Table 12 that when the seismic intensity is VIII, the seismic economic loss of the Ningyuan East River 2# Bridge under the E1 seismic action is between 0 yuan and 198,950 yuan; The seismic economic loss under the action of seismic fortification is between 1,657,920 yuan and 2,331,950 yuan; Under the E2 seismic action, the seismic economic loss is between 2,924,520 yuan and 3,713,740 yuan. The seismic economic loss of Laowan Middle Bridge under the E1 seismic action is between 0 yuan and 68,930 yuan; The seismic economic loss under the action of seismic fortification is between 392,470 yuan and 574,430 yuan; Under the E2 seismic action, the seismic economic loss is between 1,286,710 yuan and 1,423,260 yuan. The seismic economic loss of Jinyi Road Inner River Bridge under the E1 seismic action is between 0 yuan and 252,600 yuan; the seismic economic loss under the action of seismic fortification is between 1,412,910 yuan and 2,104,990 yuan; Under the E2 seismic action, the seismic economic loss is between 4,709,570 yuan and 5,342,370 yuan. When an earthquake occurs, in order to quickly rescue and relieve disasters, it is particularly important whether the bridge at the throat of traffic can be smooth and unimpeded. After the government and other emergency rescue departments conduct on-site disaster assessment, they can quickly assess the cost of repairing the bridge according to the loss range corresponding to the 'three levels' of earthquake resistance as a reference value, which can provide a reference for the government and other emergency rescue departments, and can also be used as a reference value for seismic capacity of post-earthquake bridges.

5 Conclusions

By collecting the seismic damage data of the highway girder bridge damaged in the Wenchuan earthquake, selecting the appropriate damage level classification method, classifying and analysing the seismic damage of the bridge, establishing the empirical vulnerability matrix and vulnerability curve, combining the loss rate and structure damage analysis, establish the loss rate-based seismic economic loss model and the probability-based seismic economic loss model, and then predict the seismic economic loss of highway girder bridges. Research indicates:

1. The initial vulnerability matrix is improved by using the beta empirical distribution function to fit the damage probability histogram. According to the actual earthquake damage dates, the empirical vulnerability curve is established by selecting the two-parameter log-normal distribution function as the vulnerability function, and using the simultaneous estimation method to estimate the parameters. The probabilistic method is used to analyse the seismic hazard, which fully considers the random characteristics of earthquakes, and can more reasonably assess the economic loss of bridge earthquakes.
2. Six highway girder bridges in the Wenchuan earthquake are selected, which are continuous girder bridges, 20m/span simply-supported girder bridges and 30 m/span simply-supported girder bridges. These bridges are calculated using the loss rate-based seismic economic loss model and the probability-based seismic economic loss model, and the calculated results are compared with the actual dates. The results show that the difference between the calculation results of the loss rate-based seismic

economic loss model and the actual seismic economic loss is within the range of between 8.35% and 25.69%, and the difference between the calculation results of the probability-based seismic economic loss model and the actual seismic economic loss is within the range of between 3.39% and 18.60%, they are within the acceptable range, which verifies the feasibility and accuracy of the model.

3 Three existing highway girder bridges are selected, and in the seismic intensity of degree VIII, the loss rate-based seismic economic loss model and the probability-based seismic economic loss model are respectively used. And the economic losses are respectively predicted under the E1 seismic action, the action of design earthquake and the E2 seismic action, and the seismic economic loss of the bridge structure is quantitatively analysed by economic indicators. The prediction results can provide a reference for the design of similar bridges, and can also be used as a basis for the seismic capacity of the post-earthquake bridges.

Acknowledgements

The research described in this paper was financially supported by the Natural Science Foundation of Gansu Province, China, Grant No. 20JR10RA237.

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