Analysis of probability matrix model for seismic damage vulnerability of highway bridges

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ABSTRACT

The present study was aimed at assessing more accurately the seismic vulnerability and performance of highway bridges in an earthquake-damaged area. Based on mathematical statistics (data collection) and a probability model, (i) survey data for 2134 bridges in 22 highway sections (47 sub-sections) affected by the Wenchuan earthquake on May 12, 2008 were obtained and analysed, (ii) Gaussian and exponential regression models were developed, (iii) the empirical seismic-damage vulnerability function, plane, surface and curve model of the 22 highway sections with sample number and failure ratio were established, and (iv) a regression parameter matrix was constructed considering the empirical seismic-damage data. Using the method of probability exceedance, the bridge vulnerability curve models considering the seismic-damage exceedance probability of each section were analysed, and a parameter matrix model (mean seismic-damage index) was proposed to evaluate and predict the seismic vulnerability of regional bridges. Based on creating the actual seismic-damage sample database, vulnerability point-cloud models of the 22 highway bridges were constructed, and the vulnerability probability matrix, function, curve and point-cloud model of each highway section can be used to evaluate and estimate the vulnerability of regional bridges in the future.

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1. Introduction

The theory of vulnerability probability is an important tool for analysing the disaster risk of engineering structures and evaluating and predicting their vulnerability, and it is an effective tool for determining various types of structural damage empirically. The majority of empirical investigation data after an earthquake indicate that most casualties and economic losses were due to the failure of engineering structures. As typical engineering structures, bridges are important structural systems and crucial...
components of transportation networks and lifeline engineering, and they play a supporting role in post-seismic emergency rescue and disaster relief. For many years, seismic engineering experts and scholars worldwide have carried out extensive research on the vulnerability assessment and prediction analysis of bridges and other typical engineering structures by using the theory of vulnerability probability.

Using the theory of vulnerability-exceedance probability, Ramadan et al. (2020) studied a 430-m-long bridge, extracted 18 real bedrock ground-motion parameters (peak ground velocity) from the database, and established the vulnerability curve model of the parameters by using incremental dynamics and the method of exceeding the limit force. Based on the nonlinear static method, Monteiro et al. (2019) proposed a method for analysing the vulnerability of reinforced concrete (RC) bridges, and they developed probability failure curves for RC bridges exceeding specific limit states under different intensity levels. Cheng et al. (2019) proposed an improved vulnerability analysis method for probabilistic seismic risk assessment of bridge structures, and they evaluated the seismic performance of a typical self-anchored bridge. Tolentino et al. (2020) proposed an inelastic cumulative-damage vulnerability assessment method for RC girder bridges under seismic load, and they analysed the cumulative damage of bridges of different ages. Martin et al. (2019) used a multi-risk framework to assess the vulnerability of a long-span suspension bridge under the coupled action of an earthquake and extreme wind, and they presented the probability-exceedance and vulnerability curve and surface of the entire structure under different damage states.

Shekhar et al. (2020) considered the revision of the seismic design of highway bridges around the world and their existing defects, developed a high-fidelity nonlinear finite-element model and used seismic vulnerability risk analysis and the probability method to study a failure probability model of bridge piers. Considering the influences of ground motion and material and geometric characteristics on the vulnerability of high-rise (Pahlavan et al. 2016; Castaldo and Amendola 2021) and ordinary box-girder concrete bridges, Soleimani (2020) and Ramadan et al. (2020) proposed a probabilistic seismic demand model based on nonlinear time-history analysis, obtained the vulnerability curve and concluded that there are obvious seismic risks in high-altitude regions.

In China, the majority of high-pier bridges have been built in the southwest. Chen (2020) used probability vulnerability analysis to analyse the vulnerability of bridges under near-fault ground motions, taking the pier columns and rubber bearings as the vulnerable components; using nonlinear history analysis and a probabilistic demand model, they obtained the vulnerability curve and analysed the seismic defects of high piers. Martinez et al. (2017) used two sets of ground-motion records from the Chile earthquake on August 8, 2010 to conduct incremental dynamic analysis on a two-span simply supported girder bridge; they established the vulnerability curve and proposed an improved probabilistic method for assessing the bridge’s seismic risk and evaluating its seismic design. According to the characteristics of bridges in regions of different intensity, Simon and Vigh (2016) selected an integral precast multi-span bridge in Hungary in a moderate-intensity region as their research object; they established nonlinear numerical models of the parameter vulnerability for different layouts,
analysed the collapse probability of piers with different heights and obtained the vulnerability curves.

Vulnerability analysis using different probability and regression models is not limited to bridges, and many researchers have applied this method to typical building structures, highways, dams and the natural environment (Castaldo et al. 2019; Hassaninia et al. 2019; Tang and Huang 2019; Foulser-Piggott et al. 2020; Grant 2020; Hancilar et al. 2020; Suzuki and Junio 2020; Trevlopoulos et al. 2020; Rosti et al. 2021). The method of vulnerability probability analysis has been applied extensively to various engineering structures and is a common method for evaluating the vulnerability of such structures.

However, most vulnerability analysis methods are focused mainly on (i) establishing a finite-element model, (ii) single-scale-model shaking-table tests, (iii) ground-motion intensity (peak ground acceleration or velocity) (Simon and Vigh 2016; Chen 2020; Shekhar et al. 2020) and (iv) investigating the actual damage of a typical individual structure. The theory of vulnerability probability has been used widely to study single bridges but less so groups of bridges (in particular, the vulnerability of a regional group of bridges was evaluated by using the macroseismic intensity scale and classification of earthquake damage to lifeline engineering). Assessing the vulnerability of typical regional bridge structures is somewhat limited and fuzzy and is relatively inaccurate for bridge structures damaged in different degrees in an earthquake.

It is difficult to obtain the umbrella damage of regional group bridges by analysing the seismic damage of a typical single bridge. To obtain the actual seismic vulnerability properties of group bridges in different seismic intensity areas, we use multidimensional parameters to establish a regional bridge vulnerability assessment model based on typical earthquake and verify the rationality of the multidimensional model by using bridge data from empirical field investigations. The present study considered only highway bridges as typical engineering structures and studied their overall regional vulnerability. On May 12, 2008, a strong earthquake (Mw = 7.9) occurred in Wenchuan County in China and caused different degrees of damage to the bridges in the earthquake region. From May to October of the same year, experts from the China Earthquake Administration (CEA), the Ministry of Transport and scientific research institutes and universities from different countries formed an expert investigation group to inspect the earthquake damage of bridges in the Wenchuan earthquake area in batches.

To assess more accurately the vulnerability of bridges on the highway sections in the overall seismic region, the present study selected sample data for the seismic damage of 2134 bridges on 22 highway sections (47 sub-sections) in the provinces of Sichuan, Gansu and Shaanxi (Chen et al. 2012). Then, according to the distribution of bridge samples in different highway sections, the anti-seismic design and the macroseismic intensity scale (Chinese Seismic Intensity Scale), (i) a probability matrix model and numerical analysis were used to analyse the bridge vulnerability of each section, (ii) vulnerability probability matrix models of the 22 highway sections were established and (iii) nonlinear vulnerability models based on the parameters of sample number (SN), failure ratio (FR) and exceedance probability (EP) were developed. (iv) A set of innovative two-dimensional and three-dimensional numerical models
(plane and surface) for evaluating the vulnerability of regional group bridges are proposed, and innovative vulnerability point cloud and nonlinear curve models of highway bridges in different sections are established. To obtain more accurately the overall damage situation of different sections of the bridges, an empirical seismic-damage probability matrix model was then calculated in combination with a mean seismic damage index (MSDI) matrix model. A regional vulnerability matrix probability model with MSDI as the vulnerability parameter was established. It also provides a necessary reference for the revision of seismic intensity scales and seismic ground motion parameters zonation map of China.

2. Brief introduction to field reconnaissance of highway bridges

Historical seismic-damage data indicate that the Wenchuan earthquake damaged many highway bridges to varying degrees. To conduct in-depth research on bridge seismic damage, improve the seismic capacity of highway bridges and promote the effective development of disaster prevention and mitigation work, China’s relevant earthquake-damage assessment institutions have successively organised many highway-bridge seismic-resistance experts, scientific researchers and bridge engineers to form more than 200 seismic-damage reconnaissance teams to carry out empirical seismic-damage investigations of various engineering structures in earthquake regions.

The observation zone covered 41 cities and counties in the provinces of Sichuan, Shaanxi and Gansu in multiple intensity regions and more than 2200 bridges and 56 tunnels on 47 expressways and national and provincial highways. The investigation involved mainly collecting bridge design data, construction years, seismic design intensities, actual intensity evaluations, ground-motion parameters and damage characteristics of engineering structures, among which the damage done to bridge structures was relatively prominent. Based on the seismic intensity distribution map issued by CEA and USGS, as depicted in Figure 1 (Yuan 2008; Wald et al. 2011), the reconnaissance teams carried out empirical field investigations of bridges in multiple
regions. Because of the unbalanced spatial distribution of the survey samples, this paper selects the provinces of Sichuan (SC), Shaanxi (SX) and Gansu (GS) as the sample areas for analysis and performs statistics and induction. Figure 2 shows the distribution of the 2134 empirical bridge-damage samples in the survey area and the 22 highway sections. According to the requirements of the code for seismic damage classification of lifeline engineering (GB/T 24336-2009, China) (Li et al. 2021b) and the bridge seismic code, and combined with the global typical intensity scales (EMS-98, MSK-81 and China seismic intensity scale (CSIS-08)), the seismic-damage investigation teams evaluated the vulnerability grade (VG) of various bridge samples in the Wenchuan-earthquake investigation region. According to the degree of bridge damage, the VG is divided into five levels (basically intact (DS1), slightly damaged (DS2), moderately damaged (DS3), severely damaged (DS4) and destroyed (DS5) (Li and Chen 2020; Li et al. 2021a, 2021b, 2022d). The vulnerability assessment criteria are summarised in Table 1.

According to the statistics of the seismic-damage investigation data, the main bridge types in the seismic area were simply supported girder (SSG), continuous girder (CG), arch bridge (AB), suspension bridge (SB), a combination of SSG and CG (SSC), and cable-stayed bridge (CSB). Figure 3 shows the quantity distribution of seismic-damage investigations for the various bridge types, and the statistical data indicate that the proportion of girder and arch bridges was relatively large, accounting for 99.7% of the overall sample.

According to the empirical seismic-damage situation, the reconnaissance teams made detailed plans for the seismic-damage assessment of those two types of bridge. The investigation of girder bridges involved mainly whether the beam body had fallen girders and plane displacement and whether there were possibilities of (i) beams falling, (ii) cracking of the bridge deck, diaphragm and main girder, (iii) cracking and damage of bent caps and blocks, (iv) damage to the bridge-deck pavement, (v)
Table 1. Standards for seismic-damage assessment of bridges with different vulnerability grades (GB/T 24336 2009, CSIS-08).

| Vulnerability grade | Details of seismic-damage assessment (GB/T 24336 2009) |
|---------------------|-------------------------------------------------------|
| Basically intact (DS1) | No damage to structural members of the bridge; inconspicuous deformation of bridge deck; individual non-structural members may be damaged, continue to use without repair. |
| Slightly damaged (DS2) | No seismic damage occurred to load-bearing components such as bridge deck, abutments, piers, arches, towers and main beams; local surface concrete peeling, guardrails, expansion joints, abutment cone slope and other non-bearing components are damaged, and the support connection parts are slightly deformed, so it can pass without repair or slight repair. |
| Moderately damaged (DS3) | Remarkable cracks in pier concrete, but no obvious inclination; the protective layer peels off but does not damage the concrete in the core area, and the bearing capacity of the piers decreases significantly; cracks in the concrete at the bridge ends; displacement of main girders, but there is still reliable support, no risk of falling beams; abutments are slightly damaged, and their back and wing walls are cracked. The transverse connections of the arch bridge are cracked, and the columns on the arches are slightly cracked. |
| Severely damaged (DS4) | Serious displacement of main girders, but they can still be supported reliably without the risk of falling beam. There are obvious through-cracks or multiple shear joints in the pier concrete, which extend to the core area, peel off, and seriously crack and incline; abutments are damaged, back and wing walls are seriously cracked or collapsed, and abutment caps (cap beams) are cut. The main arch ring of the arch bridge is transversely penetrated and cracked, the column on the arch is broken, and the transverse connection is broken. |
| Destroyed (DS5) | The whole bridge or some of the spanning units have collapsed, the falling beams, piers and abutments are broken or may collapse at any time, and the piers are crushed or sheared. |

Figure 3. Distribution of samples of various bridges in observation region.

displacement of pier and abutment foundations, (vi) shear, collapse and cracking of pier columns and (vii) damage to abutments, abutment body and cone slope. The investigation of arch bridges involved mainly (i) cracking or collapse of transverse walls and web arches, (ii) flatness of the bridge deck and settlement of filling materials on the arches, (iii) cracking and displacement of side walls, (iv) bearing voids and displacement of the carriageway slabs of beam-type abdominal arch bridges and (v) cracking or collapse of main and abdominal arches.
To assess more effectively and accurately the seismic damage and vulnerability of bridge structures, the observation teams conducted their investigation work according to different survey lines. First, a seismic-damage assessment was made of the appearance of the bridge body, and the basic situation of damage to the bridge structure was recorded in detail. Next, the relevant detection equipment was used to detect the development of bridge cracks, girder displacement, deformation, bearing displacement and pier displacement, the aims being to (i) make the survey results more detailed and accurate and (ii) provide valuable reference data for research into bridge vulnerability.

3. Vulnerability matrix model of typical highway bridge

Researching the vulnerability of highway bridges with empirical seismic damage involves mainly evaluating the vulnerability levels of highway bridges damaged by typical earthquakes. Combined with a vulnerability probability model, the empirical vulnerability matrix of each bridge was established by processing the samples. In the present study, the probabilities and statistics of 2134 bridge-damage samples in 22 highway sections (47 sub-sections) were calculated according to the vulnerability probability model.
classification and evaluation standard, and the empirical seismic-damage probability plane, surface, and matrix model (MM) of each section based on SN and FR was established, as shown in Figures 4, 5 and Appendix. To analyse the vulnerability of highway bridges in different road sections, it is necessary to analyse the vulnerability of bridges in different sections, propose a group of nonlinear fitting models, use the actual seismic-damage sample data to verify the model, and establish the bridge vulnerability matrix model of each highway section.

Figure 4. Continued.
3.1. Bridge vulnerability model considering SN

To evaluate more accurately the vulnerability of the 22 highway bridges across the three provinces and obtain the overall damage situation of the bridges in the observation region, this study made statistics and induction of bridge samples of 22 highway

Figure 4. Continued.
sections respectively. After the bulk of program editing, the bridge samples of the multiple highway sections were summarised statistically, and a Gaussian model was found to offer the best approximation of the seismic-damage sample points (SDSPs).

Therefore, a Gaussian first nonlinear regression model (GFRM) was used to analyse the regression model of the bridge samples of each road section, as expressed by

Figure 5. Bridge vulnerability surface model of 22 highway sections (47 sub-sections) considering FR parameter.
Among them, the bridge vulnerability models of 47 sub-sections in the 22 highway sections were regressed with an interactive shape-preserving model (the PCHIP model), as reported in Figure 6. Here, $N_G$ is the SN of actual bridge damage under different vulnerability grades ($V_G$), the values of which are selected according to the

$$N_G = a_1 e^{\left(-\frac{(V_G - b_1)^2}{2c_1}\right)},$$  

(1)

Figure 5. Continued.
seismic vulnerability grades (DS1–DS5). To facilitate the establishment of a continuous regression function model, the five seismic vulnerability grades are taken as the integers 1–5, respectively, and $a_1$, $b_1$ and $c_1$ are the vulnerability regression parameters. Table 2 summarises the regression-model parameter matrix of the 22 highway sections. Note that when using a Gaussian regression model, the dispersion of bridge samples in sections S301 and G317 is larger. To ensure the fitting degree of the curve model, the PCHIP model was used for regression.

The vulnerability model analysis of the 22 highway sections (47 sub-sections) leads to the conclusion that most of the bridge damage in each section is of grades DS1 and DS2, especially in Junkun, Hurong, Chengyu, Chengduxian, G318, Xiaorong, S309, S301 and G212; the curve of the SN parameter model reaches its peak in the DS1–DS2 interval, which indicates that the seismic damage of bridges on these sections is relatively slight, and the low damage of these bridges could be due mainly to the low ground-motion intensities (intensity regions) in these regions. The regression curves of S105, G108, S205, S210, S211, S209 and G213 indicate that either a monotonically decreasing change or the peak value occurred between DS2 and DS3, and the number of higher VGs is relatively small. The bridge damage of S106, S302 and
Figure 6. Bridge vulnerability model (GFRM and PCHIP) curves of 22 highway sections (47 sub-sections) considering SN parameter.
Figure 6. Continued.
Dujiangyanx is relatively serious, and the curves either reach their peak values at the DS3 level or exhibit a monotonically increasing trend. The main reason for this may be that these sections are located in high-intensity regions and have relatively weak seismic capacity. The changes of the model curves of S303, S306 and G317 are relatively stable, and the quantity distribution of each VG is relatively balanced. The model established in this section could be used for the seismic damage assessment and prediction of bridge vulnerability in these sections in the future. However, the damage analysis of a single bridge should be considered comprehensively in combination with different bridge types, site conditions, seismic design measures and other factors.

### 3.2. Bridge vulnerability model considering FR

FR is an effective parameter index for evaluating the vulnerability of engineering structures, and it is used widely in research into the structural vulnerability of bridges and buildings (Li and Liu 2022a, 2022b, 2022c). To study the bridge vulnerability of different highways under the FR factor, the bridges of the 22 highway sections (47 sub-sections) were counted according to the FR parameter, as indicated by Table 2, Equation 1 and exponential first nonlinear regression model (EFRM) are developed, as expressed by

\[
FR_G = a_2 e^{(b_2 V_G)},
\]

where \(FR_G\) represents the FR of actual bridge failure under different \(V_G\), and \(a_2\) and \(b_2\) are the regression parameters of the vulnerability index model. Applying the EFRM to Chengyuxian, S106 and S209 and the GFRM to the other sections (goodness of fit, variance and robustness), nonlinear regression analysis was conducted on the bridge samples of each section, and the vulnerability curve model and vulnerability parameter matrix model based on FR were obtained, as summarised in Figure 7 and Table 3.

According to the analysis results of the vulnerability model based on FR, a large proportion of the bridge damage in the overall observation area (22 highway sections) is concentrated in the DS1 and DS2 grades, and there is a peak value in this interval, showing a decreasing trend at a higher level. To a certain extent, this shows that the

| Highway section name | \(a_1\)  | \(b_1\)  | \(c_1\)  | Highway section name | \(a_2\)  | \(b_2\)  | \(c_2\)  |
|----------------------|--------|--------|--------|----------------------|--------|--------|--------|
| Jingkun              | 111.2  | 1.652  | 0.7774 | Hurong               | 67.74  | 1.661  | 0.6756 |
| Chengyuhan           | 7.188  | 1.5    | 0.4865 | Chengduxian          | 14.85  | 1.745  | 0.8865 |
| S105                 | 16.29  | 0.7621 | 3.681  | S106                 | 11.65  | 2.76   | 0.5312 |
| G108                 | 37.02  | 0.8328 | 1.65   | S205                 | 42.95  | —1.51  | 3.104  |
| S210                 | 22.45  | 0.2829 | 1.963  | S211                 | 1.367 \times 10^{392}  | —702.6 | 27.19  |
| G212                 | 12.49  | 2.033  | 1.4    | G213                 | 15.06  | 0.2695 | 3.546  |
| S302                 | 9.528  | 6.128  | 4.144  | S303                 | 7.897 \times 10^{09}   | —1578  | 125.1  |
| G318                 | 33.91  | 1.585  | 0.9953 | Xiarong              | 156.2  | 1.803  | 0.663  |
| Dujiangyanx          | 25.03  | 2.968  | 0.764  | S209                 | 15.7   | 2.456  | 0.4651 |
| S301                 | ———   | ———   | ———   | S306                 | 8.213  | 1.502  | 1.253  |
| S309                 | 65.59  | 1.458  | 0.4664 | G317                 | ———   | ———   | ———   |

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**Table 2. Bridge vulnerability model matrix of 22 highway sections based on SN parameter.**
Figure 7. Bridge vulnerability model (GFRM and EFRM) curves of 22 highway sections considering FR parameter.
bridge failure in the overall seismic area basically achieved the seismic design goal of no collapse in a large earthquake.

The bridge damage of Jingkun, Hurong, Chengduxian, S211, G317, S309, S301, Xiarong, S306, G318 and S210 was relatively light. The bridge vulnerability regression curves for Chengyuhua, S105, G212, G213, S303 and S209 are inclined towards DS3 and DS4, which indicates that the bridge damage on these sections was more serious than the previous group. The bridge damage of the S302 and Duijiangyanx sections was relatively serious, and the main reason for this was that the displacement of some sub-segments of these two sections was close to the macro epicentre, which led to serious bridge damage. The bridge damage of S106, G108 and S205 was similar, but S205 was slightly higher than the other two bridges.

According to the analysis results for the bridge vulnerability of each section, most of the bridges ensured the stability of the stress system of the main structure, and only a few bridges suffered from instability, falling beams, and local or overall collapse. For most bridges built after the 1990s, the relevant requirements of the seismic design code have been considered, showing good seismic capacity. However, a large number of data show that the proportion of the DS2 grade was obviously increased, and a considerable bulk of the non-force components of the bridges were damaged. This should attract necessary attention regarding reasonably strengthening the bridge seismic measures and making DS2 ratio transfer to DS1 grade so as to improve the seismic performance of the bridges.

### 3.3. Bridge vulnerability model considering damage exceedance probability (DEP)

The damage to bridges by earthquakes in different regions exhibits remarkable discrepancy. Researchers evaluate or predict the seismic damage of bridges via risk analysis and vulnerability characteristics, and many studies have indicated that the DEP vulnerability model is effectively for evaluating the actual seismic damage of bridges (Simon and Vigh 2016; Martinez et al. 2017; Tolentino et al. 2020). In the present study, the VG was classified according to five limit states (DS1–DS5), and the boundary between adjacent grades was taken as the threshold value. Combined with the models and method of DEP analysis, model analysis of the 22 highway sections and

| Highway section name |  \( a_1/a_2 \) |  \( b_1/b_2 \) |  \( c_1 \) | Highway section name |  \( a_1 \) |  \( b_1 \) |  \( c_1 \) |
|----------------------|----------------|----------------|---------|----------------------|----------------|----------------|---------|
| Overall region       | 0.4742         | 1.537          | 1.307   | Hurong               | 0.844          | 1.657          | 0.6779   |
| Jingkun              | 0.7318         | 1.688          | 0.7857  | Chengduxian          | 0.6044         | 1.821          | 0.9505   |
| Chegnyuhuan          | 0.703          | -0.4565        | ——      | S105                 | 0.3124         | 0.5616         | 3.822    |
| S106                 | 2.158          | -1.193         | ——      | S205                 | 0.6314         | 0.1751         | 2.14     |
| G108                 | 0.7959         | 0.1845         | 1.789   | S211                 | 6.462 \times 10^{36} | -72.06 | 7.912   |
| S210                 | 1.246          | -0.7251        | 2.181   | G213                 | 0.3614         | 0.5474         | 3.178    |
| G212                 | 0.4721         | 2.194          | 1.161   | S303                 | 2.293 \times 10^{14} | -284.7 | 48.83   |
| S302                 | 0.2977         | 3.525          | 2.122   | G317                 | 1.194 \times 10^{81} | -130.4 | 9.614   |
| G318                 | 0.62           | 1.46           | 0.9702  | S306                 | 0.5143         | 1.502          | 1.268    |
| Duijiangyanx         | 0.6812         | 2.965          | 0.7686  | S301                 | 5.12 \times 10^{35} | -77.63 | 8.663   |
| S209                 | 0.3284         | -0.1671        | ——      | Xiarong              | 0.8439         | 1.801          | 0.6562   |
| S309                 | 0.9994         | 1.427          | 0.5984  |                     |                |                |         |
their sub-sections was conducted, and the bridge DEP model curve of each sub-section was obtained. To obtain the bridge vulnerability of the 22 sections relatively accurately from the perspective of DEP parameter analysis, the exceedance probability of each sub-section was averaged, and the bridge vulnerability DEP curve model of each section based on mean value (M) was obtained, as illustrated in Figure 8.

The DEP model of bridge vulnerability in the overall earthquake region indicates that the parameter exceeds 0.8 within the DS2 level, which in turn indicates that the damage to most of the bridges in the overall seismic area was relatively light. The damage to the Jingkun, Hurong and Chengyuhua bridges was similar and light. For the bridge in Chengduxian, the damage to the CD-PZ section was slightly lighter than that to the other sub-sections. The bridge damages in the S105, G212, G213, S302, S303 and Dujiangyan sections was relatively serious, the main reason being that those sub-sections were located in high-intensity regions. Therefore, the seismic design methods and measures for bridges in this area should be strengthened to improve their seismic capacity. The bridges in the other sections can reach the probability of exceeding 0.9 at the level of DS3 or less. To improve the seismic capacity of bridges in different road sections, multi-level seismic design of bridges should be considered, and the construction quality should be guaranteed.

Figure 8. Bridge vulnerability model (DEP) curves of 22 highway sections (47 sub-sections).
4. Vulnerability matrix model for highway bridges considering MSDI

To evaluate the seismic damage of engineering structures more accurately and study their seismic vulnerability characteristics, researchers have carried out extensive research using the seismic damage index (SDI) as a parameter. Pan et al. (2020) selected Park and Ang as SDIs to analyse the vulnerability of traditional low-rise light-weight timber structures in southwest England, and they gave the relationship...
curve between the system SDI and seismic duration. Zheng et al. (2020) proposed a seismic damage index parameter for evaluating earthquake risk; taking the city of Jiangyou in China as an example, they analysed the correlation between the seismic vulnerability of groups of buildings and direct economic loss. Cao et al. (2019) analysed 144 high-speed-railway piers by combining numerical analysis and experiment; they proposed SDI parameters for evaluating the seismic response of the piers, and

Figure 8. Continued.
Table 4. VG and $d_{DS}$ intervals (GB/T 1774217742, 2008; CSIS-08).

| VG median | $d_{DS}$ intervals |
|-----------|--------------------|
| DS1 0.05  | $0.00 < d_{DS} < 0.10$ |
| DS2 0.20  | $0.10 < d_{DS} < 0.30$ |
| DS3 0.43  | $0.30 < d_{DS} < 0.55$ |
| DS4 0.70  | $0.55 < d_{DS} < 0.85$ |
| DS5 0.93  | $0.85 < d_{DS} < 1.00$ |

Table 5. Bridge vulnerability matrix model of 22 highway sections (47 sub-sections) based on MSDI.

| Highway route name | Sub section name | MSDI | Highway route name | Sub section name | MSDI |
|--------------------|------------------|------|--------------------|------------------|------|
| Jingkun            | CD-MY            | 0.214          | 0.1361  | 0.058 | 0.292 | 0.18 |
|                    | MY-GY            | 0.2785         | 0.1866  | 0.094 | 0.114 | 0.0605 | 0.007 |
| Hurong             | CDE              | 0.245          | 0.1596  | 0.074 | 0.297 | 0.2071 | 0.115 |
|                    | CDW              | 0.2315         | 0.1499  | 0.068 | 0.144 | 0.083  | 0.022 |
|                    | CD-NC            | 0.238          | 0.1535  | 0.069 | 0.158 | 0.0963 | 0.034 |
| Xiaorang           | CD-CQ            | 0.2665         | 0.1764  | 0.086 | 0.1   | 0.05   | 0   |
| Chengyuhuan        | SN-HM            | 0.188          | 0.116   | 0.044 | 0.4665| 0.3536 | 0.236 |
|                    | SN-CQ            | 0.3            | 0.2     | 0.1   | 0.475 | 0.369  | 0.26 |
|                    | CD-PZ            | 0.222          | 0.1415  | 0.061 | 0.2575| 0.1751 | 0.091 |
|                    | CD-DJY           | 0.2925         | 0.2016  | 0.109 | 0.141 | 0.0816 | 0.022 |
|                    | CDWJ-GL          | 0.311          | 0.2176  | 0.122 | 0.216 | 0.1398 | 0.063 |
| Dujiangyanx        | DJY-YX           | 0.5625         | 0.4454  | 0.321 | 0.247 | 0.1679 | 0.087 |
| S105               | PZ-BC            | 0.3785         | 0.2852  | 0.189 | 0.6605| 0.5441 | 0.421 |
|                    | BC-QC            | 0.456          | 0.3584  | 0.258 | 0.5525| 0.4359 | 0.313 |
| S106               | CY-DY            | 0.227          | 0.2404  | 0.149 | 0.325 | 0.0759 | 0.019 |
|                    | DY-ZJ            | 0.128          | 0.071   | 0.014 | 0.4465| 0.3409 | 0.228 |
| G108               | GY-QPG           | 0.11           | 0.0575  | 0.005 | 0.79  | 0.6927 | 0.5885 |
|                    | YA-PSG           | 0.2425         | 0.1658  | 0.087 | 0.691 | 0.5758 | 0.4565 |
|                    | GN-NQ            | 0.212          | 0.134   | 0.056 | 0.608 | 0.5149 | 0.4165 |
| S205               | PW-JY            | 0.314          | 0.2315  | 0.147 | 0.2885| 0.2054 | 0.119 |
|                    | AB               | 0.186          | 0.1145  | 0.043 | 0.2475| 0.1659 | 0.083 |
|                    | JL-WD            | 0.2205         | 0.1442  | 0.067 | 0.18  | 0.11   | 0.04 |
| G317               | WC-MRK           | 0.1485         | 0.0902  | 0.031 | 0.253 | 0.169  | 0.084 |

Figure 9. Vulnerability point clouds of 22 highway bridges (47 sub-sections).
they verified those parameters in dynamic tests. The SDI is also used extensively for RC structures, masonry structures, bottom-frame seismic-wall structures and hydraulic dam structures (Chen et al. 2020; Kassem et al. 2020). However, there has been less research involving SDI parameters for analysing the vulnerability of all the bridge samples of each highway section in an earthquake region.

To understand the seismic damage of regional highway bridges in various sections, the following matrix model of parameters (MSDI) for assessing the vulnerability of regional bridges is proposed herein:

$$[MSDI]_{Sub} = [\Omega_F] \times [d_{DS}],$$

where $d_{DS}$ is the SDI of the bridge vulnerability grade ($VG$), $\Omega_F$ is the bridge FR of vulnerability grade DS, and $[MSDI]_{Sub}$ is the MSDI matrix of the bridges of each highway sub-section ($d_{DS}$ is the upper limit ($u$), mean value ($m$) and lower limit ($d$)), as indicated by Table 4.

Combined with the model and bridge sample survey data, the vulnerability matrix model of the 47 sub-sections of the 22 highway sections under an earthquake was developed, and the vulnerability matrix model and point-cloud chart of the 47 highway sub-sections based on the MSDI parameters were obtained, as depicted in Table 5 and Figure 9.

According to the established MSDI vulnerability parameter matrix and point-cloud chart, the 47 sub-sections of the 22 highway sections were damaged in varying degrees; in particular, the damage to bridges in sections DJY-YX, WC-YX, BC-MX, JY-BC and YX-WL was relatively serious. The MSDI ($u$) of most bridge sub-sections was less than 0.3, and the damage was relatively light, which is consistent with the actual seismic-damage investigation and verifies the correctness of the MSDI vulnerability model to a certain extent.

5. Conclusion

In this study, a new model for evaluating the vulnerability of group bridges in different intensity areas is proposed. Combined with the numerical modal, two-dimensional and three-dimensional numerical calculation theory, a regional bridge vulnerability model based on multidimensional fragility parameters is established, and the rationality of the model is verified by using the seismic damage data of 2134 actual bridges. The conclusions are as follows:

i. Seismic-damage investigation data for 2134 bridges in 22 highway sections (47 sub-sections) affected by the Wenchuan earthquake on May 12, 2008 were collected and summarised, and the vulnerability grades defined by CSIS-08 and (GB/T 24336 2009) were statistically analysed.

ii. Based on the statistics of the highway bridge samples in the 47 sub-sections, the novel vulnerability matrix considering SN and FR parameter factors was established. Combined with nonlinear and probabilistic model analysis methods, the GFRM and PCHIP were used to perform regression analysis on the seismic-damage samples of the parent sections and sub-sections, respectively, and the vulnerability curve and regression parameter matrix model based on SN were obtained.
iii. To ensure the fitting degree of the regression model, in addition to the above analysis methods, this paper introduced the EFRM to perform the regression analysis based on the FR parameter for the bridge samples of each road section, obtained the vulnerability regression model curve and regression parameter matrix of the 22 highway sections, and carried out the damage analysis of bridges in each section.

iv. Depending on the numerical modal, two-dimensional and three-dimensional numerical calculation theory, the vulnerability plane and surface models of regional bridges based on FR were established, and the model was verified by 2134 bridge samples from 22 highway sections. Combined with the DEP model, the vulnerability DEP models of the overall seismic region, the 47 sub-sections and the 22 parent sections were established, and the vulnerability comparison and evaluation of bridges in each section were carried out.

v. The calculation method of the highway bridge vulnerability matrix model considering MSDI was proposed, and the model method was verified by using empirical seismic-damage sample survey data. The bridge vulnerability matrix model and point-cloud distribution map based on the MSDI parameters in the 47 sub-sections were obtained, and a comparative analysis based on the vulnerability parameters was given. The above conclusions can be used to evaluate and predict the vulnerability of typical bridge sections (in the same or similar seismic regions) in the future.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

All models, data and codes that support the findings of this study are available from the CONTACT upon reasonable request

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# Appendix

Bridge vulnerability matrix model of 22 highway sections (47 sub-sections) affected by Wenchuan earthquake.

| Highway route name | Sub-section name | SN and FR (%) of vulnerability grade | Total |
|--------------------|------------------|-------------------------------------|-------|
|                    |                  | D51 | D52 | D53 | D54 | D55 |       |
| Jingkun            | Chengdu-Mianyang (CD-MY) | 85/47 | 94/51 | 2/3 | 0/0 | 0/0 | 182/100 |
|                    | Mianyang-Guangyuan (MY-GY) | 25/21 | 88/72 | 8/7 | 0/0 | 0/0 | 121/100 |
| Hurong             | Chengdu (CDE) | 27/30 | 62/68 | 2/2 | 0/0 | 0/0 | 91/100 |
|                    | Chengdux (CDW) | 24/38 | 37/59 | 2/3 | 0/0 | 0/0 | 63/100 |
|                    | Chengdu-Nanchong (CD-NC) | 27/31 | 59/69 | 0/0 | 0/0 | 0/0 | 86/100 |
| Xiarong            | Chengdu-Chongqing (CD-CQ) | 36/20 | 143/77 | 6/3 | 0/0 | 0/0 | 185/100 |
| Chengyuhuan        | Suining-Huima (SN-HM) | 5/56 | 4/44 | 0/0 | 0/0 | 0/0 | 9/100 |
|                    | Suining-Chongqing (SN-CQ) | 0/0 | 1/100 | 0/0 | 0/0 | 0/0 | 1/100 |
| Chengduxian        | Chengdu-Pengzhou (CD-PZ) | 14/39 | 22/61 | 0/0 | 0/0 | 0/0 | 36/100 |
|                    | Chengdu-Dujiangyan (CD-DJY) | 6/25 | 14/58 | 4/17 | 0/0 | 0/0 | 24/100 |
|                    | Chengduwenjiang-Gonglai (CDWJ-GL) | 2/22 | 5/56 | 2/22 | 0/0 | 0/0 | 9/100 |
| Duijiangyanx       | Duijiangyan-Yingxiu (DJY-YX) | 1/3 | 5/14 | 25/67 | 4/11 | 2/5 | 37/100 |
| S105               | Pengzhou-Beichuan (PZ-BC) | 20/41 | 7/14 | 14/29 | 8/16 | 0/0 | 49/100 |
|                    | Beichuan-Qingchuan (BC-QC) | 14/24 | 18/31 | 11/19 | 10/17 | 5/9 | 58/100 |
| S106               | Congzhou-Deyang (CZ-DY) | 19/48 | 2/4 | 19/48 | 0/0 | 0/0 | 40/100 |
|                    | Deyang-Zhongjiang (DY-ZJ) | 6/86 | 1/14 | 0/0 | 0/0 | 0/0 | 7/100 |
| G108               | Guangyuan-Qipanguan (GY-QPG) | 21/95 | 1/5 | 0/0 | 0/0 | 0/0 | 22/100 |
|                    | Yaan-Pusagang (YA-PSG) | 56/55 | 24/24 | 21/21 | 0/0 | 0/0 | 101/100 |
|                    | Guning-Ningqiang (GN-NQ) | 33/44 | 42/56 | 0/0 | 0/0 | 0/0 | 75/100 |
| S205               | Pingwu-Jiangyou (PW-JY) | 27/56 | 5/10 | 10/20 | 7/14 | 0/0 | 49/100 |
|                    | Aba (AB) | 12/57 | 9/43 | 0/0 | 0/0 | 0/0 | 21/100 |
|                    | Jiangluo-Wudu (JL-WD) | 28/51 | 22/40 | 5/9 | 0/0 | 0/0 | 55/100 |
| S209               | Malukou-Hongyuan (MLK-HY) | 0/0 | 6/60 | 4/40 | 0/0 | 0/0 | 10/100 |
| S210               | Baoxing-Zhuokeji (BX-ZKJ) | 27/93 | 2/7 | 0/0 | 0/0 | 0/0 | 29/100 |
|                    | Feixianguan-Markang (FXG-MRK) | 14/29 | 24/49 | 11/22 | 0/0 | 0/0 | 49/100 |
|                    | Hanzhong (HZ) | 18/78 | 5/22 | 0/0 | 0/0 | 0/0 | 23/100 |
| S211               | Ludingdanba-Markang (LDDDB-MRK) | 24/78 | 5/16 | 2/6 | 0/0 | 0/0 | 31/100 |

(continued)
| Highway route name     | Sub-section name                         | SN and FR (%) of vulnerability grade | Total |
|-----------------------|------------------------------------------|--------------------------------------|-------|
|                       |                                          | DS1       | DS2       | DS3       | DS4       | DS5       |       |
| Hanzhong-Nanzheng     |                                          | 12/100    | 0/0       | 0/0       | 0/0       | 0/0       | 12/100|
| G212                  | Guangyuan-Yaodu (GY-YD)                  | 1/3       | 12/40     | 14/47     | 3/10      | 0/0       | 30/100|
| Bikou-Guanzigou       |                                          | 0/0       | 6/60      | 2/20      | 1/10      | 1/10      | 10/100|
| Wudu-Guantouba        |                                          | 21/44     | 19/40     | 8/16      | 0/0       | 0/0       | 48/100|
| G213                  | Langmusi-Nalitai (LMS-NLT)               | 40/82     | 8/16      | 1/2       | 0/0       | 0/0       | 49/100|
|                       | Langmusi-Chuanzhusi (LMS-CZS)            | 15/49     | 14/45     | 2/6       | 0/0       | 0/0       | 31/100|
|                       | Chuanzhusi-Wenchuan (CZS-WC)             | 19/49     | 13/33     | 7/18      | 0/0       | 0/0       | 39/100|
|                       | Wenchuan-Yingxiu (WC-YX)                 | 0/0       | 6/11      | 28/51     | 12/22     | 9/16      | 55/100|
|                       | Yingxiu-Duijiangyan (YX-DJY)             | 2/6       | 5/14      | 21/60     | 6/17      | 1/3       | 35/100|
| S301                  | Jiuzhaigou-Gansuji (JZG-GSJ)             | 25/87     | 3/10      | 1/3       | 0/0       | 0/0       | 29/100|
| S302                  | Zhongxiangkou-Langhekou (ZXK-LHK)        | 2/18      | 1/9       | 8/73      | 0/0       | 0/0       | 11/100|
|                       | Beichuan-Maokian (BC-MX)                 | 1/2       | 6/13      | 9/18      | 8/17      | 24/50     | 48/100|
|                       | Jiangyou-Beichuan (JY-BJ)                | 2/9       | 2/9       | 5/23      | 9/41      | 4/18      | 22/100|
| S303                  | Yingxiu-Wolong (YX-WL)                   | 3/16      | 4/21      | 4/21      | 2/10      | 6/32      | 19/100|
|                       | Rilong-Danba (RL-DB)                     | 7/47      | 3/20      | 5/33      | 0/0       | 0/0       | 15/100|
| S306                  | Hanyuan-Baixionggou (HY-BXG)             | 7/44      | 7/44      | 2/12      | 0/0       | 0/0       | 16/100|
| S309                  | Mianxian-Lvyang (MX-LY)                  | 25/60     | 17/40     | 0/0       | 0/0       | 0/0       | 42/100|
| G317                  | Wenchuan-Markang (WC-MRK)                | 40/87     | 2/4       | 4/9       | 0/0       | 0/0       | 46/100|
| G318                  | Yaan-Rlangschan (YA-RLS)                 | 31/36     | 47/54     | 9/10      | 0/0       | 0/0       | 87/100|
|                       | Rlangsshan-Kangding (RLS-KD)             | 17/63     | 10/37     | 0/0       | 0/0       | 0/0       | 27/100|
| Total                 |                                          | 841/40    | 892/42    | 279/13    | 70/3      | 52/2      | 2134/100|