Performance-based Rapid Evaluation Method for Post-earthquake Traffic Capacity of Bridge System

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Abstract. As the key node of highway transportation line, bridges are easy to be damaged under earthquake. When bridge earthquake damage occurs, traffic will often be interrupted, resulting in traffic network paralysis in disaster areas, seriously affecting the development of post-earthquake rescue work, thereby further aggravating the loss of personnel and property. In this paper, a performance-based method for evaluating the post-earthquake capacity of bridge system is proposed, and the post-earthquake operational status of the bridge system is evaluated. The results show that the performance-based assessment of bridge capacity after earthquake is of great value in evaluating the operation status of bridge system and making operational management decisions. Based on the fragility analysis of bridge components, the I-PCM method can be used to quickly establish the fragility curve of bridge system; meanwhile, combined with the performance-based evaluation model of seismic damage bridge capacity, the rapid evaluation of bridge capacity after earthquake is completed.

1. Introduction
China is around two major seismic zones, where seismic activities are frequent and strong, causing huge casualties and property losses to the society. When an earthquake strikes, the road transportation system will be damaged in different forms and degrees. These damage states will cause the interruption of transportation lines in the disaster area, trigger secondary disasters, and bring unpredictable impact on the development of subsequent earthquake relief work. Studies have shown that the "golden 72 hours" after the earthquake occurs, during this period of time, the probability of survival of people in the disaster area is high, but as time goes by, the probability of people's survival is getting lower and lower. For example, the 1995 Hanshin 7.3 earthquake in Japan caused the interruption of urban road traffic, and rescue workers could not quickly reach the severely affected area, causing the disaster area personnel to miss the best rescue opportunity[1]. In the 2008 Wenchuan earthquake in China, although the rescue speed is rare in the world, the rescue work was still delayed due to the destruction of roads and bridges, and secondary disasters occurred frequently.

Because of its structural characteristics, the bridge structure often becomes the weakest link in the seismic performance of highway transportation lines. Once the bridge structure is damaged, it is difficult to restore its function in a short time, which leads to the interruption of the entire rescue line. Therefore, it is of great significance to evaluate the capacity of bridge structures after the earthquake.

Scholars at home and abroad have conducted relevant researches on the capacity of bridge systems after earthquakes. The United States built the CATS system in the 1970s to evaluate the traffic
capacity of the highway system after an earthquake[2]; Japan evaluates the bearing capacity and traffic capacity of bridges from two aspects: early assessment and on-site assessment[3]; Lan, R Q et al.[2] proposed an assessment method for the damage degree and capacity of a single bridge structure under earthquake action; Duan, M Z et al.[4] based on the existing bridge seismic damage data. The model for evaluating the capacity of roads after the earthquake was revised, and the study showed that the prediction results of the new evaluation model were more accurate; Zhang, J H et al.[5] studied the theoretical model of the capacity of bridges after the earthquake, and verified them through calculation examples. The validity of the theoretical model; Ge, S J et al.[10] used the drift rate of the bridge pier and the relative deformation of the support as damage indicators, and quantified the damage indicators.

At present, most of the literature evaluates the capacity of earthquake-damaged bridge systems based on bridge detection technology or theoretical analysis models. Performance-based methods for assessing the capacity of bridge systems after earthquakes are often based on the bridge component level, or are limited to theoretical model research. As we all know, bridge systems are more susceptible to damage than any single component under the action of earthquakes. At present, there are relatively few studies on related aspects.

This paper proposes a performance-based method for evaluating the capacity of a bridge system after an earthquake. Taking a small and medium-span continuous beam bridge as an example, considering the uncertainty of ground motion input, the finite element program OpenSees is used to establish a nonlinear time history analysis model. The vulnerability analysis of bridge piers and bearing components is carried out; then the improved edge product method is used to analyze the vulnerability of the bridge system; finally, the evaluation model is combined to realize the rapid evaluation of the capacity of the bridge system after the earthquake.

2. Evaluation Method for Post-earthquake Traffic Capacity of Bridge

2.1. Analysis Method of Bridge Structure Vulnerability
The essence of performance-based bridge structure vulnerability analysis method is to apply structural performance seismic design theory to vulnerability analysis method. Vulnerability analysis refers to the probability that the structure will reach or exceed the established limit state under the action of a given earthquake intensity $IM$. It can be expressed by the following formula

$$P_r = P[EDP \geq S_c | IM]$$

In the formula, $EDP$ is the structural requirement; $S_c$ is the structural capability. As a part of the full-probability decision-making framework, seismic vulnerability analysis can provide a basis for seismic design, reinforcement and evaluation. At present, the theoretical analysis method, that is, the numerical analysis method, is often used in engineering. This paper adopts the theoretical vulnerability analysis method based on nonlinear dynamic analysis.

2.2. Analysis Method of Bridge System Vulnerability
At present, scholars at home and abroad have carried out a lot of research work on the vulnerability analysis of bridge structures. These research results basically stay at the level of bridge components[5-7]. However, as a large-scale structure, bridges cannot be counted. The number components form a system according to a certain logical relationship. Studies have shown that[8,11], as a system, a bridge is more likely to be damaged in an earthquake than any single component. If the correlation between components is not considered, the failure probability of the bridge system will be underestimated. Therefore, the assessment of bridge capacity after the earthquake should be based on the results of the vulnerability analysis of the bridge system.

In fact, the logical relationship between the failure modes of the various components in the bridge system is very complicated. It is almost impossible to accurately obtain the failure probability of the system. Therefore, in the analysis of bridge vulnerability, the common practice is to simplify it into a series model. That is, if one component in the bridge system fails, the entire system is considered to
have failed. The advantage of doing so is that it can conservatively estimate the failure probability of the bridge system and make the analysis result safer. Then for the series system, the failure probability \( P_{\text{sys}} \) of the bridge system can be expressed by the following formula.

\[
P_{\text{sys}} = 1 - \Phi(\beta, \rho) = 1 - \int_{-\infty}^{\beta} \cdots \int_{-\infty}^{\beta} \frac{1}{(2\pi)^{m/2}} \exp\left(-\frac{1}{2} x'^T \Sigma^{-1} x\right) dx_1 dx_2 \cdots dx_n
\]

(2)

In the formula, \( \Phi(\beta, \rho) \) is the multivariate normal cumulative distribution function; \( \beta \) is the reliability index corresponding to the \( i \) th component; \( m \) is the failure mode number; \( \rho = \left[ \rho_{ij} \right]_{m \times m} \) is the failure mode correlation coefficient matrix; \( X \) is the \( m \)-dimensional standard normal random vector.

From equation (2), it can be seen that the core of the solution to the failure probability of a structural system is the solution to \( \Phi(\beta, \rho) \). At present, there are numerical integration method, boundary method, and approximation method for solving \( \Phi(\beta, \rho) \). The numerical integration method has the most accurate calculation results, but the calculation process is cumbersome and the calculation efficiency is relatively low; the calculation principle of the boundary method is simple, but it is limited to give a wider failure probability range[13]; in order to overcome the above two calculation methods For the shortcomings, Yuan and Pandey[12] proposed an improved version of the conditional edge product method, that is, the I-PCM method. The calculation principle is as follows:

\[
\Phi(\beta, \rho) = \prod_{i=1}^{m} \Phi(\beta_{m(i-1)})
\]

(3)

\[
\approx \Phi(\beta_{m(m-1)}) \times \Phi(\beta_{m(m-2)}) \times \cdots \times \Phi(\beta_{m2}) \times \Phi(\beta_{1})
\]

In the formula, \( \beta_{ijkl} \) is the conditional normal quantile, which shows that its calculation is essentially a complex multi-dimensional integration process. Yuan and Pandey[12] proposed a simplified expression:

\[
\beta_{ijkl} = \Phi^{-1}\left[1 - \Phi_{\beta_{ijkl}}\right] = \Phi^{-1}\left[-\beta_{ijkl} - \beta_{ijkl} \rho_{ijkl}\right]
\]

(4)

\[
\Phi_{\beta_{ijkl}} \approx \Phi\left(c_{ijkl}\right)
\]

(5)

\[
c_{ijkl} = -\beta_{ijkl} + \rho_{ijkl} \rho_{ijkl} D_{ijkl} I_{ijkl} / \Phi\left(c_{ijkl}\right)
\]

(6)

\[
D_{ijkl} = \phi\left(c_{ijkl}\right) / \Phi\left(c_{ijkl}\right)
\]

(7)

(8)

In the formula: \( k = 1, \ldots, m - 1; \quad i, j = k + 1, \ldots, m \), formula (4) ~ formula (8) is the calculation process of the improved conditional edge product method (I-PCM method). According to the calculation principle of the I-PCM method, we only need to know the correlation coefficient \( \rho_{(m \times m)} \) between the different failure modes of the structure and the reliability index \( \beta_{ijkl} \) between the different components, and then the failure probability of the structural system can be calculated using the I-PCM method.

2.3. Performance-based Evaluation Method For Post-earthquake Traffic Capacity of Bridge System

In performance-based seismic design theory, structural damage is usually divided into five levels: namely no damage, slight damage, medium damage, severe damage, and complete damage. Literature [2] gives the traffic conditions under these five damage states based on the statistical results of previous bridge earthquake damages, as shown in Table 1.
Table 1. Weight value of bridge system capacity.

| Damaged state | No damage | Slight damage | Moderate damage | Severe damage | Completely damaged |
|---------------|-----------|---------------|----------------|--------------|-------------------|
| Traffic Capacity | 0.85 $< TA \leq 1.0$ | 0.75 $< TA \leq 0.85$ | 0.5 $< TA \leq 0.75$ | 0.3 $< TA \leq 0.5$ | 0 $< TA \leq 0.3$ |
| Weights $K_i$ | 1 | 0.8 | 0.65 | 0.3 | 0 |

The capacity model of the bridge after the earthquake can be calculated by the following formula:

$$TA = \sum P_i \times K_i$$  \hspace{1cm} (9)

In the formula, $TA$ is the capacity index of the bridge system after the earthquake; $P_i$ is the percentage of the bridge system under the five damage states; and $K_i$ is the weight value of each damage state in Table 1.

For $P_i$, it can be calculated by the following formula:

$$\begin{align*}
P_0 &= 1 - P_{f_i} \left(E_{1|i|m}\right) \\
P_1 &= P_{f_i} \left(E_{1|i|m}\right) - P_{f_i} \left(E_{2|i|m}\right) \\
P_2 &= P_{f_i} \left(E_{2|i|m}\right) - P_{f_i} \left(E_{3|i|m}\right) \\
P_3 &= P_{f_i} \left(E_{3|i|m}\right) - P_{f_i} \left(E_{4|i|m}\right) \\
P_4 &= P_{f_i} \left(E_{4|i|m}\right)
\end{align*}$$  \hspace{1cm} (10)

In the formula, $P_0, P_1, P_2, P_3, P_4$ respectively represent the percentage of the structural system under the five states; $E_1, E_2, E_3, E_4$ and $P_{f_1}, P_{f_2}, P_{f_3}, P_{f_4}$ respectively represent the slight damage, moderate damage, severe damage, complete damage event and the corresponding system failure probability in the vulnerability analysis.

Finally, the capacity of the bridge system after the earthquake is evaluated according to the $TA$ value. The evaluation results are shown in Table 2.

Table 2. Performance-based Bridge System Capacity Judgment

| Traffic Capacity | Unblocked | Restrict | Ban |
|------------------|-----------|----------|-----|
| Traffic volume   | 100%      | 50%      | 0   |

3. Example bridge analysis model and ground motion input

3.1 Finite element model establishment

This paper takes a common domestic small and medium span continuous beam bridge as an example, with a span layout of 3×30m. The upper structure uses C50 concrete T-beams, composed of 4 T-beams, and the bridge deck is 8m wide. The lower structure uses C40 concrete. The pier adopts a double-column pier with a diameter of 1.5m. The reinforcement adopts HRB335 steel, the longitudinal reinforcement ratio is 0.8%, and the hoop ratio is 0.4%. Piers 1# and 4# adopt PTFE slide bearings, and piers 2# and 3# adopt plate rubber bearings. The type of site where the bridge is located in the calculation example is Type II.

Based on the OpenSees analysis platform, this paper establishes an example bridge nonlinear dynamic analysis model. The main girder is simulated by elastic beam elements, and the structural self-weight and the second-stage paving and other loads are uniformly applied to the beam elements in
the form of additional loads; the bridge piers are designed according to ductile members, so elastoplastic fiber elements are used for simulation; the constitutive relationship between concrete and steel bars is adopted Concrete 01 and Steel 02 materials; the support is simulated by zero length element in OpenSees. Because of the good address conditions of the bridge in the calculation example, in order to simplify the calculation, the pile-soil effect is not considered. The bridge layout and mechanical model are shown in Figure 1.

3.2 Earthquake input
In this paper, 50 seismic waves matching the bridge site type of the example are selected from the PEER strong earthquake database in the United States. The epicentral distance of these seismic waves is greater than 20km and the magnitude is 6.0 to 7.0. The average response spectrum and the mean ± standard deviation of the 50 selected seismic waves are shown in Figure 2 when the damping ratio $\zeta=5\%$. According to the existing research results, it can characterize a variety of ground motion parameters. Based on the research results of Padgett et al.\cite{14} on the efficiency and applicability of ground motion parameters, the peak acceleration (PGA) is selected as the example bridge earthquake. At the same time, this paper only studies the structural response of the example bridge under the action of longitudinal seismic waves.

4. Vulnerability analysis of bridge system
4.1 Component damage index
A large number of bridge earthquake damage investigation reports pointed out that components such as bearings, piers, etc. are extremely vulnerable to damage during earthquakes, resulting in reduced or
even loss of bridge capacity. Therefore, this paper selects bridge piers, plate rubber bearings, and PTFE slide bearings as the object of component vulnerability analysis. When analyzing the vulnerability of bridge structures, it is necessary to quantify different types of structural damage indicators based on performance levels.

There have been a lot of studies to formulate structural damage indicators and corresponding limit states based on the damage state or the loss of bearing capacity. Structural damage indicators usually use curvature ductility, displacement ductility or relative displacement to quantify structural damage. In this paper, combined with the research results of related literatures [8,10,15], the damage indicators of key bridge components of the calculation examples are defined from different aspects, as shown in Table 3.

Table 3. Weight value of bridge system capacity.

| Component name          | Damage index                     | Slight damage | Moderate damage | Severe damage | Completely damage | References |
|-------------------------|----------------------------------|---------------|-----------------|---------------|-------------------|------------|
| Pier                    | Curvature ductility ratio(μp)    | 1<μp≤2        | 2<μp≤4          | 4<μp≤7       | μp>7              | [9],[10]   |
| Plate rubber bearing    | Displacement ductility ratio(μd) | 1<μd≤1.5      | 1.5<μd≤2.0      | 2.0<μd≤2.5   | μd>2.5            | [8]        |
| PTFE slide bearing      | Displacement (Δ,m)               | 0.09<Δ≤0.15   | 0.15<Δ≤0.2      | 0.2<Δ≤0.3    | Δ>0.3             | [8]        |

4.2 System vulnerability analysis
In the seismic vulnerability analysis of bridges, it is often assumed that the structural bearing capacity and structural requirements follow a logarithmic normal distribution, then the formula (1) can be rewritten into the standard normal distribution form:

$$P_j = \Phi \left( \frac{\ln(\bar{EDP}) - \ln(\bar{S}_c)}{\left(\beta_{EDP}^2 + \beta_C^2\right)^{1/2}} \right)$$  \hspace{1cm} (11)

In the formula, $\bar{EDP}$ and $\beta_{EDP}$ are the mean and logarithmic standard deviation of structural demand; $\bar{S}_c$ and $\beta_C$ are the mean and logarithmic standard deviation of structural carrying capacity. According to HAZU99, when $IM$ use PGA, $\left(\beta_{EDP}^2 + \beta_C^2\right)^{1/2} = 0.5$

According to the research results of Cornell et al.[11], $\bar{EDP}$ and $IM$ have the following relationship:

$$\ln(\bar{EDP}) = a \ln IM + b$$  \hspace{1cm} (12)

In the formula, 2 is a constant, which can be obtained by regression of the least square method. Then according to formula (11) and formula (12), the vulnerability curve of the bridge member of the example is calculated, and then the vulnerability curve of the bridge system of the example is calculated using the I-PCM method, as shown in Figure 3.
It can be seen from Figure 3 that with the increase of PGA, for various components in the bridge system, the failure overtaking probability shows an increasing trend under the four damage states; under the earthquake action, the bearing structure is relatively more susceptible to damage, especially in the two states of severe damage and complete failure; at the same time, compared with other members, the PTFE sliding bearing has the highest probability of failure under each damage state, and it has become an example bridge The components in the system that are most vulnerable to earthquake damage; compared with the component vulnerability curve, the failure probability of the bridge system is greater than the failure probability of any single component in the system at the same PGA level. Therefore, a single component vulnerability curve is used. Assessing the vulnerability of the bridge structure results in an overestimation of the seismic capacity of the structure.

5. Performance-based Evaluation For Post-earthquake Traffic Capacity of Bridge

Based on the vulnerability curve of the bridge system formed by the I-PCM method, this paper evaluates the capacity of the bridge after the earthquake. According to formula (10), the probability of the bridge system being in five damage states under a given PGA is calculated, and the results are shown in Table 4.

| PGA | Damaged state | No damage | Slight damage | Moderate damage | Severe damage | Completely damage |
|-----|---------------|-----------|---------------|-----------------|---------------|-------------------|
| 0   | 100%          | 0         | 0             | 0               | 0             | 0                 |
| 0.1 | 89.35%        | 9.48%     | 0.95%         | 0.21%           | 0.01%         |                   |

Figure 3. Vulnerability curve of bridge component and system
According to formula (9) and Table 1, the capacity index $TA$ value of the bridge system after the earthquake is calculated under different PGA levels. At the same time, the operating status of the bridge in the calculation example is determined according to Table 2, and the analysis results are shown in Table 5.

| PGA | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|---|
| $TA$ | 0.98 | 0.77 | 0.51 | 0.31 | 0.17 | 0.09 | 0.05 | 0.03 | 0.01 | 0.01 |

Traffic Capacity

| Unblocked | Unblocked | Restrict | Ban | Ban | Ban | Ban | Ban | Ban |

It can be seen from Table 5 that when PGA<0.3g, the operating state of the bridge in the example is not affected by the earthquake, and there is no need to control the traffic flow; when 0.2g<PGA<0.4g, the bridge traffic flow needs to be limited by 50%; When PGA ≥ 0.4g, measures such as closed traffic and timely inspection, repair and reinforcement should be adopted for the bridge in the example.

6. Conclusion
This paper proposes a performance-based method for evaluating the capacity of a bridge system after an earthquake. A three-span prestressed continuous T-beam bridge is analyzed and the following conclusions are obtained:

(1) Performance-based Rapid Evaluation Method for Post-earthquake Traffic Capacity of Bridge System is an important part of performance-based structural seismic analysis. It has very important application value for assessing the operating status of the bridge system after the earthquake and making operational management decisions;

(2) As a complex structural system, the bridge is more susceptible to damage than any component in the earthquake. It is not appropriate to use the result of a single component vulnerability analysis to evaluate the capacity of the bridge after the earthquake; when the bridge has different components If the reliability index and the correlation coefficient between the components are known under a given ground motion intensity, the I-PCM method can be used to quickly establish the vulnerability curve of the bridge system;

(3) Based on the example bridge system vulnerability curve, combined with the earthquake-damaged bridge capacity assessment model, this paper realizes the rapid assessment of the bridge capacity after the earthquake, that is, the bridge operating status under a certain level of earthquake intensity is given, and its research results It can provide a theoretical reference for managers' decision-making.
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