Research on seismic fragility analysis of regular bridges based on response spectrum analysis method

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Abstract. In this paper, the incremental dynamic analysis (IDA) of a real bridge is carried out by using the nonlinear time-history analysis method and the response spectrum analysis method respectively, and the results of structural response under different earthquake intensity are obtained. Ductility coefficient is used for damage index, and the damage probability of the structure in different damage state is obtained by using logarithmic demand-capacity ratio, and then the seismic fragility curves of the structure are established. To improve the precision of fragility curve of major damage state and failure state by modifying the fitting function is also studied. The results show that the simple linear elastic method is reliable for calculating the seismic response of regular bridges. The seismic response calculated by the response spectrum analysis method could be used as the demand for establishing the fragility curves of regular bridge.

1.Introduction
Seismic fragility analysis is considered as an effective analysis method in the structure's seismic performance evaluation. At present, there are two types of the fragility analysis methods: empirical analysis and theoretical analysis. Empirical analysis method is to calculate the mean value and standard deviation of structural earthquake demand by statistical analysis of existing earthquake damage records. However, the empirical fragility analysis method is not feasible due to the limitation of seismic damage records. Many scholars began to use the theoretical analysis method, according to the calculation results to simulate the structural earthquake damage. This method has high controllability and strong applicability. It has more advantages than empirical analysis method, especially in the area which lacks earthquake damage records, and that is the reason why it is favoured by researchers. The seismic fragility curves of structures in theoretical fragility analysis is generally expressed by the two-parameter lognormal cumulative distribution function:

\[ P(D \geq C | IM = x) = \Phi\left(\frac{\ln(x/\theta)}{\beta}\right) \]

(1)

The above formula represents the demand exceeds the capacity probability under the earthquake with strength of IM=x; \( \Phi() \) is the standard normal cumulative distribution function; \( \theta \) is the mean value of the fragility function, the larger the value \( \theta \) is, the stronger the seismic resistance of the structure will be; \( \beta \) is the standard deviation of the fragility function, which reflects the uncertainty of the fragility function. Therefore, solving the response demand of the structure under the earthquake is significant to establish an accurate fragility curve. In previous studies, some scholars took response spectrum analysis method to calculate earthquake demand, and others undertook nonlinear time history analysis method to calculate earthquake demand. Hwang and Jernigan\textsuperscript{[1]} used elastic response spectrum analysis to
calculate the seismic demand of bridges in Memphis; Ouyang et al. [2] used elastic response spectrum analysis method to analyse the seismic fragility of highway bridges in Kentucky; Mackie and Stojadinovic [3] based on a seismic wave database containing 100 waves, it takes the earthquake distance and magnitude into account, and a 2-span girder bridge was taken as an example to establish a finite element model then carry out nonlinear time history analysis directly; Zhang et al. [4] selected 100 seismic waves and used nonlinear time-history analysis method to analyse the seismic fragility of piers of regular bridge; Wu et al. [5] used IDA method to select 15 seismic waves to analyse the fragility of the bridges with high piers and long spans.

Although the calculation results of nonlinear time history analysis method are accurate, the workload is huge and process of calculation is time-consuming when calculating the simple structure like regular bridge; While, the response spectrum analysis method is simpler than the nonlinear time history analysis method, and it is also the basic analysis method widely used in the specifications for seismic design of bridges in various countries for the regular bridge seismic design. However, the seismic fragility analysis based on response spectrum analysis method is mainly used to took the method of demand-capacity ratio coefficient, in which the capacity was determined as described in the Seismic Retrofitting Manual for Highway Bridges, and the capacity demand ratio also consistent with those indicated in the Seismic Retrofitting Manual for Highway Bridges, but this damage index is a general evaluation for one type of bridge, lacking of differentiation for specific bridges. In addition, in previous studies, peak ground acceleration (PGA) is mostly used as seismic intensity parameter in response spectrum-based fragility analysis. Through calculation, it has been found that when PGA has been taken as the intensity parameter, the structural response under the same earthquake intensity has a larger discreteness. However, when spectral acceleration at the fundamental period of a bridge (Sa) has been taken as the intensity parameter, the discreteness is smaller. Therefore, this paper proposes to take response spectrum analysis method to analyse the demand of regular bridges with spectral acceleration at the fundamental period of a bridge (Sa) as the ground motion intensity parameter. In addition, the ductility coefficient is used as the damage index, and the seismic fragility curve is established and calibration against the results of time history analysis method.

2. Seismic Demand and Fragility Curve Calculation Method

2.1. Requirement calculation method

RITZ method is taking for modal analysis of the structure, the quality participation coefficients of longitudinal and transverse direction considered are above 90%.

In response spectrum analysis method, the design response spectrum is obtained according to the Specification for Seismic Design of Highway Bridges (JTC/T2231-01-2020), multimode response spectrum method was adopt to calculate the seismic effect with CQC method to calculate the seismic effect. When the structure is in the elastic stage, the flexural rigidity of the structure is calculated according to the full cross section, when the structure enters the plastic stage, the equivalent linear elastic analysis method is adopted to calculate. At this time, the reduction coefficient of equivalent stiffness is considered.

\[
E \times I = \frac{M}{\varphi}
\]  

(2)

Where, \(E\) is the elastic modulus of the pier, \(I\) is the flexural moment of effective section of the pier, \(M\) is the equivalent yield moment, and \(\varphi\) is the equivalent yield curvature. The axial force-moment-curvature curve of the pier bottom section was used to calculate the equivalent yield curvature and equivalent yield moment M of the section according to the principle of equal displacement and equal energy.

In the time history analysis method, the damping of the structure is determined according to the Rayleigh damping, the direct integral method is used to calculate the seismic response of the structure. When the structure enters the inelastic state, the fibre model can not only accurately simulate the
mechanical properties of the bending member, but also consider the local damage state of the fibre in the section, so the fibre element model is adopted to reflect the elastic-plastic properties of the structure.

2.2. Fragility curve establishing method

At present, there are four methods to establish the theoretical fragility curves: The cloud method considering the uncertainty of capacity-demand-ground motion simultaneously[6]; Numerical simulation method based on calculating the frequency beyond the damage threshold values; Maximum Likelihood Estimate method[7]; Logarithmic demand-capacity ratio method[8]. In this paper, the spectral acceleration at the fundamental period of a bridge is selected as the ground motion intensity parameter, and the logarithmic demand-capacity ratio method combined with incremental dynamic analysis (IDA) is adopted to establish the seismic fragility curve of the structure. Assuming that the fragility curve conforms to the lognormal cumulative distribution; the seismic fragility function can be expressed as:

\[ P_f = P [\frac{S_d}{S_c} \geq 1] = \Phi \left( \frac{\lambda}{\sigma} \right) \]  \hspace{1cm} (3)

Where, \( S_d \) represents structural seismic demand; \( S_c \) represents seismic capability; \( \lambda \) and \( \sigma \) are the mean and standard deviation of \( \ln(S_d/S_c) \) respectively. Pan et al. [8] proved that the quadratic regression analysis was more accurate in predicting the seismic fragility of bridges through research:

\[ \lambda = a \ln(IM)^2 + b \ln(IM) + C \]  \hspace{1cm} (4)
\[ \sigma = \sqrt{\frac{S_r}{N \times (N - 2)}} \]  \hspace{1cm} (5)
\[ S_r = \sum_{i=1}^{N} (y_i - \lambda_i)^2 \]  \hspace{1cm} (6)

The regression mean and logarithmic standard deviation were obtained by using the least square method according to formula (4) and (5) respectively, and then the probability of different damage states was calculated by using formula (3), and the seismic fragility curve of the structure was established.

3. Selection of Seismic Waves

Considering the particularity of near-field earthquakes, it is recommended that near-field seismic records be processed separately from the seismic database, otherwise the dispersion of seismic responses may be too wide. Therefore, the epicentre distance of the seismic records selected in this paper is far than 20km. In addition, different seismic waves are uncertain due to the difference of the mechanism of earthquake disaster, the type of engineering site and the spectral characteristics of seismic waves themselves. So, many seismic waves are needed to simulate the uncertainty in seismic fragility analysis. Existing studies on IDA method have shown that the results can reach a certain accuracy when the number of records reaches 10-20. The response spectrum graphs of 20 seismic waves selected from PEER database in this paper are shown in Figure.1.

![Figure.1 Response spectrum acceleration of seismic wave](image-url)
4. Bridge model and Damage index

4.1. Bridge Model
Midas Civilis used in this paper to build the full bridge model of the real bridge. As shown in Figure 2. This bridge is a four-span continuous beam bridge, each span is 18 meters. Superstructure, the main beam is made of C40 concrete, single box single chamber section, the cross-section area is 2.7m². The vertical bending stiffness is 0.52m⁴, The lateral bending stiffness is 11.95m⁴. Substructure, the pier is 8 m high, 1.5 m diameter circular cross section, concrete grade is C30, longitudinal reinforcements are 25 Φ32, concrete cover thickness is 6cm. The stirrup of pier column adopts spiral stirrup with diameter of 16mm and spacing of 10cm. The pier top bearing is 500×650×50 laminated rubber support. According to the Specification for Seismic Design of Highway Bridges (JTC/T2231-01-2020), this bridge is a regular bridge. The fibre division of pier section is shown in Figure 3. Axial force-Moment-Curvature analysis is performed with XTRACT on the section of pier, the M-φ curve is shown in Figure 4.

4.2. The Damage Index
The damage of bridge superstructure is rare according to the previous seismic damage records, so the damage of bridge superstructure in earthquake which is not discussed in this paper. In addition, according to the Chinese seismic specification, the foundation belongs to the capacity protection member, which is required to remain in the elastic state during the design. Therefore, the damage of the bridge foundation during the earthquake will not be discussed herein. According to the theory of bridge seismic system, the regular bridge selected herein adopts the ductile seismic design of pier column, and the structural damage will mainly occur on the pier bottom. It can be seen from the calculation results that the stress and deformation of the support will be significantly reduced when the pier enters plasticity, and only seismic fragility analysis of the bridge pier should be carried out when the support is designed as a capacity protection component. In this paper, the displacement ductility ratio is used as the damage index of pier, It is determined by referring to the research production of Hwang[9], which is also the
most commonly used as damage index determination method for bridge seismic fragility analysis at present, the results of the bridge’s damage index are shown in Table 1.

| Damage state   | Damage index |
|----------------|--------------|
| No damage      | $\mu \leq 1$ |

Table 1. Pier damage index (Continued)

| Damage state   | Damage index         |
|----------------|----------------------|
| Minor damage   | $1 < \mu_d \leq 1.37$ |
| Moderate damage| $1.37 < \mu_d \leq 3.86$ |
| Major damage   | $3.86 < \mu_d \leq 6.86$ |
| Failure        | $\mu_d > 6.86$ |

5. Seismic demand and fragility analysis

5.1. Seismic Demand

The incremental dynamic analysis of the 20 seismic waves selected above was carried out using time history analysis method and response spectrum analysis method respectively to obtain the seismic demand of the bridge, extract the mean value of displacement results of pier top under each earthquake intensity. According to the damage index defended above, the incremental dynamic curves of logarithmic demand-capacity ratio in different damage states can be obtained by using the least square nonlinear fitting method, as shown in Figure 5~Figure 8. The horizontal axis stands for the log value of ground motion intensity parameters, and the vertical axis stands for the logarithmic demand-capacity ratio value. The fitting curves obtained by response spectrum analysis in each stage of damage are below the time-history analysis results, and as the earthquake intensity increases, the distance between the two curves is slowly increases, this is due to the fact that the simplified response spectrum analysis method cannot accurately simulate the change of stiffness after the structure enters the nonlinear state. In the acceleration range selected herein, the area difference enclosed by the fitting curves obtained by reaction spectrum analysis method and time history analysis method is 14.93%, which can be considered as a sufficient approximation.

![Figure 5 Minor damage IDA curve](image1)

![Figure 6 Moderate damage IDA curve](image2)
5.2 Fragility Curve

After obtaining the demand-capacity ratio curves of the pier, the damage probability of the pier under different earthquake intensity levels is calculated according to the introduced above. When calculating the probability of damage, the standard deviation of the result of time history analysis can be calculated by the formula (5) given above; However, in response spectrum analysis, the result of the seismic response under the same earthquake intensity is a certain value, so it is impossible to obtain standard deviation by formula (5). In order to facilitate the comparison between the two methods, the standard deviation of the two methods is unified with the empirical value 0.4 given in HAZUS99[10]. Then, according to formula (3), the fragility curves of each damage stage obtained by using time history analysis method and response spectrum analysis method are established. Figure.9~ Figure.12. In minor damage and moderate damage state, the fragility curves obtained by reaction spectrum analysis method is approximate to obtained by time history analysis method, and the difference is not more than 20%. However, under the condition of major damage and failure state, the two curves differ greatly, this is because the effective stiffness of the pier column section is determined according to the equivalent M-φ curve when the reaction spectrum analysis is used to calculate the pier top displacement, the higher plastic degree of the section, the greater the difference will be. When the displacement ductility coefficient is between 1 and 2, the accuracy of the fragility curves calculated by the reaction spectrum analysis method are acceptable; When the displacement ductility coefficient as the capability index exceeds 2, the damage probability obtained by response spectrum analysis is too low to reflect the major damage and completely damage probability of the structure.

IDA fitting function of logarithmic demand-capacity ratio could be found that in the fitting function (λ) of two calculation methods results, at any kind of damage state the difference (Δ) of constant term is a constant value. In order to improve the accuracy of seismic fragility curves obtained by response spectrum analysis in major damage and failure states, suppose that the constant term of the fitting function obtained by response spectrum analysis is equal to that obtained by time history analysis, the modified fitting function is obtained $\lambda n = \lambda - \Delta$, then the damage probability of the structure in each damage state is calculated by using the modified logarithmic demand-capacity ratio IDA fitting function. The modified fragility curves are shown in Figure.13~ Figure.16. After modification of the fitting curve, the area difference enclosed by the two logarithmic demand-capacity ratio IDA curves was reduced from 14.9% to 14.4%, and the response spectrum analysis fragility curves obtained after modification was generally closer to the time-history analysis fragility curve, especially in the state of major damage and failure state.
6. Conclusion

In this paper, an incremental dynamic analysis is carried out for a regular bridge by using time history analysis and response spectrum analysis, respectively. According to the calculated results of the two methods, the corresponding Logarithmic demand-capacity ratio IDA curves is obtained, according to the fitting Logarithmic demand-capacity ratio IDA curves, the pier's fragility curves are established by taking the displacement ductility coefficient of pier top as the damage index. The following conclusions can be drawn:

By comparing the demand-capacity IDA curves calculated by response spectrum analysis and time history analysis with the Logarithmic demand-capacity ratio method, the overall difference between the two curves within the scope discussed in this paper is only 14.9%. Therefore, for regular bridges, it is feasible to use response spectrum analysis method in seismic fragility analysis with logarithmic demand-capacity ratio method;

According to the calculation, when the pier column produces plastic hinge, the stress and deformation of the bridge bearing will decrease, which is consistent with the concept of ductile seismic design. Therefore, for the regular bridge with ductility design, when the bearing is designed as the capacity...
protection member, that is, before the pier column enters the plasticity, the bearing has enough bearing capacity and will not be damaged. For this specific regular bridge, it merely discusses about the fragility of the piers.

Owing to the response spectrum analysis based on \(M-\varphi\) curve only with a stiffness reduction, when the displacement ductility coefficient is greater than a certain value, the displacement of the pier top results will not be a good approximation of nonlinear time history analysis results, which led to minor damage and moderate damage state fragility curve is more reliable, but large damage and completely damage state fragility curve have relatively bigger difference. Therefore, a method to modify the constant term of the fitting curve expression of reaction spectrum analysis is proposed. According to the comparison between those curves which are generated from the improved reaction spectrum analysis results and time history analysis results respectively, the difference between the two curves is reduced from 14.9\% to 14.4\%, and the calculated fragility curve is also closer to the fragility curve obtained through time history analysis.

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