Research on Seismic Vulnerability of Continuous Beam Bridges Based on Incremental Dynamic Analysis Method

Peizhi Wang^{1,*}

¹Civil Engineering, School of Highway Engineering, 710061 Xi'an, China

Abstract. The seismic vulnerability of highway continuous girder bridges is analyzed to provide theoretical basis for the study of multi-stage fortification and seismic design of such bridges. Based on the concept of performance seismic design, five performance levels of structures are determined, and the displacement ductility ratio of piers is taken as the performance quantitative index to calculate the damage limit values of bridges in different limit states. On this basis, IDA analysis method is used to calculate 20 subjects. Based on the reliability theory, logarithmic regression fitting analysis is carried out to obtain the seismic vulnerability curve. The theoretical vulnerability curve is indicated that the bridge has good comprehensive seismic performance. Under 0.3 g ground motion, the probability of minor damage, moderate damage and serious damage are 57.9%, 44.7% and 3.6% respectively. The comprehensive seismic performance of bridges and the probability of exceeding the damage status at all levels are reflected in the results, the guiding significance to analysis of the seismic performance of the entire traffic and the formulation of emergency rescue plans.

1 Introduction

Seismic vulnerability can usually be expressed by vulnerability curve [1]. And incremental dynamic analysis (IDA) is a parameter analysis method developed in recent years to evaluate the seismic performance of structures [2]. This method extends the single time history analysis to incremental time history analysis, which combines many advantages of static pushover analysis and non-linear time history analysis, so it is also called "dynamic pushover analysis". It is also called "dynamic pushover analysis" for multi-freedom structural systems and long-span bridge structures with high piers. There are many applications in seismic analysis.

In this passage, the damage boundaries of piers and columns in diverse degrees are given. The seismic response of the structure is obtained by finite element model combined with incremental dynamic analysis method, and the vulnerability curve is formed based on the traditional reliability theory. The failure mode and damage probability of this kind of bridge are discussed, which provides a theoretical basis for evaluating the seismic performance of this kind of bridge and predicting and preventing the seismic disaster of the bridge.

2 Vulnerability curve analysis method based on IDA

At present, there are two main methods to study the vulnerability curve at home and abroad: empirical vulnerability method and theoretical vulnerability method. The method of forming theoretical vulnerability curve is

divided into damage surpassing statistics based on numerical simulation and direct regression fitting method based on reliability [3]. Based on the second method, the seismic response of structure is obtained by incremental dynamic method. Combining with damage index of structure performance, the ductility index of seismic response is fitted by linear regression after logarization, and different structures are calculated. At last, the vulnerability curve is drawn. The formation process of seismic vulnerability curve is as follows.

(1) Several ground motion records are generated according to the standard response spectrum given in site safety report, and a reasonable ground motion intensity parameter is selected.

(2) Select several ground motion records and adjust each record to 0.1-1.0 g with a set of amplitude modulation coefficients. The increment can be 0.05 g or 0.1 G.

(3) According to the support arrangement of long-span continuous girder bridge, the dangerous section of the most disadvantageous pier and column is determined, and the damage limit is calculated by choosing reasonable quantitative index of seismic performance. Finally, the damage index of different damage degree of the structure is obtained.

(4) A series of non-linear time-history analysis of the finite element model is carried out in combination with the selected amplitude-modulated ground motion, and the seismic responses of the pier top displacement or the curvature of the pier bottom are obtained.

(5) Linear regression analysis is carried out after logarization of structural response obtained from non-linear time history analysis, and the linear regression

* Corresponding author: 2018121063@chd.edu.cn

equation of logarithm of structural ductility index and logarithm of ground motion parameters is obtained, as shown in equation (1).

Then, the transcendence probability of structures at different failure stages is calculated by equation (2) and equation (3), of which μ_d , μ_c obeys logarithmic normal distribution.

$$\ln(\mu) = a + b \ln(PGA) \quad (1)$$

$$P_f = P\left[\frac{\mu_d}{\mu_c} \geq 1\right] \quad (2)$$

$$P_f = \phi\left[\frac{\ln\left(\frac{\mu_d}{\mu_c}\right)}{\sqrt{B_c^2 + B_d^2}}\right] = \phi\left(\frac{a + b \ln(PGA) - \ln(\mu_c)}{\sqrt{B_c^2 + B_d^2}}\right) \quad (3)$$

In the formula, a and b refer to regression fitting coefficients respectively, and μ_d , μ_c refer to structural demand and structural capability respectively.

3 Definition and quantification of seismic performance level of structures

3.1 Definition of seismic performance level of structures

At present, in the authoritative theoretical framework of performance-based seismic design of structures at home and abroad, it is suggested that the basic seismic fortification principle should be extended. Five performance levels are proposed, i.e. full operation, basic operation, life safety and near collapse. In order to adapt to the current design method of limit state theory of highway bridge structures, document [4] suggests that performance-based seismic design of bridges should consider not only structural failure limit state and normal service limit state, but also limited damage limit state. The five seismic performance levels of highway bridges can be qualitatively described as non-damage, minor damage, moderate damage, severe damage and local failure or collapse, as shown in Table 1.

Table 1. Description of bridge seismic performance

Performance level	Damage description	Functional State Description
Standard I	No damage	Normal passage of vehicles
Standard II	Slight injury	Normal operation function can be restored by general renovation.
Standard III	Moderate injury	It can be restored to use after emergency repairs and resumed to normal operation

		after permanent repairs.
Standard IV	Serious injury	Temporary reinforcement can restore some operation functions
Standard V	Local failure or collapse	Partial collapse, loss of function, irreparable

3.2 Quantification of seismic performance level of structures

In performance-based seismic design of bridges, it is permissible for some structures to be damaged to varying degrees. Under this premise, traditional mechanical concepts cannot fully describe the performance level of bridge structures, so quantitative indexes of deformation, energy or other damage must be adopted. For long-span continuous girder bridges, the main girder maintains the elastic stage during the earthquake, the cover girder and the foundation. Foundation is usually designed according to capacity protection components, and pier column is the most vulnerable component, and the damage of pier column often directly leads to the loss of bridge function, so the seismic damage of bridge can be attributed to the seismic damage of pier. The displacement ductility ratio of pier column provided by Hwang is suggested as the quantitative index of seismic performance of bridge [5], which can be defined as

$$\mu = \frac{\Delta}{\Delta_{cy1}} \quad (4)$$

In the formula, Δ is the maximum displacement of pier top during earthquake, Δ_{cy1} is the displacement of pier top when the longitudinal tension steel bar at pier bottom reaches the yielding state for the first time.

4 Project cases

4.1 Project overview

This bridge is located in a province in southern China. Its superstructure is Cast-in-situ Continuous Box Girder with single box and single chamber structure. Its span combination is 55 m + 4 × 90 m + 55 m. The height of box girder and the thickness of bottom slab are designed by parabola twice. The pier is thin-walled box pier with half pier 6.5 m in width and 2.5 m in thickness. The lateral side of the bridge is designed with triangular outburst and C40 concrete. HRB400 steel bars are used for Pier longitudinal reinforcement and stirrups, and grade III steel bars with a diameter of 28 mm are used for longitudinal reinforcement, with an average spacing of 10 cm, and grade III steel bars with a diameter of 16 mm are used for stirrups with a spacing of 0.3 m. The bridge belongs to hilly and depression landform, the site type is medium-hard soil, and the site type is type II. The Cross section and distribution of reinforcement is shown in Figure 1.

And the bridge layout of Hanjiang river bridge is shown in Figure 2.

Fig. 1. Cross section and distribution of reinforcement

Fig. 2. Bridge layout of Hanjiang river bridge

4.2 Establishment of engineering model

In general, in the design of multi-span continuous beam bridge, the middle pier uses fixed support, while the side pier uses movable support, so the middle pier of this kind of bridge goes forward. The simplified model of bridge example is shown in Figure 3. OpenSees is used to establish the finite element model of the bridge. The pier adopts Nonlinear Beam-Column Elements and considers the P-Delta effect; the pier section adopts the fiber model, the concrete constitutive model adopts Concrete02 Mander model, and the concrete section is divided into protective layer concrete and core concrete, and the core concrete is considered the improvement of the compressive strength of stirrups. Steel02 model is used to define all material properties and then divide the fiber sections to assign corresponding material properties to different fibers. The middle pier and the upper structure are connected by fixed hinges, and the main beam action is simplified as the vertical mass load acting on the top of the main pier.

Fig. 3. Simplified model of bridge

4.3 Selection of ground motion

The effective duration of seismic wave should be 5-10 times of the basic period of the structure. According to the analysis of the dynamic characteristics of the structure, the basic period of the bridge is 5.34 s. In addition, a large number of studies have shown that 15-20 seismic waves can meet the accuracy requirements of incremental dynamic analysis. Therefore, 30 s artificial fitting of 20 seismic waves is finally selected.

4.4 Performance level and damage index

The displacement ductility ratio proposed by Hwang is used as the quantification index of pier damage, and the structural damage state is divided into five grades: no damage, slight damage, moderate damage, serious damage and complete damage. According to the curvature ductility index, the displacement ductility ratio of each failure state is calculated by the method of reference [5]. The ductility index of bottom section for pier is shown in Table 2 and the results are shown in Table 3.

Table 2. Ductility index of bottom section for pier

First yield curvature	Equivalent yield curvature	Curvature of concrete under compressive strain of 0.004
1.264×10^{-3}	1.494×10^{-3}	9.181×10^{-3}

Table 3. Calculated results of damage index

Failure state	Failure criterion
No damage	$u < 1$
Slight damage	$1 < u \leq 1.1820$
Moderate damage	$1.1820 < u \leq 2.7239$
Serious damage	$2.7239 < u \leq 5.7239$

4.5 Vulnerability Curve

Vulnerability curve refers to the probability curve of structural demand exceeding structural resistance under different ground motion intensities. Twenty horizontal seismic waves with a 50-year exceeding probability of 2.5 % are selected by the author, and the peak acceleration *PGA* is taken as the ground motion parameter. The incremental dynamic method is used to adjust 20 seismic waves to the ground motion records of *PGA* from 0.05 to 0.8 g. A total of 320 seismic waves are calculated by IDA time history analysis. The average displacement and displacement ductility ratio of pier top under 20 seismic waves with different earthquake intensity are shown in Table 4. When the structural capacity and structural demand under earthquake are described as lognormal distribution, the failure probability of bridge structures with different damage degrees is also lognormal

distribution. Linear regression analysis is carried out with logarithmic value of PGA as abscissa and logarithmic value of displacement ductility ratio of pier and column as longitudinal coordinate, and a linear regression function is obtained (Figure 4).

Table 4. Time history analysis results of IDA

PGA / g	Mean Relative Displacement of Pier Top / mm	Displacement ductility ratio
0.05	50.820	0.140 989
0.10	111.177	0.308 440
0.15	178.375	0.494 867
0.20	249.923	0.693 365
0.25	317.255	0.880 165
0.30	392.293	1.088 342
0.35	482.669	1.339 073
0.40	585.714	1.624 951
0.45	659.687	1.830 175
0.50	718.175	1.992 439
0.55	815.735	2.263 100
0.60	848.467	2.353 909
0.65	956.251	2.652 935
0.70	1 021.663	2.834 410
0.75	1 096.525	3.042 101
0.80	1 302.372	3.613182

It can be seen from Figure 4 that the scatter points are well surrounded by the straight line of the regression function, which shows that the regression function can better reflect the relationship between the structural response and the ground motion parameters. By substituting the regression function into equation (3), the exceeding probability function under damage state can be obtained as shown in equation (5)

$$Pr = \phi \left[\frac{\ln \left(\frac{\mu_d}{\mu_c} \right)}{\sqrt{\beta_c^2 + \beta_d^2}} \right] = \phi \left(\frac{1.4868 + 1.1517 \ln(PGA) - \ln(\mu_c)}{\sqrt{\beta_c^2 + \beta_d^2}} \right) \quad (5)$$

According to the empirical value provided by HAZUS99 (which has nothing to do with the structure type and damage state of the bridge), it should be taken as follows:

When PGA is an independent variable, $\sqrt{\beta_c^2 + \beta_d^2}$ is 0.5; the average bearing capacity of the structure is c , i.e. the damage limit value of each performance level; ϕ is a standard normal distribution function. Figure5 shows the seismic vulnerability curve of pier No. 12 as an example.

Fig. 4. Regression fitting curves

Fig. 5. Seismic vulnerability curves

As can be seen from the Figure 5, under 0.3 g ground motion, the probability of minor damage, moderate damage and serious damage are 57.9%, 44.7% and 3.6% respectively. When PGA is below 0.4 g, the growth rate of minor and moderate damage is very fast. It shows that in this stage, the development of minor and moderate damage of bridges is very rapid, and is very sensitive to the change of earthquake ground motion intensity. When PGA reaches 0.5 g, the exceedance probability of minor and moderate damage basically reaches 100%, indicating that when the peak ground acceleration reaches 0.5 g, the bridge has reached the intermediate damage standard. The serious damage state should occur when the PGA exceeds 0.2 g, and the complete damage state should occur when the PGA exceeds 0.4, and the growth rate of both is relatively flat. Under the same PGA , the exceeding probability of the complete damage is far less than the first

three damage probabilities, which shows that the bridge structure has good safety and is not easy to occur complete damage.

5 Conclusion

(1) Highway bridges, as the most important link in highway transportation network, should be guaranteed to play their role under earthquake disasters as far as possible. Considering safety, economy and applicability, the seismic performance of the normal service function is divided into five grades and described qualitatively and quantitatively.

(2) To evaluate the damage degree of structure by means of quantification, it is necessary to correspond the damage degree with the quantification index of failure criterion. It is a reasonable choice to use displacement ductility ratio as the quantification index.

(3) Seismic vulnerability curve can directly reflect the difference of seismic performance of bridges. According to the curve, it is easy to obtain the damage probability of bridges under a certain horizontal earthquake motion, which provides a basis for bridge prediction and prevention of earthquake disasters.

(4) For general highway continuous girder bridges, the probability of minor damage and moderate damage is far greater than that of serious damage. Management departments should pay attention to the daily monitoring and damage repair of highway continuous girder bridges.

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