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Unlabeled mode features of bridge structure sparse coding depth learning monitoring

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Abstract. In order to explore the effect of pile-soil interaction on the seismic vulnerability of continuous bridge of high-speed railway, this Paper takes a certain typical continuous bridge of high-speed railway as an example, and uses the IDA method (incremental dynamic analysis method) and the finite element software OpenSees to respectively establish two kinds of seismic vulnerability analysis models, of which one takes into account the pile-soil interaction while the other one does not. According to the type of the site, 20 seismic waves are selected for nonlinear time history analysis, and 200 calculated working conditions are obtained by amplitude modulation. Four kinds of failure limit states are defined, and the relationship between seismic demand and ground motion intensity indices under different failure limit states is established through the regression analysis. Based on the normal distribution assumption and first-order reliability theory, the vulnerability curves of the bridge at various failure stages are drawn; and through the comparative analysis of the calculation results of the two models, it is found that the seismic internal force response is reduced but the discreteness of internal force is increased if considering the pile-soil interaction; the displacement of bridge structure under seismic action is increased, but the displacement discreteness is reduced. The calculation result shows that, the influence of pile-soil interaction on the seismic vulnerability of bridge is relatively great and can not be neglected in the calculation of vulnerability. Considering the pile-soil interaction can make the seismic vulnerability calculation of bridge more accurate.

Key words. IDA method, Continuous bridge, Pile-soil interaction, Seismic vulnerability analysis, OpenSees.

1. Introduction

Damage of earthquake to the bridge structure is relatively serious. In recent years in China, Wenchuan earthquake, Yushu earthquake and so on all seriously

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damaged the structure of bridge as a transportation hub, which not only caused huge economic losses but also brought about a lot of secondary problems. Therefore, it is very important to conduct the seismic risk analysis on the bridge.

Seismic risk analysis involves a wide range and vulnerability analysis is one of the important aspects of it. The vulnerability of the structure in the earthquake refers to the exceeding probability of structure having a particular failure state under the seismic ground motion action of certain intensity. Therefore, the seismic capacity of the bridge structure can be evaluated through the vulnerability analysis. The results of seismic vulnerability calculation are mainly expressed by the vulnerability curve, and the relationship between the vulnerability of bridge structure and other parameters is as follows:

$$Fragility = P[EDP \geq LS|IM]\,. \tag{1}$$

In the equation, *LS* (limit state) represents the curvature of structural failure state; *IM* (intensity measure) represents the ground motion intensity, and *EDP* is the engineering demand parameter.

At present, the pile-soil interaction is not sufficiently considered in the domestic analysis of seismic vulnerability of bridge[1–12]. Under the earthquake action, the motion relationship of the pile-soil system is:

$$K\delta + C\dot{\delta} + M_P\ddot{\delta} = -M_P\ddot{u}_g\,. \tag{2}$$

In the above formula: K is the whole stiffness matrix of the structure, which is obtained by the superposition of the stiffness matrix of pile and soil; C is the whole damping matrix of the structure, which is obtained by the superposition of the damping matrix of pile and soil, and the damping matrix of pile is calculated by Rayleigh method; M_P is the mass matrix of pile; $\delta, \dot{\delta}, \ddot{\delta}, u_g$ are respectively the displacement vector, speed vector, accelerated speed vector and input accelerated speed vector of pile.

Seen from above equation, the soil mass surrounding the pile will have nonlinear deformation and show damping energy characteristic under the earthquake action. In view that pile-soil system has a huge impact on the seismic response of bridge structure, it is very necessary to take into account the pile-soil interaction in the analysis of vulnerability.

Based on the IDA method, this Paper has analyzed the seismic vulnerability of a continuous bridge of high-speed railway under pile-soil interaction. In addition, through the nonlinear time history analysis of the finite element model in OpenSees and using the lognormal assumption, the vulnerability curve of bridge bearing and pier under pile-soil interaction is drawn. The effect of pile-soil interaction on the seismic vulnerability of continuous beam is obtained by comparing the vulnerability curve of pile-free model.

2. Pile-soil interaction

Under seismic action, the pile-soil interaction on the bridge dynamic characteristics is mainly shown in three aspects [13]:

(1) System damping will increase, the natural period of vibration will increase and vibration mode may change but it is uncommon.

(2) When the structure in the hard site, the internal force of system will reduce and its displacement will increase.

(3) When the structure is in the soft site, the surface input under the influence of the structure will be different from that under no structure, and internal forces and displacements are likely to make changes in the input characteristics of the foundation increase.

In the finite element analysis of bridge seismic response, the most ideal way is to establish the integrated model of bridge structure and foundation soil. When the pile-soil is numerically modeled as a whole, it is necessary to consider the influence of the free length of the soil and establish a more accurate pile-soil contact constitutive. It is easy to see that the pile-soil integrated analysis will be complicated in the process and there will be difficulties in its practical application.

Nowadays the main method is to use the concentrated mass method to regard the foundation and the ground and the superstructure as the same system, and input into each soil layer with seismic ground motions for seismic analysis, in which, foundation and ground discreteness is the quality-spring-damping system. When the model is established, the piles are discretized into several concentrated mass points, and the springs and dampers in transverse bridge direction and longitudinal bridge direction are then set on the corresponding nodes of the pile. During the time history analysis, ground motion is input to each soil layer. In calculating the stiffness of soil spring, the commonly used methods are our normative "m method" and P-y curve method.

"M method" is to stratify the soil according to a certain thickness and then simplify the pile and soil interaction as a group of linear spring models along the pile, so that it is discretized into an ideal parameter system, where the upper structure and pile foundation are regarded as a whole to analyze the dynamic response, and the values of specific parameters are taken according to the standard. For the sake of simple analysis, the stiffness of soil spring is calculated by "m method" in this Paper.

3. Establishment of finite element model

3.1. Bridge engineering profile

The bridge is a prestressed concrete continuous bridge of a certain passenger line with span arrangement of (48 + 80 + 80 + 48) m, as shown in Fig. 1. The main beam is a single-box single-cell box beam, and the beam bottom curve is quadratic parabola. Of which, the concrete grade of the pier and the bearing platform is C35 and C40 respectively, and the box beam adopts C50 high performance concrete. The longitudinal-steel and hoop-steel of the pier are HRB400 and HRB335 respectively. The main beam adopts QZ series' spherical bearing; each fulcrum is set with two bearings, and the fixed bearing is set on the 3 # pier. Site conditions are divided into three categories and the characteristic period of ground motion response spectrum is 0.45 s.

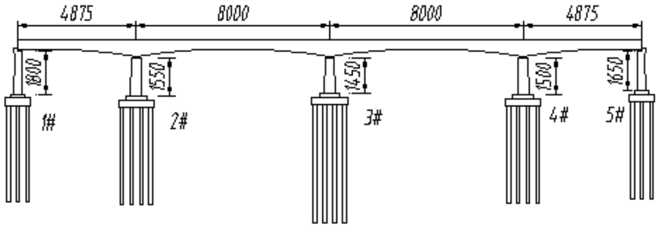

Fig. 1. Arrangement of bridge spans(cm)

3.2. Finite element model

In this Paper, the main beam, pier and bearing members of bridge structure are simulated by three different types of modules in OpenSees software. As there are two bearings in the transverse bridge direction, in order to more accurately simulate the bearing of actual bridge, the main beam and the pier are respectively connected with the rigid arm, and the bearing is placed at the end of the rigid arm. Of which, the main beam is simulated by Elastic-Element and linear elastic materials, and the pier is one of the vulnerable components in seismic analysis, for which its nonlinear factor must be fully considered. Therefore, we use the nonlinear beam column element in OpenSees to simulate the main pier and transition pier. The bearing is an important component to transfer load, and the bearing simulation adopts the Zero-Length Element in OpenSees. In the modeling process, the simple supported beam at both ends is considered as a boundary condition.

Out of the principle of capacity protection, pile foundation shall be considered in accordance with the elasticity. The group piles are connected to the bearing platform by a rigid arm and a node is set at the center of each soil layer. And at the node position, the soil springs in transverse bridge direction and longitudinal bridge direction are built to simulate the restriction effect of soil on the pile foundation. The stiffness of the soil spring is calculated by the "m method". The soil spring is simulated using the Zero-Length Element in OpenSees and the stiffness of it is defined using the uniaxial Material Elastic in OpenSees. The finite element model of whole bridge is shown in Fig. 2.

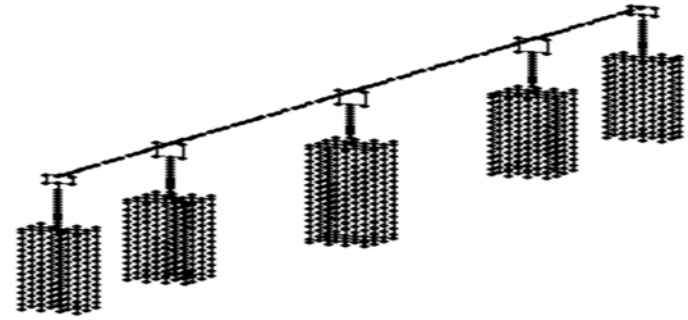

Fig. 2. Finite element model of whole bridge

4. Vulnerability analysis

4.1. Selection of seismic waves

In this Paper, the incremental dynamic analysis method (referred to as IDA method) in parameter analysis method is selected, which mainly includes the two kinds of parameters including structural performance and ground motion intensity. The response of the structure under the earthquake is not only related to the structural form and its material properties, but also related to the characteristics of the ground motion, such as the amplitude, spectrum and duration of the ground motion. Since the intensity peak of seismic waves is easily modified in the IDA method, only the spectral characteristics and duration should be considered in the selection of seismic waves.

Considering the randomness of the earthquake, seismic wave selection should be as comprehensive as possible; in the IDA method, in order to meet the accuracy of structural seismic analysis, the number of seismic waves selected should be not less than 10. Based on these factors and according to the geological condition of the bridge, select 20 seismic waves in the PEER database, and by regarding the peak acceleration of ground as the ground motion intensity parameter, module the amplitude of each line of seismic waves for 10 times to increase the peak acceleration from 0.1g to 1.0g.

4.2. Definition of failure state

The ductility of the pier column is often used as the main index to measure the structural failure state in the analysis of the seismic vulnerability of the bridge. According to the Japanese scholar Shinozuka's research on the failure state of the bridge, the bridge structure failure is divided into the four types: mild, moderate, serious and structural collapse.

Based on the actual situation of the site, the Paper selects the bridge pier failure and bearing failure as the failure states of bridge.

(1) Definition of pier failure condition

In accordance with the failure degree of bridge pier and bearing, the structural damage is divided into mild, moderate, serious and failure the four levels. In this Paper, the engineering demand parameters are taken as the curvature of the pier bottom, and through the four key points φ'_y, φ_y, ϕ_d and φ_u in the moment-curvature curve of pier bottom, the four kinds of damage states of pier are defined. Of which, ϕ'_y is the curvature when the main reinforcement in pier tensile area yields firstly I; ϕ_y is the curvature of equivalent yield point; ϕ_d is the curvature when the concrete protective layer of pier is crushed; and ϕ_u is the limit curvature of pier. See Table 1 for the specific divisions.

Table 1. Definitions of pier failure states

Damage state	Damage principle
Basically intact	$\varphi \leq \varphi'_y$
Slight damage	$\varphi'_y \leq \varphi \leq \varphi_y$
Moderate damage	$\varphi_{\overline{y}}^{\leq} \varphi \leq \varphi_d$
Serious damage	$\varphi_{\overline{d}}^{\leq} \varphi \leq \varphi_u$
Structural failure	$\varphi \geq \varphi_u$

(2) Definition of bearing failure state

According to the relevant literature [10] and the Specification of Spherical Bearing for bridge [14], in defining the damage states of movable bearing, the allowable displacement of the selected bearing is regarded as the slight damage boundary, and the maximum permissible displacement of the bridge bearing in this Paper is 150mm. See Table 2 for the definitions of bearing failure states.

Table 2. Definitions of bearing failure states

Damage state	Damage principle
Basically intact	$D \leq 150mm$
Slight damage	$150mm \leq D \leq 200mm$
Moderate damage	$200mm \leq D \leq 250mm$
Serious damage	$250mm \leq D \leq 300mm$
Complete failure	$D \geq 300mm$

4.3. Regression analysis

After the calculation results are obtained, sort out the curvature of the pier bottom and the displacement of the bearing and extract the maximum response of each condition. According to the PGA, divide working condition results into groups, and the results with the same PGA shall be a group; through taking the logarithmic mean of the biggest 20 responses of each group, 10 data points can be got in the coordinate. And through the regression analysis of the 10 data points, the function relation between the seismic demand and peak acceleration can be got.

$$\ln(u) = A\ln(PGA)+B\,. \tag{3}$$

Where, u is structural seismic demand; A and B are coefficients of regression equation.

Calculate the logarithmic standard deviation of the maximum response of 20 working conditions in each group, and the relation equation between the standard deviation of response logarithm and PGA.

$$\beta_i = \sqrt{S_{ri}/(n-1)}\,. \tag{4}$$

Where, β_i represents the logarithmic standard deviation of the ith group;

S_{ri} represents the quadratic sum of Group i data's logarithmic value and the logarithmic mean, $S_{ri} = \sum_{j=1}^{n=20} [\ln(\mu_i^j) - \overline{\ln(\mu_i)}]^2$.

It is found through comparison that adoption of equations (5) and (6) for the fitting of logarithmic standard deviation of the curvature of the pier and the displacement of the movable bearing can achieve a better effect.

$$\beta_\varphi = A(PGA)^2 + B(PGA) + C\,. \tag{5}$$

$$\beta_d = A(PGA)^3 + B(PGA)^2 + C(PGA)+D\,. \tag{6}$$

Under the action of input earthquake along the bridge direction, apart from suffering from the inertial force generated by its own mass, pier also suffers from the inertial force generated by the mass of upper structure, especially for the pier where the fixed bearing locates (No. 3 pier). The result of finite element analysis shows that the curvature of the pier where fixed bearing locates under the action of earthquake along the bridge direction is much bigger than that of other piers. Therefore, the Paper only analyzes the damage situation of the pier where the fixed bearing locates and the specific results are shown in the below Fig. 3 and Fig. 4.

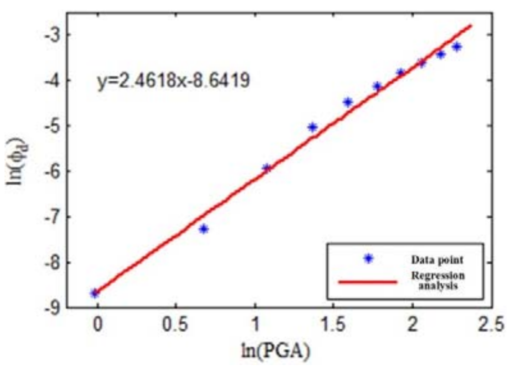

Fig. 3. Regression analysis of pier bottom demand

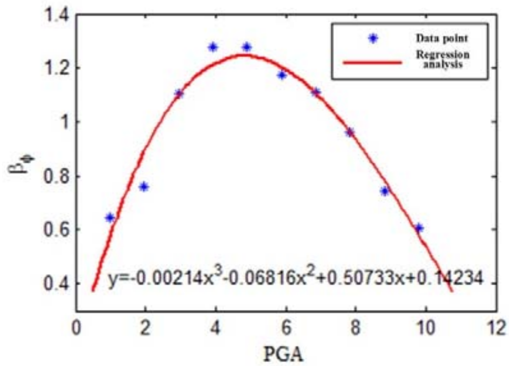

Fig. 4. Regression analysis of pier bottom demand standard deviation

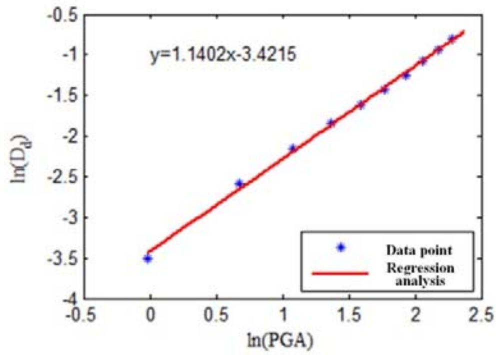

Fig. 5. Regression analysis of movable bearing demand

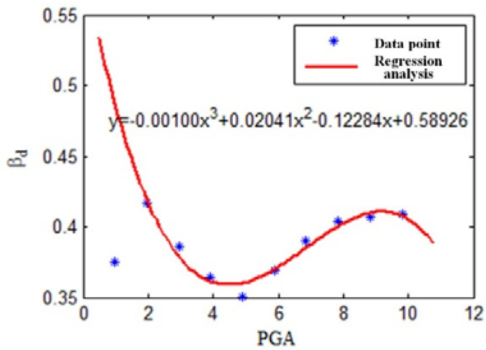

Fig. 6. Regression analysis of movable bearing demand standard deviation

4.4. Drawing of vulnerability curve

The failure probability of the structure in a certain state can be determined by the Equation (7):

$$p_f = p_r(\mu_d/\mu_c \geq 1) = \Phi(\frac{\lambda}{\sigma}) = \Phi\left[\frac{\ln(\overline{\mu_d}/\overline{\mu_c})}{\sqrt{\beta_d^2 + \beta_c^2}}\right]. \quad (7)$$

Where, p_f represents the failure probability of the structure in a certain state; μ_c, μ_d are respectively the structural capacity and the demand; $\overline{\mu_c}, \overline{\mu_d}$ are respectively the structural capacity and the demand mean; β_c, β_d are respectively the logarithmic standard deviations of the structural capacity and demand.

The vulnerability curves shown in the Fig. 7 and Fig. 8 can be got from it.

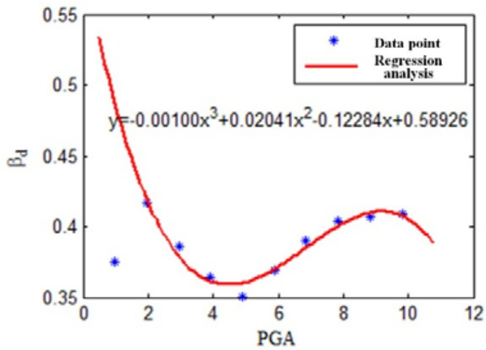

Fig. 7. Vulnerability curve of pier

It can be seen from Fig. 7 that: when PGA is 0.2 g, the exceedance probability of slight damage to the pier is about 0.95, and the exceedance probability of occurrence of moderate damage is about 0.90; when PGA is less than 0.3 g, the pier will not be seriously damaged; when PGA is 0.8 g, the exceedance probability of occurrence of structural failure is 0.98. It can be seen, under the action of the earthquake in the longitudinal bridge direction, the probability of structural failure is higher.

It can be seen from Fig. 8 that: when PGA is 0.4 g, the exceedance probabilities of four kinds of damage are respectively 0.11, 0.19, 0.32 and 0.52; when PGA is 1.0g, the exceedance probability of structural failure is 0.78.

Based on above results, it can be got that: the exceedance probability of occurrence of various damages to bearing is less than that to pier.

5. Comparative analysis

In order to study the effect of pile-soil interaction on seismic vulnerability of bridge, a contrast model is established to remove pile foundation and direct pier bottom consolidation. And the effect is analyzed according to the calculation results and the calculation formula of vulnerability. Specifically, the seismic response and

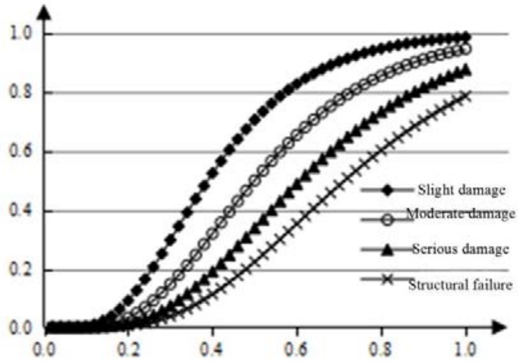

Fig. 8. Vulnerability curve of bearing

the logarithmic standard deviation of seismic response are additionally illustrated. Under the action of earthquake, the curvature comparison of the fixed piers is shown in Table 3, and the displacement comparison of the movable bearing is shown in Table 4.

Table 3 shows that: under the action of earthquake, the pile-soil interaction has a great influence on the curvature of the fixed pier; when the PGA is 0.2g -0.3g, the curvature of the fixed pier increases; in other cases, the curvature of the fixed pier is reduced. The change of curvature shows that the pile-soil interaction has a great influence on the internal force of fixed pier. And such influence is affected by both the characteristics of the soil layer and the input characteristics of the ground motion.

Table 4 shows that: under the action of earthquake, the pile-soil interaction makes the maximum displacement of movable bearing larger.

Table 3. Curvature comparison of fixed pier under the action of earthquake

PGA	0.1g	0.2g	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g	0.9g	1.0g
Without pile	0.02	0.05	0.08	0.12	0.15	0.19	0.22	0.26	0.31	0.37
With pile	0.03	0.07	0.12	0.16	0.20	0.24	0.29	0.34	0.39	0.45

Table 4. Displacement comparison of movable bearing under the action of earthquake

PGA	0.1g	0.2g	0.3g	0.4g	0.5g	0.6g	0.7g	0.8g	0.9g	1.0g
Without pile	0.02	0.05	0.08	0.12	0.15	0.19	0.22	0.26	0.31	0.37
With pile	0.03	0.07	0.12	0.16	0.20	0.24	0.29	0.34	0.39	0.45

Figure 9 shows that: under the action of earthquake, the pile-soil interaction has a great influence on the fixed pier standard deviation of logarithm; at 01g-0.8g, the discreteness of calculation result is made bigger, showing that the internal force of the structure along with the input of different waves by ground motion when

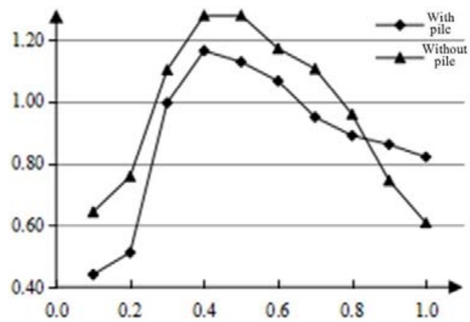

Fig. 9. Comparison of pier bottom curvature standard deviation of logarithm

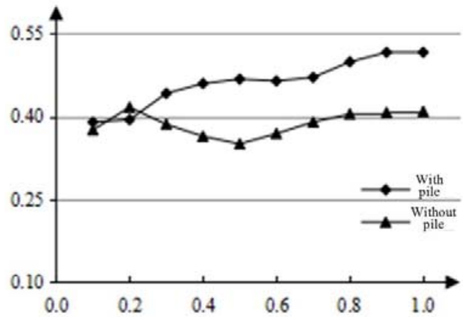

Fig. 10. Comparison of bearing displacement standard deviation of logarithm

considering the pile-soil interaction is bigger than that without considering the pile-soil interaction.

Figure 10 shows that: under the action of earthquake, the pile-soil interaction has a great influence on the movable bearing displacement standard deviation of logarithm, and in most cases, it will lead to small discreteness of bearing, showing that in most cases, considering the pile-soil interaction will make the discreteness of movable bearing displacement calculation smaller. Such change is caused due that soil itself has large deformation, making the bearing displacement larger on one side; on the other side, it is caused due that soil shows a certain damping characteristic.

The vulnerability curves of bearing with pile and without pile are drawn in the same figure for comparative analysis.

Fig. 11 shows: when the PGA is small, the exceedance probabilities of various failures of pier without piles are less than that of model with pile; when the PGA is relatively bigger, the exceedance probabilities of various failures of model with pile are less than that of pier without pile. Fig. 12 shows that, under the condition without pile, the exceedance probabilities of various failures of bearing are all less than that under the condition with pile.

In Fig. 11, if considering the pile-soil interaction, the pier vulnerability is smaller and then larger than that without pile. The data in Table 5 shows that when the PGA is 0.2g- 0.3g, the pile-soil interaction increases the curvature of the fixed pier.

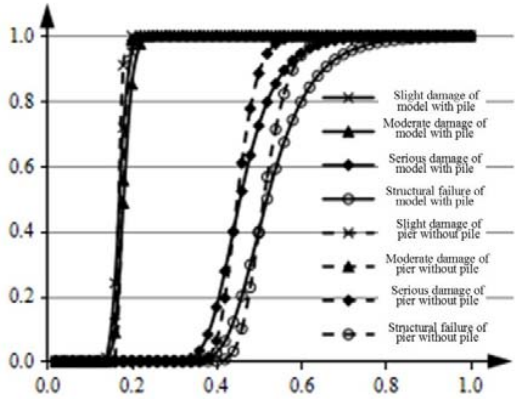

Fig. 11. Comparison of vulnerability curve of pier

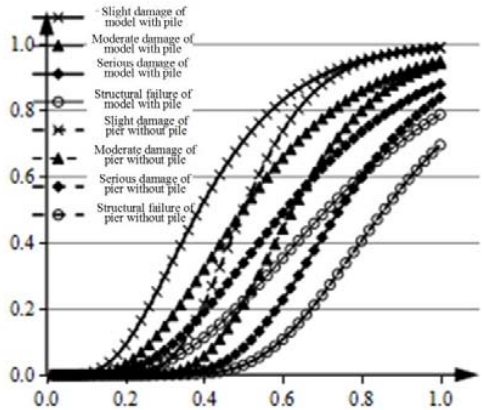

Fig. 12. Comparison of vulnerability curve of bearing

However, due to the interaction of pile and soil, the discreteness of the calculation results becomes smaller and the vulnerability is not increased.

In Fig. 12, after considering the pile-soil interaction, the bearing vulnerabilities under conditions of with pile or without pile are both increased, which is caused due that, the bearing displacement is common bigger under the condition with pile.

Based on above analysis, it can be got that: the pile-soil interaction changes the seismic response of continuous beam on one hand; on the other hand, it changes the discreteness of calculation results. The pile-soil interaction's influence on the seismic vulnerability is also the common influence result of the two aspects.

6. Conclusion

In this Paper, the seismic vulnerability analysis of a continuous beam bridge of a certain high-speed railway considering the pile-soil interaction is completed; the vulnerability curves of pier and bearing are respectively drawn with IDA method in OpenSees software and according to the regression analysis and definitions of failure states. And then through the comparison with the model without pile and based on the relevant formula of vulnerability as well as specific analysis, some conclusions below are got in this Paper: (1) the exceedance probabilities of various damages to bearing are all less than that to pier and the vulnerability of bridge structure is controlled by pier; (2) in most cases, the pile-soil interaction makes the internal force smaller but makes internal force discreteness larger; besides, the interaction makes the displacement larger but displacement discreteness smaller; (3) the influence of pile-soil interaction on the vulnerability of bridge is the common result of its influence on the discreteness of seismic response and calculation result; (4) during the process of vulnerability calculation, considering the pile-soil interaction can make the calculation result more accurate.

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