Seismic Safety Evaluation of Bridge Structures Based on Inelastic Spectrum Method

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ABSTRACT:
In recent years, Push-over analytical method was regarded as a new evaluation method for seismic resistance capacity of structure in some advanced countries. More available information can be obtained from Push-over analysis than from elastic static, even elastic dynamic analysis and the method is easy to be operated. Its basic elements, analysis process and the state-of-the-art are reviewed and the elastic spectrum from the Chinese Seismic Resistance Design Code for Highway Engineering (JTJ 004-89) was improved in order to take the inelastic effect into account herein. The inelastic demand spectra for four site conditions were derived by means of Vidic's strength reduction factors. The factors were studied in detail. By comparing capacity curves of bridge structure with the demand elastic spectrum, the earthquake resistance of bridge structure can be estimated. Furthermore, it is applied to evaluate seismic resistance capacity of a real bridge example in this paper. The results show that Pushover method can replace inelastic dynamic history analysis method in some cases.

KEYWORDS: evaluation, bridge structures, reduction factor, inelastic spectrum

1. INTRODUCTION

Response spectrum method is used to evaluating seismic resistance capacity of structures in earthquake engineering. This method is restricted to linear elastic characteristics of structures and single degree of freedom systems in theory. But under most circumstances, response spectrum method is used to analyzing inelastic characteristics of structures (most structures are multiple-degree-of-freedom systems) approximately. Structures need have enough deformation and dissipation capacity to resist moderate degree or infrequence degree earthquake. Otherwise, the earthquake effect determined by elastic response spectrum is unusual large, and furthermore, it's too wasteful for structure design. Performance-based design concepts which take into account ductile and deformation of structures can mitigate the destroy effects caused by moderate degree or infrequence degree earthquake. But, inelastic response spectra need to be established.

2. ESTABLISH INELASTIC SPECTRUM

Implementation of performance-based seismic design criteria into structural engineering practice requires simplified analysis procedures to estimate inelastic characteristics of structures for ground motions in which the structure is expected to behave nonlinearly. Usually, engineering structures would enter inelastic stage when those undergoing intensive earthquake motion effect. Combination of above reason and additional effect of some other factors (such as period, ductile and damping of structure) make structural dynamics based seismic design of structure quite complex. For the purpose of integrative consideration of the effects of these factors, nonlinear structural design is simplified to quasi-static structural design in engineering.

In general, there are two methods to get inelastic response spectrum: the first method is acting reduction factor to linear elastic response spectrum; the other method is getting nonlinear elastic response spectrum directly by statistic analysis of spectra, the spectra are obtained from nonlinear analysis of structures by acting real strong ground motion records on them. Apparently the last method can obtain precise results if ground motion of local site condition can be predicted accurately. But, the first method is in common usage. Not only because the amount limitation of real strong ground motion records can't obtain inelastic response spectrum in general engineering practice sense, but also because it can apply existing research achievement of response spectrum theory.

Strength reduction factor is not only the key to obtain enactment earthquake force for traditional strength based seismic design of structures, but also is the main foundation to determine inelastic response spectrum when carry out performance-based design to structures. But how to obtain the important factor is a difficult thing. Currently, most counties seismic codes still adopt the strength reduction factor which relied on past earthquake disaster experience.

The strength reduction factor method was developed from equal energy principle and equal displacement principle provided by Newark and hall in the 1970'. The strength reduction factor was once one of the hottest research issues after that time. After recent years research, other scholars also separately proposed several kind of expressions of strength reduction factor (Newark & Hall，1973；Krawinkler & Nassar，1992；Vidic，Fajfar & Fischinger，1994；Riddell & Hidalgo，1989；Tso & Naumoski，1991；Miranda & Bertero，1994；Fanlichu，2001,et al). One may refer the related literature about the model discussion and the contrast.

The relationship between strength reduction factor and ductile factor can be defined as following:

$$R(\mu)=\frac{F_y(\mu=1)}{F_y(\mu=\mu_i)} \tag{2.1}$$

Relationship modal of R-μ provided by Vidic is

$$R=c_1(\mu-1)^{c_R}\frac{T}{T_0}+1 \qquad T\le T_0 \tag{2.2}$$

$$R=c_1(\mu-1)^{c_R}+1 \qquad T>T_0 \tag{2.3}$$

$$T_0=c_2\mu^{c_T}T_g \tag{2.4}$$

Where T_g is intrinsic period of the structure, and μ is the ductility factor defined as the ratio between the maximum displacement and the yield displacement, c_1, c_2, c_R and c_T are parameters rely on hysteretic characteristics and damping ratio of structure (table 2.1).

Whether R-μ relationship is accurate or not that influences the precision of capacity spectrum method directly. If R value is oversized, intersection point of capacity spectrum curve and demand spectrum curve is premature, calculated quantity of structure plastic hinge is few than real situation. The result underestimates the structure earthquake resistance ability, it is not economical. If R value is excessively small, the analysis result would exaggerate the structure real earthquake resistance ability, and it is insufficient security to structure. Further because the hysteretic characteristics consume energy and cumulative damage of structure would causes the R value reduce slightly, it is quite ideal that selects the moderate R value model.

Comparison were carried out between four kind of R-μ values models which provided by Vidic in figure 1. This article suggests to use the first kind of and the third kind model of Vidic model. At the same time, if the ratio (α) between structural stiffness after capacity curve yielding and initial elastic stiffness is too big, it may use the second-order of μ-1 term to consider of α when calculate R value.

$$R=c_1[\frac{\alpha}{2}(\mu-1)^2+\mu-1]^{c_R}\frac{T}{T_0}+1 \qquad \mathrm{T}\le T_0 \tag{2.5}$$

$$R=c_1[\frac{\alpha}{2}(\mu-1)^2+\mu-1]^{c_R}+1 \qquad T_0>\mathrm{T} \tag{2.6}$$

$$T_0 = T_g \tag{2.7}$$

Table 2.1 Factors of Vidic's models (damping ratio=5%)

models		c_1	c_2	c_R	c_T
Hysteretic characteristics	damping				
Q style 1	Proportionate to mass	1.0	1.0	0.65	0.30
Q style 2	Proportionate to instantaneous stiffness	0.75	1.0	0.65	0.30
Two-line style 1	Proportionate to mass	1.35	0.95	0.75	0.20
Two-line style 2	Proportionate to instantaneous stiffness	1.10	0.95	0.75	0.20

The elastic spectrum from the Chinese Seismic Resistance Design Code for Highway Engineering (JTJ 004-89) (in figure 2) was improved in order to take the inelastic effect into account. The inelastic demand spectra for four site conditions were derived by means of Vidic's strength reduction factors (in figure 3). The maximum earthquake influence factors of special level of seismic intensity in horizontal are showed in table 2.2.

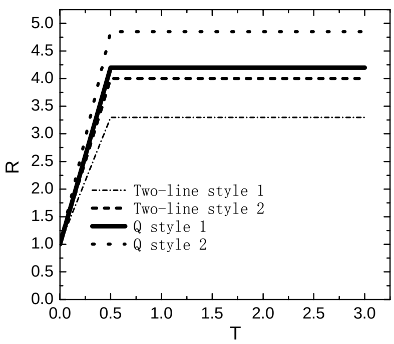


Figure 1 The comparison of four R-μ relationships of Vidic's models(μ=4)

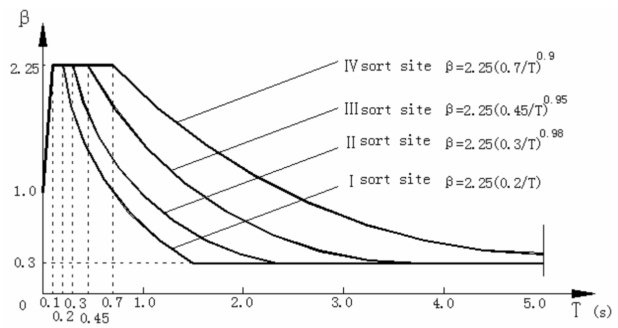
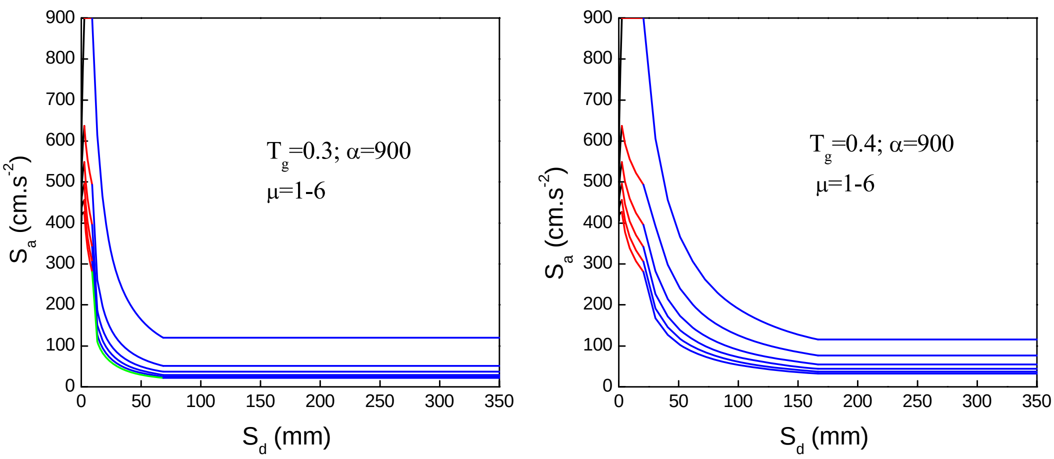
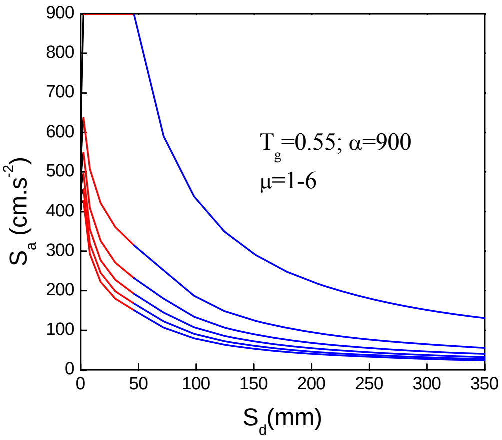


Figure 2 Response spectrum of the Chinese Seismic Resistance Design Code for Highway Engineering (JTJ 004-89)

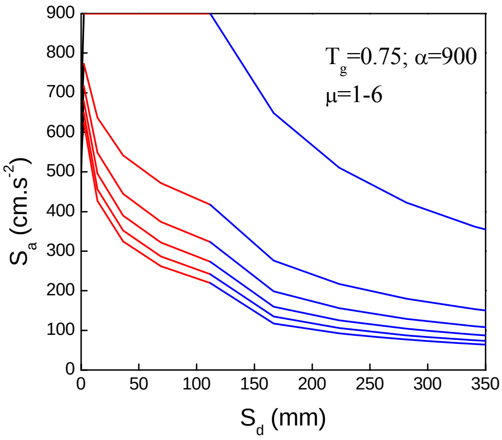


(a) The demand spectra under 8 degree Infrequence Earthquake of Ⅰ site condition

(b) the demand spectra under 8 degree Infrequence Earthquake of Ⅱ site condition



(c) The demand spectra under 8 degree Infrequence Earthquake of III site condition



(d) the demand spectra under 8 degree Infrequence Earthquake of IV site condition

Figure 3 the demand spectra under 8 degree Infrequence Earthquake for four site conditions

Table 2.2 The maximum earthquake influence factors of special level of seismic intensity in horizontal

Earthquake Influence	6 degree	7 degree	8 degree	9 degree
Regularity Earthquake	0.04	0.08	0.16	0.32
Infrequence Earthquake	—	0.50	0.90	1.40

3. ESTIMATING EARTHQUAKE RESISTANCE ABILITY OF BRIDGE STRUCTURE BY MEANS OF PUSH-OVER METHOD

3.1 Basic Principle of PUSH-OVER Method

The PUSH-OVER method requires exerting invariable vertical load and maintenance in the structure, simultaneously exerts some kind of distributed horizontal load, Horizontal load monotonous increase until the component submits. Thus the elastic-plastic performance of structure under the horizontal static load is obtained. This method was developed early by Imbsen and Penzien, and then was proposed to be used in the bridge earthquake resistance ability evaluation. Usually between the neighboring expansion joint in bridge structure was treated as the spatial independent frame, the superstructure hypothesis is rigidity. At the preliminary stage, analysis is in the direction which considered (along the bridge or across the bridge) to carry on collapses analysis to the independent bridge pier, thus the elastic-plastic performance of the component is obtains. Then, simulating the bridge pier's stiff as inelastic spring for the entire frame analysis, calculating the initial rigidity center of the overall frame, exerting monotonous increase horizontal load，and according to frame inelasticity growth level continually readjusting organization rigidity until the structure achieved scheduled destruction(becomes the organization or displacement exceeds limitation).

3.2 Examples

PUSH-OVER method was applied to evaluate a bridge structure's security on earthquake resistance. Displacements of structure's top point at each different step as well as the ratio of corresponding total horizontal force to the structure own quality and each inelastic demand spectrum curve of corresponding site condition were drawn in a same figure. If the structure response curve can pass through the corresponding demand spectrum curve, it means that the structure can resist the earthquake intensity which that demand spectrum reflects. Otherwise, the structure needs to be reinforced or redesigned. The determinate inelastic demand spectrum is in S_a-S_d form, it is very convenient that draw it with PUSH-OVER analysis result of structure in base shear-top point displacement in the same place.

An oversea bridge was finished in 1991, it has two-column style reinforcement concrete bridge piers. One unit was selected as the analysis object. The unit has a span of 45 meters and has a height of 23.5 meters. The reinforcement concrete level is *C*30. Earthquake resistances design level of this bridge is intensity 8, and location is in Ⅲ site condition. The profile of bridge pier is showed in figure 4. In view of the fact that this bridge completely uses the board style rubber supports and various bridge piers match the reinforcement to be same, therefore selects 3 typical bridge piers when carries on the Push-over analysis. The Push-over analysis model is established according to the method which Chinese Seismic Resistance Design Code for Highway Engineering (JTJ 004-89) recommended. The calculation parameters of two-column style bridge piers are showed in table 3.1.

Table 3.1 Calculation parameters of bridge piers

Number	Height（mm）	Diameter（mm）	Reinforcement ratio (%)	$N/f_c A$	Longitudinal bar level	Intrinsic period (s)	Ductility factor
D1	12000	1800	1.01	0.23	Ⅱ	0.72	4.61
D2	18600	1800	1.01	0.23	Ⅱ	1.24	6.2
D3	20500	1800	1.01	0.23	Ⅱ	0.69	6.32

It can see from figure 5, this structure can resist intensive 8 degree infrequence earthquake, it satisfies anti-collapse checking calculation. The conclusion is consistent with the other computations result by means of other method carried out by the author.

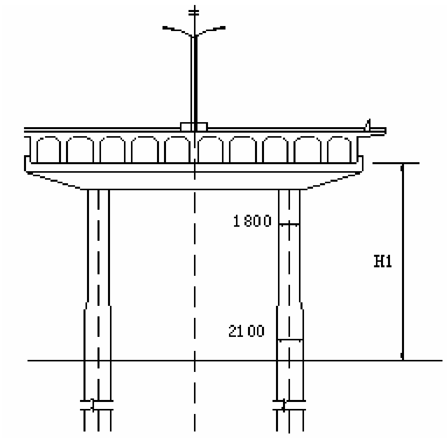


Figure 4 Profile of example structure

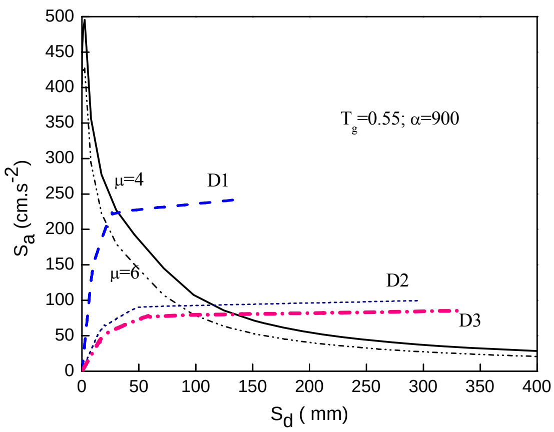


Figure 5 The PUSH-OVER analysis result of example structures

4. CONCLUSIONS

1. The bridge structure earthquake resistance security can be effectively evaluated by jointly using PUSH-OVER analysis method and inelastic response spectrum. This method has successfully been applied to predict bridges security on earthquake resistance in some places. The certain other type structures may apply this method to evaluate the structure security on earthquake resistance, too.
2. The determinate inelastic demand spectrum is in S_a-S_d form, it is very convenient to draw it with PUSH-OVER analysis result of structure in base shear-top point displacement form in the same place. Some other structures which don’t suit the PUSH-OVER method analysis can use the other means to obtain the structural capacity curve, then, apply the method supposed in this article to evaluate structure safety on earthquake resistance.
3. Using what kind of R-μ relation form has not stipulated in our country bridge earthquake resistance standard.

This problem have been paid close attention and intensively discussed by the multitudinous earthquake researcher. Inelastic demand spectra were gotten mostly by applying the overseas scholar provided strength reduction factor directly when carried out performance-based structure design in China. Because the other countries' standard design spectra have certain differences, these spectra may not completely reflect the characteristics of Chinese earthquake ground movement, also may not completely reflect the characteristic of Chinese design response spectrum. Therefore, the direct application of overseas achievements of inelastic demand spectra has some shortcomings, too. It is necessarily to establish strength reduction factors that are suitable for the inelastic design spectrum of Chinese standard by according to the Chinese actual situation and fully using Chinese strong earthquake record.
4. For each time evaluation, there only need to draw the obtained capacity curve according to certain request with the corresponding inelastic response spectrum in the same place, it can reduce the engineering staff's massive computing time.

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