A New Strategy to Assess the Seismic Energy Dissipation Safety of Reinforced Concrete Bridge Piers

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***Abstract*-In this study, a new strategy to assess the seismic energy dissipation safety of reinforced concrete bridge pier was proposed. Based on dynamic energy equation of multi-degree structures and inverse deduction of Park-Ang damage model under given displacement and damage controlling conditions, a real highway circular bridge pier was analyzed to show the feasibility of present theory and method by use of popular finite element software. The results show that the real ability of energy dissipation of the reinforced concrete circular bridge pier can be calculated under given displacement and damage controlling conditions and then the safety factor can be obtained subsequently in varied earthquake waves corresponding to different seismic classes and damage index where the complex non-linear calculation process related to the restoring force model of the structure becomes unnecessary. The strategy involved in this paper is very simple and easy to be realized which can make full use of the advantage of finite element software and may provide effective means for the seismic assessment of existing or proposed reinforced concrete bridge piers.**

Keywords- Dynamic Time Course Analysis; Seismic Energy Equation; Seismic Energy Dissipation Safety Assessment; Reinforced Concrete Bridge Pier; Park-Ang Damage Model

I. INTRODUCTION

At present, time-history analysis is the most mature and reliable method for seismic response analysis. Because of the fact that the time-history analysis cannot describe the energy-related damage when bridge pier displacement does not exceed the limit, so the damage index equation is widely used to analyze structural seismic damage based on the time-history analysis.

Related to the structural damage analysis, it has been widely recognized that the energy is one of the key factors in structural damage, and much work.

Such as the calculation of the total seismic input energy, the influencing factors and their distribution, etc. have been carried out and even a fairly standard elastic or elastic-plastic input energy spectrum has been formatted. But as to the key issue how much seismic energy dissipation capacity that the structures possess in the end, there are still no definite quantitative conclusions. Therefore, structural seismic performance evaluation based on the real seismic energy dissipation capacity or structural energy dissipation capacity safety reserve analysis could not be further carried through. In addition, in current method, in order to calculate the hysteretic energy dissipation of structures directly and to predict structural damage, one must assume the material restoring force model. As we know, the assumption of restoring force model and the error of the damage model can result in that predicted results do not meet with the realities, and the non-linear calculation process will be time-consuming and troublesome.

For bridge structures, the degree of damage under seismic loading was mainly determined on seismic capacity of substructure [1, 2], usually, excessive substructure displacement leads to girder falling, girder collision or bridge piers are destroyed seriously under earthquake repeated cyclic loading. Hence, the ductility design theory allows bridge piers to generate a certain degree of ductile failure in the earthquakes, but excessive bridge pier displacement of seismic response leading to girder collision or heavy damage which can’t be repaired is still not hoped. Flexible structure can help to alleviate seismic action, but its stiffness may be too small that affects the safety of driving, so the common way is to seek a balance between improving the seismic performance and ensuring normal usage, and give the structure a certain displacement or stiffness constraints. Based on the above considerations, this paper proposes that reasonable controlling conditions of displacement and damage should be used to consider the real energy dissipation capacity of structure and as a basis for discussing structural seismic safety reserve. On the premise that the calculation of input energy and study of structural elastic-plastic response displacement estimation are very mature, the calculation involved in this paper can effectively avoid complex non-linear calculation process related to the restoring force model, and it is very simple and easy to be realized.

II. STRUCTURAL ENERGY RESPONSE UNDER SEISMIC ACTION

The dynamic response equation of multi-degree-of-freedom system under seismic loading is

$$[\boldsymbol{M}]\left\{\ddot{u}\right\}+[\boldsymbol{C}]\left\{\dot{u}\right\}+[\boldsymbol{K}]\{\boldsymbol{u}\}=-[\boldsymbol{M}]\{\boldsymbol{I}\}\ddot{u}_g(t) \tag{1}$$

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Where [M] is the mass matrix, [C] is the damp matrix, [K] is the stiffness matrix, {I} is an array whose elements are composed of 0 or 1 related to the degrees of freedom under seismic loading, $\left\{\ddot{u}\right\}$ is the structural acceleration vector, $\left\{\dot{u}\right\}$ is the structural velocity vector, $\{u\}$ is the structural displacement vector; $\ddot{u}_g(t)$ is the ground acceleration time history.

The time-history analysis theory is: inputing known seismic wave for structures, and solving Eq. (1) with numerical method in the time domain, then obtaining structural displacement, velocity and acceleration vectors at any time. According to whether taking the influences of structural material nonlinearity on [K] into consideration, the time-history analysis can be divided into two types which are elastic time-history analysis and nonlinear time-history analysis.

Left multiply $\left\{\dot{u}\right\}^T$ on both sides of Eq. (1) at the same time, and calculate the integral on $[0,t]$, then obtain relative energy equation of the multi-degree-of-freedom system [3] as

$$\begin{aligned}&\int_0^t \left\{\dot{u}\right\}^T [\boldsymbol{M}]\left\{\ddot{u}\right\}dt+\int_0^t \left\{\dot{u}\right\}^T [\boldsymbol{C}]\left\{\dot{u}\right\}dt+\\ &\int_0^t \left\{\dot{u}\right\}^T [K]\{u\}\,dt=-\int_0^t \left\{\dot{u}\right\}^T [M]\{I\}\ddot{u}_g(t)dt\end{aligned} \tag{2}$$

Total energy absorbed by structure in an earthquake is

$$E_I(t)=-\int_0^t \left\{\dot{\boldsymbol{u}}\right\}^T [\boldsymbol{M}]\{\boldsymbol{I}\}\ddot{\boldsymbol{u}}_g(t)dt$$

Total structural kinetic energy is

$$E_K(t)=\int_0^t \left\{\dot{\boldsymbol{u}}\right\}^T [\boldsymbol{M}]\left\{\ddot{\boldsymbol{u}}\right\}dt$$

Total structural damp energy is $E_D(t)=\int_0^t \left\{\dot{u}\right\}^T [\boldsymbol{C}]\left\{\dot{u}\right\}dt$

Structural deformation energy is $E_Y(t)=E_S(t)+E_H(t)=\int_0^t \left\{\dot{\boldsymbol{u}}\right\}^T [\boldsymbol{K}]\{\boldsymbol{u}\}\,dt$

$E_S(t)$ and $E_H(t)$ are structural elastic strain energy and hysteretic energy respectively.

Since structural elastic deformation energy will release and turn into damping or hysteretic energy after earthquakes, the final energy equation actually is

$$E_I(t)=E_D(t)+E_H(t) \tag{3}$$

III. PARK-ANG DAMAGE MODEL OF REINFORCED CONCRETE PIER

Based on a large number of failure experimental data of reinforced concrete beams and columns in the United States and Japan, Ang, Wen and Park (1985) proposed the two-parameter seismic damage model of reinforced concrete where the linear combination of normalized maximum displacement and normalized hysteretic energy is used to formulate the damage evaluation expression [4~7],

$$D=\frac{\delta_m}{\delta_u}+\beta\frac{\int d\varepsilon}{Q_y\delta_u} \tag{4}$$

Where D is the structural damage index; δ_m is the maximum displacement responses under earthquake loading; δ_u is the structural ultimate deformation under monotonic loadings; Q_y is the structural yield strength; $\int d\varepsilon$ is the cumulative

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hysteretic energy; β is the combination parameter which changes from 0 to 0.85, the average is about 0.1 ~ 0.15, and it can be calculated as

$$\beta = (-0.447 + 0.073\lambda + 0.24n_0 + 0.314\rho_t) \times 0.7^{100\rho_\omega} \tag{5}$$

Where λ is the shear span ratio, the value is 1.7 when $\lambda < 1.7$; n_0 is the ratio of axial compression stress to strength, the value is 0.2 when $n_0 < 0.2$; ρ_t is the total longitudinal reinforcement ratio, the value is 0.75% when $\rho_t < 0.75\%$; ρ_ω is the volume stirrup ratio.

For bend failured components, β also can be calculated as

$$\beta = \left[0.37n_0 + 0.36\left(k_p - 0.2\right)^2\right] \times 0.9^{\rho_\omega} \tag{6}$$

Where k_p is the normalized tensile reinforcement ratio, and $k_p = r_t f_y / (0.85 f_c)$, where f_y is the yield strength of tensile reinforcement; f_c is the concrete compressive strength; ρ_t is the tensile reinforcement ratio, others are the same as the Equation (5).

For classification of the Damage index, based on many results, the Literature [6] presented the damage indexes of different earthquake damage levels listed in Table I.

TABLE I SEISMIC DAMAGE CLASS AND DAMAGE INDEX D

Seismic damage class	Basically no damage	Slight damage	Medium damage	Serious damage	Collapse
Damage index D	0～0.2	0.2～0.4	0.4～0.6	0.6～0.9	>0.9

IV. INVERSE DEDUCTION OF PARK-ANG DAMAGE MODEL AND ASSESMENT OF SEISMIC ENERGY DISSIPATION SAFETY

A. Introducing of Control Conditions of Displacement and Damage

If one calculates structural energy dissipation in an earthquake directly and inserts it in the above-mentioned damage model to evaluate damage index, some kind of restoring force model must be used to calculate the hysteretic energy option in Eq. (4). However, all kinds of current restoring force models are idealized ones in accuracy, and from the definition of hysteretic energy option in Eq. (2), we can find that $\{\dot{u}\}$, $[K]$ and $\{u\}$ are all related to hysteretic models, so the direct integration of hysteretic energy is not only time-consuming, troublesome and hard to be realized, but also may yield secondary error more or less besides the error of damage model itself.

In addition, in calculation process of all energy options in Eq. (2), if the bridge becomes invalid because of its excessive displacement or damage, the total calculation process will be meaningless [8]. Therefore, some reasonable restrictions should be introduced in to ensure the reasonability of the calculation course. Only the structural failure control criterion is defined, the valid seismic energy dissipation capacity based on the criterion can be obtained and the exaggeration of structural seismic energy dissipation capacity can be avoided.

With regard to the ultimate displacement of structure earthquake response, usually, there are the following provisions [9] as shown in Fig. 1 and Eq. (7).

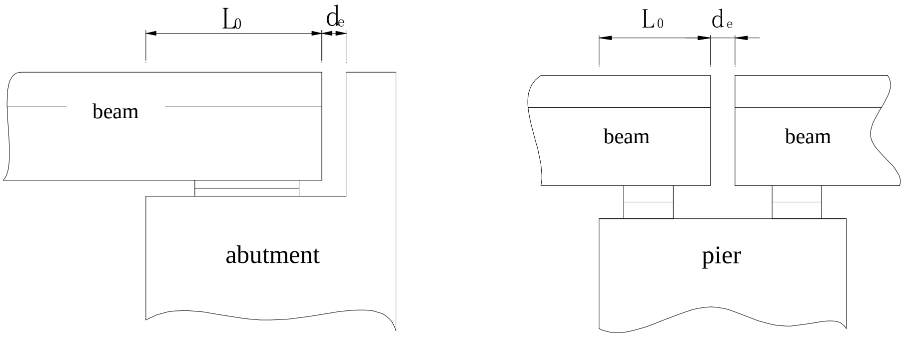

Fig. 1 Displacement restriction in pier and abutment

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$$u_{\max} \leq \begin{cases} d_e - d_a \\ L_0 - l_a \\ u_a \end{cases} \tag{7}$$

Where $u_{\max}$ is the maximum earthquake displacement; d_e and d_a stand for the expansion joint space and necessary safety clearance respectively; L_0 and l_a stand for the supporting length of beams and its safety length respectively; u_a is the structural allowable displacement calculated according to yielding displacement u_y and limited displacement u_u, that is

$$u_a = u_y + \frac{u_u - u_y}{s_f} \tag{8}$$

Where s_f is the safety factor.

As to the damage index D, it can be determinated according to Table 1, and the criterion: no damage under minor earthquake, repairable under moderate earthquake and no collapse under strong earthquake.

B. Pier Seismic Energy Dissipation Capacity under Given Condition of Displacement and Damage Index

Actually, if above-mentioned constraints are given certainly, the hysteretic energy dissipation capacity of the pier is a determinated value which is associated with its cross-section characteristic, reinforcement, etc. and it is easy to be obtained by inverse deduction of Eq. (4).

Select and insert the displacement limit δ_m^* and damage limit value D_0 in Eq. (4), we can obtain

$$D_0 = \frac{\delta_m^{\ *}}{\delta_u} + \beta \frac{\int d\varepsilon}{Q_y \delta_u} \tag{9}$$

By inverse deduction, then the energy dissipation capacity can be calculated as,

$$E_H = \int d\varepsilon = \frac{1}{\beta}\left(D_0 - \frac{\delta_m^{\ *}}{\delta_u} \right) Q_y \delta_u \tag{10}$$

According to the Literatures [10] and [11], there is a certain relationship between structural hysteretic energy dissipation and the total energy dissipation ,that is

$$E_H = \eta_H E_I \tag{11}$$

The total energy dissipation capacity would be

$$E_I = \frac{E_H}{\eta_H} \tag{12}$$

Insert Eq. (9) in Eq. (12) and obtain

$$E_I = \frac{E_H}{\eta_H} = \frac{1}{\eta_H \beta}\left(D_0 - \frac{\delta_m^{\ *}}{\delta_u} \right) Q_y \delta_u \tag{13}$$

Define the total energy dissipation as CA which is the energy dissipation capacity of pier in controlling conditions, namely,

$$CA = E_I = \frac{E_H}{\eta_H} = \frac{1}{\eta_H \beta}\left(D_0 - \frac{\delta_m^{\ *}}{\delta_u} \right) Q_y \delta_u \tag{14}$$

C. The Need of One Pier'S Seismic Energy Dissipation Capacity and Seismic Energy Dissipation Safety Factor in an Earthquake

According to the former discussion, to maintain the safety in the course of earthquake, a pier must absorb all earthquake input energy under the circumstance that both the maximum displacement and damage index do not exceed the restriction.

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Define the total earthquake input energy as the need of one pier's seismic energy dissipation capacity in an earthquake named DM which can be obtained from Eq. (2) by numerical integration, that is,

$$DM = E_I(t) = -\int_0^t \left\{\dot{u}\right\}^T \left[\boldsymbol{M}\right]\left\{\boldsymbol{I}\right\}\ddot{u}_g(t)dt \tag{15}$$

Much of research shows that structural earthquake input energy represented by Eq. (15) can be calculated by non-linear time history analysis through direct integral calculation, or by the total input energy calculation of structural elastic response, the error between the two is tiny [10, 12]. It is obvious that elastic method can simplify the calculation process greatly and save computer resources, especially, the elastic vibration mode iteration method mentioned in Literature [13] even can be accomplished artificially based on elastic single-degree-of-freedom input energy spectra.

According to Literature [11], when calculating DM by elastic method, a correction coefficient η (advised value is $\eta = 0.05$) can be used to modify the result, then DM can be calculated as

$DM = (1+\eta)DM_0 \quad (\eta = 0.05) \quad (16)$ Where DM_0 is the earthquake input energy calculated by elastic method, which also can be calculated by elastic time history analysis based on Equation (15) or elastic input energy spectra mentioned in Literature [13]..

Define $r = \dfrac{CA}{DM}$ as seismic energy dissipation safety factor, according to Eqs. (14), (15) and (16), we can obtain,

$$r = \frac{CA}{DM} = \frac{\dfrac{1}{\eta_H \beta}\left(D_0 - \dfrac{\delta_m^{\ *}}{\delta_u}\right)Q_y\delta_u}{-\int_0^t \left\{\dot{u}\right\}^T \left[\boldsymbol{M}\right]\left\{\boldsymbol{I}\right\}\ddot{u}_g(t)dt} \tag{16}$$

Or

$$\rho = \frac{CA}{DM} = \frac{\dfrac{1}{\eta_H \beta}\left(D_0 - \dfrac{\delta_m^{\ *}}{\delta_u}\right)Q_y\delta_u}{(1+\eta)DM_0} \tag{17}$$

V. CALCULATION EXAMPLE

The paper takes one concrete bridge pier of a highway ramp for example and assesses its seismic energy dissipation capacity safety. The pier is of circular section, the diameter is 1.3 m, the height is 10 m, both longitudinal reinforcement ratio and stirrup reinforcement ratio are around 2%, and the concrete grade is C40. According to above mentioned method, we must calculate all parameters of Eq. (4). First, the calculation of value Q_y and δ_u is complex because of its circular section, so the two values are evaluated by finite element method. And according to Eq. (7), $\delta_m^{\ *}$ can be simply defined as the expansion joint space which is 0.08 m in the case minus necessary safety length of 0.01 m, that is to say, its value is 0.07 m. The antiseismic levels are assumed as six, seven and eight according to Chinese criterion [14] with peak ground acceleration 0.05 g, 0.1 g and 0.2 g respectively. As to the damage index, according to Table 1 and the criterion: no damage under minor earthquake, repairable under moderate earthquake and no collapse under strong earthquake. The value of D_0 can be chosen as 0.4, 0.6, 0.9 separately. In the end, according to Literature [11], the value of η_H usually is 0.6. Then the pier energy dissipation capacity CA can be calculated corresponding to different seismic classes and damage index as shown in Table 2.

TABLE II THE RESULTS OF THE SAFETY FACTOR OF THE PIER

β	$Q_y\ (t)$	$\delta_u\ (m)$	D_0	$\delta_m^*\ (m)$	η_H	$CA\ (t\cdot m)$	$DM\ (t\cdot m)$	r
0.34	243	0.25	0.4	0.07	0.6	35.73	5.56	6.43
0.34	243	0.25	0.6	0.07	0.6	95.29	22.26	4.28
0.34	243	0.25	0.9	0.07	0.6	184.63	89.04	2.07

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For calculation of DM in an earthquake, the paper takes Qian'an wave for example. By use of finite element software ANSYS, and discretizing the pier into multi-degree of freedom system shown in Fig. 2, with the boundary condition of pier bottom simplified as consolidation in accordance with the reality, the elastic time-history analyses were carried out. Due to limited space, only the displacement time history of pier top in the bridge axis direction under Qian'an earthquake wave with peak ground acceleration 0.1 g is given in Fig. 3, which shows that the maximum displacement does not exceed the restriction $\delta_m^* = 0.07m$. The value of DM obtained according to Eq. (15) and Eq. (16) by ANSYS post-processing and numerical integration is listed in Table 2.

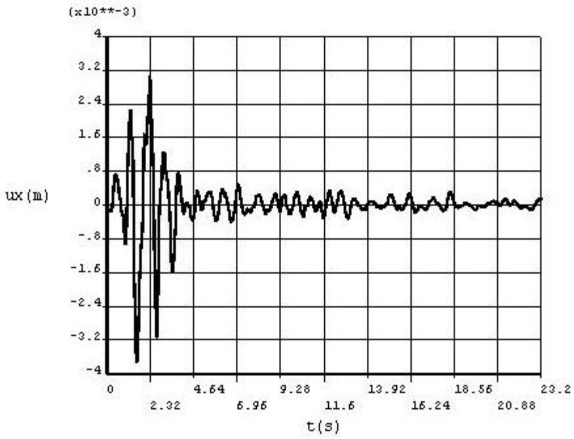

Fig. 2 The discretized model of the pier

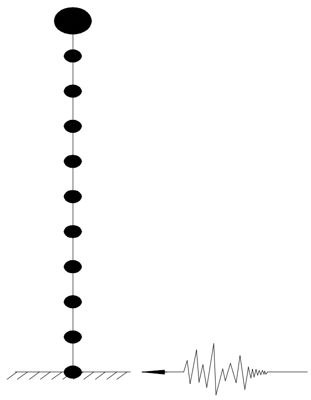

Fig. 3 Pier top displacement time-history in bridge axis direction

The results of Table 2 show that the pier's seismic energy dissipation safety factor is 6.43, 4.28, 2.07 corresponding to antiseismic levels of six, seven and eight with peak ground acceleration 0.05 g, 0.1 g and 0.2 g respectively. It's also shown that the pier's seismic energy dissipation capacity has a larger safety guarantee within the limit of displacement and damage under three antiseismic levels, and the higher the antiseismic level is, the smaller the pier's seismic energy dissipation capacity factor is.

VI. CONCLUSIONS

In this study, a new strategy to assess the seismic energy dissipation safety of reinforced concrete bridge piers was proposed. A real highway bridge pier was analyzed to show the feasibility of present theory and method by use of popular finite element software. According to the results of this study, the following conclusions can be drawn:

1. When reasonable displacement and damage controlling conditions are given, a pier's seismic energy dissipation safety factor can be obtained by energy equation based on inverse deduction of Park-Ang damage model of reinforced concrete bridge pier.

2. With structural earthquake input energy calculated in elastic method, relevant hypothesis of hysteretic energy dissipation model and complicated non-linear calculation course becomes unnecessary, the calculation involved in this paper is very simple and easy to be realized which can make full use of the advantage of finite element software.

3. The safety factor can be quantitatively analyzed in an earthquake corresponding to different seismic classes and damage index. The lower the antiseismic level is, the larger the pier's seismic energy dissipation capacity factor is, which really reflects the safety stock of the pier and accords with physical law well.

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4. The feasibility of proposed strategy shows that the present method may provide effective means for the seismic assessment of existing or proposed reinforced concrete bridge piers.

REFERENCES

[1] FAN-Lichu. The antiseismic design of long-span bridges[M]. Beijing:China, People's Communication Press, 2001：107-108

[2] ZHOU-Zhihui, ZENG-Qingyuan, XIANG-Jun.Analysis of bridge lateral rigidity for new Xinzhen Bridge[J].Journal of Central South University. 2006.37(1):165-168

[3] WANG-Mengpu, MI-Yonghong. Nonlinear seismic response analysis of the reinforced concrete frame-shear wall structure based on energy principle[J]. Earthquake Resistant Engineering and Retrofitting. 2004.04（2）15-16

[4] Park Y J , Ang H S. Mechanistic Seismic Damage Model for Reinforced Concrete[J]. Journal of Structure Engineering ,ASCE , 1985 , 111(4) : 722-739.

[5] QU-Yueqian, LIANG-Xingwen, TIAN-Ye. Evaluation of seismic damage performance based on energy analysis[J]. World Information On Earthquake Engineering. 2006.03(1):109-114

[6] OU-Jinping, HE-Zheng, WU-Bing, LONG-Xu. Seismic damage control design of reinforcement concrete structures[J]. Journal Of Building Structures. 2002.02(1):63-76.

[7] WANG-DongShen. A Comparative Study of Modified Park-Ang Model and Park-Ang Model for Structural Seismic Damage Evaluation[J]. Earthquake Resistant Engineering and Retrofitting. 2005.12 (27):138-144.

[8] XIAO-MingKui, LIU-Gang. The characteristic analysis on the hysteretic energy of the structure and influencing factors[J]. Engineering Mechanics. 2000.(supplement):242-247

[9] XIE-Xu. Seismic response and earthquake resistant design of bridge[M]. People's Transportation Press.2006:246

[10] XIAO-MingKui, LIU-Bo. Analysis of the Total Energy and Its Influencing Factors for Seismic Structures[J]. Journal of Chongqing Jianzhu University. 1996,06(2): 20-33

[11] LIU-Bo, XIAO-Mingkui. Distribution of Earthquake Total Input Energy of Structures[J]. Journal of Chongqing Jianzhu University. 1996,06 (2) : 100-109.

[12] JIANG-Hui, ZHU-Xi. Energy And Displacement Ductility Demand Imposed by Near-fault Earthquake Ground Motions[J]. Earthquake Resistant Engineering. 2005.8（4）:58-62

[13] CHENG-Guangyu, YE-Lieping. Research on Seismic Energy Demand of Elastic MDOF System[J]. Earthquake Resistant Engineering. 2006.8（4）6-9

[14] Guidelines for seismic design of highway bridges (JTG/T B02-01-2008).Beijing,Ministry of Transport of the People's Republic of China, 2008.10

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