A STUDY ON SEISMIC VULNERABILITY ANALYSIS OF CONCRETE GRAVITY DAM WITH STRAIN RATE EFFECT

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ABSTRACT

The seismic vulnerability analysis of gravity dam can predict the probability of dam damage at different levels under different seismic loads. It is significant to evaluate the seismic safety, optimize the seismic design and develop the reinforcement measures of gravity dam. Based on the uncertainty of the material parameters of concrete and the earthquake, the seismic vulnerability analysis of the Koyna gravity dam with the strain rate effect is carried out. The dam vulnerability analysis method and the seismic vulnerability curve of Koyna gravity dam are given. The results show when the strain rate effect is considered, the probability of severe damage and dam break is less than without considering strain rate effect. Dam head break, dam heel crack and combination failure are the typical seismic damages of gravity dam, which is in line with the actual damage of the Koyna dam.The results show that the dam head, dam heel and slope break are the key parts to focus.

KEYWORDS

Concrete gravity dam, Strain rate, Seismic vulnerability, Earthquake risk, Damage grade

INTRODUCTION

Seismic vulnerability analysis, as one of the three components of seismic risk assessment (seismic vulnerability analysis, seismic hazard analysis and seismic damage assessment), can predict the probability of dam damage at different levels under various seismic loads. This is of great significance to evaluate the seismic safety, optimize the seismic design and develop the reinforcement measures of gravity dam [1-3].

The seismic vulnerability analysis of the structure was first used by Kennedy [4], Varpasuo et al. [5] in seismic analysis of nuclear power stations, and the Zion method and SSMRP vulnerability analysis method was proposed by them. The first method defines the vulnerability curve as a function of seismic parameters, the second method defines the vulnerability as a function of the local reaction parameters of the structure. Hirata et al. [6] fitted the structural response and seismic parameters to obtain the structural buckling curves by the probability distribution function of reliability. Dimova et al. [7] gave the vulnerability probability of the energy dissipation structure by fitting the system structure response and vibration parameters. Lv [8] established the response spectrum form and vulnerability analysis method with the seismic parameters by comparing the different methods of dividing the site between China and the United States. Yin [9] conducted the study of seismic vulnerability and disaster loss prediction, and the theory of structural vulnerability, earthquake hazard and disaster loss assessment are obtained. Lv and Wang [10] proposed the concept of structural partial seismic vulnerability, and the reliability expression of local earthquake vulnerability was given. In the field of seismic vulnerability of concrete dams, Ellingwood and Tekie [11] gave the vulnerability curves of the Bluestone concrete gravity dam, and the vulnerability curves of the dam under dynamic and static loads are obtained, respectively. Shen et al. [12] conducted vulnerability analysis of concrete based on performance. The peak ground acceleration was taken as the independent variable, and the overall vulnerability evaluated method was obtained. Li et al. [13] conducted that the vulnerability of the concrete was affected by the mesoscopic inhomogeneity and peak ground acceleration and other factors through the study of vulnerability. The fitting process of seismic vulnerability curve was applied in the seismic vulnerability analysis of Jin'an bridge and Fengman concrete dam.

As can be seen from the above studies, because of its irreplaceable role in structural earthquake disaster assessment, the seismic vulnerability analysis is getting more and more attention all over the world, and the satisfactory conclusions have been made in some areas. However, it is not perfect in the seismic damage analysis of concrete gravity dam. In this paper, according to the relevant parameters provided by the research group Wang Haitao and Fan Wenxiao[14-15] with considering the strain rate effect of concrete and the randomness of the material parameters of gravity dam and the earthquake, the seismic vulnerability analysis of concrete gravity dam was studied, which provided the basis for the seismic risk assessment and maintenance of concrete gravity dam.

DYNAMIC CHARACTERISTICS OF HYDRAULIC CONCRETE WITH STRAIN RATE EFFECT

Tensile property

The tensile properties of hydraulic concrete at high strain rate are mainly shown as follows: with the increase of strain rate, the tensile strength and critical strain of concrete increase, and the elastic modulus and Poisson's ratio are basically unchanged. When the quasi-static strain rate is 10-5/s, according to the "Code for design of concrete structures" (GB50010-2010)[16]:

$$\sigma = (1-d_t)E_c\varepsilon \tag{1}$$

$x \le 1$

$$d_t = 1-\rho_t\left[1.2-0.2x^5\right] \tag{2}$$

$x > 1$

$$d_t = 1-\frac{\rho_t}{\alpha_t(x-1)^{1.7}+x} \tag{3}$$

$$x = \frac{\varepsilon}{\varepsilon_{t,r}} \tag{4}$$

$$\rho_t = \frac{f_{t,r}}{E_c\varepsilon_{t,r}} \tag{5}$$

Where: α_t is the parametric value of concrete uniaxial tensile stress - strain curve descending section; $f_{t,r}$ is the representative value of uniaxial tensile strength of concrete(MPa); this paper takes 1.59MPa of uniaxial test value under quasi-static strain rate; $\varepsilon_{t,r}$ is the peak tensile strain of concrete corresponding to the uniaxial tensile strength representative value $f_{t,r}$ (s^{-1}); according to the test results, the corresponding value is 0.00157/s; d_t is damage evolution parameters of concrete under uniaxial tension.

The tensile strength of concrete under high strain rate is given by the relation given in literature [15]:

$$\frac{f_s}{f_t} = 0.094 + 1.027\log(\dot{\varepsilon}_d / \dot{\varepsilon}_s) \qquad R^2 = 0.984 \tag{6}$$

Where: f_s is dynamic tensile strength (MPa); f_t is quasi-static tensile strength (MPa); $\dot{\varepsilon}_d$ is dynamic strain rate (s^{-1}); $\dot{\varepsilon}_s$ is quasi-static strain rate (s^{-1}), it is 10^{-5}/s.

Compressive property

The compressive properties of hydraulic concrete at high strain rate are mainly shown as follows: with the increase of strain rate, the compressive strength and elastic modulus of concrete increase and the critical strain decreases. When the quasi-static strain rate is 10-5/s, according to the "Code for design of concrete structures" (GB50010-2010):

$$\sigma = (1 - d_c)E_c\varepsilon \tag{7}$$

$x \leq 1$

$$d_c = 1 - \frac{\rho_c n}{n - 1 + x^n} \tag{8}$$

$x > 1$

$$d_c = 1 - \frac{\rho_c}{\alpha_c (x-1)^2 + x} \tag{9}$$

$$\rho_c = \frac{f_{c,r}}{E_c \varepsilon_{c,r}} \tag{10}$$

$$n = \frac{E_c \varepsilon_{c,\gamma}}{E_c \varepsilon_{c,\gamma} - f_{c,\gamma}} \tag{11}$$

$$x = \frac{\varepsilon}{\varepsilon_{c,r}} \tag{12}$$

Where: α_c is the parameter values of descending section of stress-strain curve of concrete under uniaxial compression, $f_{c,r}$ is representative value of the uniaxial compressive strength of concrete(MPa), in this paper, the experimental value of quasi - static strain rate of uniaxial compression test is 20.26Mpa. $\varepsilon_{c,r}$ is the concrete peak compressive strain (s^{-1}) corresponding to the uniaxial tensile strength representative value $f_{c,r}$, according to the test result, the corresponding value is 0.00921/s; d_c is the damage evolution parameters of concrete under uniaxial compression.

The compressive strength of concrete under high strain rate is given by the relational formula in Ref. [15]:

$$\frac{f_d}{f_s} = 0.99388 - 0.1008\left(\dot{\varepsilon}_d / \dot{\varepsilon}_s\right) \qquad R^2 = 0.97206 \tag{13}$$

Where: f_d is the dynamic compressive strength (MPa), fs is the quasi-static compressive strength (MPa); $\dot{\varepsilon}_d$ is the dynamic strain rate (s^{-1}); $\dot{\varepsilon}_s$ is the quasi-static strain rate (s^{-1}), it is 10^{-5}/s.

Calculation Model and Parameters of Concrete Gravity Dam

Based on the randomness of the material parameters of gravity dam and the earthquake, and combined with the strain rate effect of the concrete material, the seismic damage mode of the Koyna dam in India is simulated. The criterion of seismic damage level of Koyna gravity dam is also established.

The Koyna Dam located in Mumbai, India, is a typical concrete gravity dam, the length is 850m, the height is 103m. In 1967, it suffered 6.7 magnitude earthquake, epicenter distance was 13km, the water level in the front of dam was 91.7m. After the earthquake, the dam appeared some seismic damages. Such as [17] the upstream and downstream surface of non-overflow dam section produced a lot of distribution cracks, and the seepage quantity increased. However, the cracks whether through the dam cannot be determined.

The finite element software ABAQUS is used to analyse the seismic response of Koyna gravity dam in this paper. The calculation model is shown in Figure 1. In order to eliminate the influence of dam foundation boundary conditions on the stress of dam body, it is necessary to expand the scope of finite element model. Therefore, the foundation extends down 1.5 times the dam height from the bottom of the dam, and extends 3 times and 1.5 times respectively from the dam heel and toe to the upstream and downstream along the river direction. The model is divided into eight nodes hexahedron linear reduction integral unit C3D8R, in which there are 15200 units of dam body and 21660 units of foundation, a total of 39958 nodes. The static calculation parameters used in the model were shown in the Table 1, the concrete strength of the dam is measured by the uniaxial tension and uniaxial compressive strength at quasi-static strain rate, and the linear elastic model is adopted for the foundation of the dam.

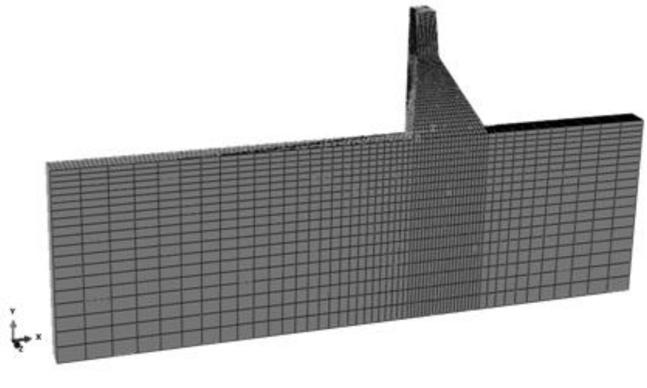

Fig. 1 - Model of Koyna dam

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Tab. 1 - Material properties of Koyna dam

	Elastic Modulus	Poisson's ratio	Density	Static compressive strength	Static tensile strength
Dam body	31.2GPa	0.2	2642kg/m^3	20.26MPa	1.59MPa
Bedrock	30.0GPa	0.2	2600kg/m^3	-	-

The material parameters of the concrete refer to the probability density function given in the design code of nuclear power plant in America [18], where the statistical values of elastic modulus, tensile strength, Poisson's ratio and density are expressed as normal distribution, the ratio of elastic modulus to center deviation is 0.18 when the tensile strength exceeds 90%, the ratio of Poisson's ratio to center deviation is 0.1 when the density exceeds 90%. The damping ratio of concrete material fluctuates greatly under the seismic load. According to the study of Housner et al.[19], when the concrete dam is subjected to a small earthquake, the damping value can be less than 0.1, while under strong earthquakes, the damping ratio may be greater than 0.15. In view of the results of this study, the damping of the gravity dam assumed in this paper is evenly distributed in the range of [0.03, 0.15].

The plastic-damage model of the concrete solid element was provided by the properties module of ABAQUS, and the data related to the strain rate can be entered in the software. When the element is in compression, the yield stress, inelastic strain and strain rate are input in the corresponding properties module, and the yield stress, cracking strain and strain rate are input in the module when the element is in tension. Therefore, the plastic-damage model without considering the strain-rate (model I) and the plastic-damage model (model II) considered the strain-rate are used in the calculation of the concrete.

In order to make the conclusion sufficient accuracy and consider the amount of calculation, 30 random samples were generated for each parameter. Taking the acceleration of the seismic wave into account, a total of 6 peak acceleration of 0.23g, 0.37g, 0.474g, 0.60g, 0.70g and 0.80g are selected to analyze the structural vulnerability of Koyna gravity dam under seismic load.

CLASSIFICATION METHOD OF SEISMIC DAMAGE LEVEL OF CONCRETE GRAVITY DAM

Due to the uncertainty of the parameters of the concrete materials and the seismic load, it is difficult for the concrete gravity dam to have the same damage even under the same seismic load. Tao and Xia [20] divide the damage of concrete gravity dam caused by the seismic load into five levels, which include basically intact, minor damage, medium damage, serious damage and dam break. The details are shown in the Table 1. (D means the earthquake damage index, the value range is $0 \le D \le 1$).

Tab.1 - Seismic damage levels and index of dams

Damage level	Summary of dam damage	Damage index(D)	Interval partition
Basically intact	The dam body is basically intact, very few parts may appear small cracks, the dam body meets the basic requirements basically	0.0	$0 \le D \le 0.1$

Minor damage	Dam cracks may have the possibility of damage, subordinate and other ancillary structures are slightly damaged, the local dam can meet the requirements by repair	0.2	$0.1 < D \le 0.55$
Medium damage	The dam can be seen a number of obvious cracks, may have a slight leakage, the destruction of the additional structure are severely damaged, need to be repaired before they can be put into use	0.5	$0.4 < D \le 0.55$
Serious damage	The dam body forms a number of through cracks, dam body structure was seriously damaged, has a severely leakage, it is difficult to meet the requirements even after the repair	0.75	$0.55 < D \le 0.85$
Dam break	Dam is completely damaged, cannot be repaired, cannot continue to complete the design function	0.9	$0.85 < D \le 1$

Figure 2 shows the typical seismic damage modes obtained by finite element analysis of Koyna gravity dam with considering the uncertainty of the seismic load and the strain rate effect of

the concrete material. It can be seen in Figure 2 (a) that the gravity dam model has only minor cracks at the dam heel, and the dam is basically intact and does not affect the function of the dam. It can be seen in the Figure 2(b) and (c) that the dam head and dam heel have obvious cracks, although it will not appear flood discharge suddenly, it also needs to be repaired as soon as possible. In the Figure 2(d), (e) and (f), the heel cracks gradually spread to the downstream surface, the bottom of the dam also appeared cracks and the cracks penetrate to the heel cracks, the dam loss its function in a certain extent.

(a) (b) (c)

Fig. 2 - Failure modes of the Koyna dam

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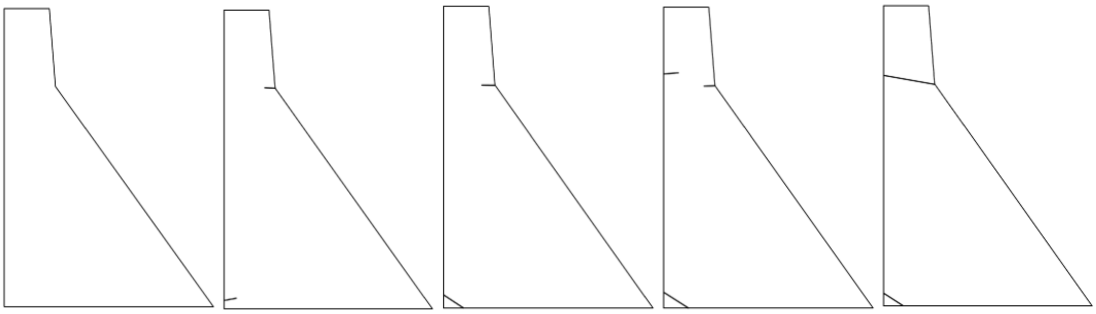
(d) (e) (f)

Fig. 2 - Failure modes of the Koyna dam

Based on the simulation results of seismic damage of Koyna gravity dam, and referred to the conclusion in Table 1, the damage of concrete gravity dam caused by the seismic load were divided into five levels, which are basically intact, minor damage, medium damage, serious damage and dam break. Simplified figure of seismic damage Koyna gravity dam is shown in the Figure 3, and the specific destruction circumstances of different level are as follows.



(a) (b) (c) (d) (e)

Fig. 3 - Seismic damage index of the dam

(1) Basically intact: The dam body is basically intact, very few parts may appear small cracks, the dam body meet the requirements basically, as shown in Figure 3 (a).
(2) Minor damage: Many locations appear small cracks, individual cracks are more obvious, some need to be repaired to meet the requirements, as shown in Figure 3 (b).
(3) Medium damage: A number of cracks have a slight leakage, the subsidiary structure and the dam crest have a large crack, need a lot of repair work can be restored, as shown in Figure 3 (c).
(4) Serious damage: Crack perforation, dam head fracture. The crack length is greater than 1/3 of the cracking path, and it is difficult to repair. But the catastrophic flood will not flow down, as shown in Figure 3 (d).
(5) Dam break: Dam is completely damaged, cannot be repaired, the dam is completely out of functionality, as shown in Figure 3 (e).

SEISMIC VULNERABILITY ANALYSIS METHOD OF CONCRETE GRAVITY DAM

There are two main ways to determine the vulnerability curve of gravity dam: One is according to the actual seismic acceleration and damage situation of the dam, the relationship between the damage level and seismic peak acceleration was established when the actual earthquake damage occurred. This method is close to the actual project, the reliability is high. However, because of lots of the influence factors of the dam vulnerability analysis, this method can only be applied in the similar vulnerability analysis, which requires a lot of statistical information, it is too difficult to be used in a wide range. The other is through the numerical simulation to obtain the vulnerability curve, this method is not affected by the actual conditions, so it can be used to analyse the seismic response of gravity dam under any conditions, it costs less manpower and material resources, and easy to use widely. According to the literature [21], the gravity dam vulnerability curve can be expressed by equation (14):

$$F = \Phi\left(\frac{\ln PGA - m_{PGA}}{\sigma_{PGA}}\right) \tag{14}$$

Where: Φ is the standard normal distribution; PGA is the peak ground acceleration; m_{PGA}, σ_{PGA} are the logarithmic mean value and logarithmic standard deviations of the acceleration peaks when the gravity dam reaches a certain level of failure,

Introducing the intermediate variables,

$$Z' = \frac{\ln PGA - m_{PGA}}{\sigma_{PGA}} \tag{15 }$$

$\overline{X} = \ln PGA$

$$Z' = \frac{1}{\sigma_{PGA}}\overline{X} - \frac{m_{PGA}}{\sigma_{PGA}} \tag{16}$$

Take Z as the ordinate, X as the abscissa to establish the coordinate system, the expression (16) is a straight line, as shown in Figure 4, $-\frac{m_{PGA}}{m_{PGA}}$, $\frac{1}{\sigma_{PGA}}$ are intercept and slope of the line respectively.

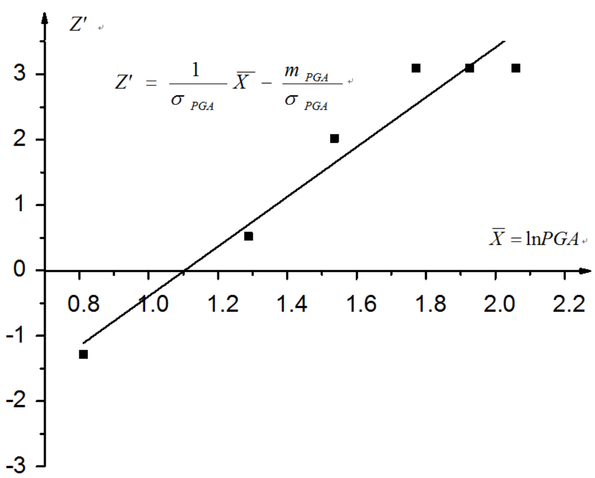


Fig. 4 - Probability of the lognormal distribution

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The simulated data was used to evaluate m_{PGA}, σ_{PGA} , and the value was substitute into equation (14), the normal distribution function with PGA as the independent variable is gained, and then the vulnerability curve can be obtained.

The seismic vulnerability analysis method adopted in this paper is to obtain the material parameters of the corresponding probability distribution by using the random sampling method firstly. Secondly, the material parameters are converted with the strain rate effect, and then the finite element analysis of the plastic - damage mechanics model was carried out under different peak seismic waves. The failure mode of the gravity dam is compared with the standard of the earthquake disaster proposed in this paper, and the probability of breakage of all levels at a certain peak acceleration can be determined. Finally m_{PGA}, σ_{PGA} can be fitted out and substituted into the formula to get the vulnerability of the seismic fragility curves of gravity dam. The basic process of gravity dam seismic vulnerability analysis is shown in Figure 5.

SEISMIC VULNERABILITY ANALYSIS OF KOYNA GRAVITY DAM

Taking Koyan gravity dam as an example, the seismic vulnerability analysis of gravity dam is carried out by using the above analysis method. In this paper, the 30 groups of material parameters without considering the strain rate and the revised 30 groups of material parameters considering the strain rate are combined with the 6 seismic waves with different peak acceleration, respectively, and a total of 360 samples were calculated by finite element method. The 360 groups of damage modes of the gravity dams are regular, but the results are not exactly same because the randomness is taken into account in the analysis process. Several representative gravity dam damage models are selected in Fig2. The seismic damage modes of 360 models were classified and categorized, and the statistical results were shown in Table 2 and Table 3.

It can be seen from Table 2 and Table 3, when the peak ground acceleration is 0.23g, the gravity dam is not damaged to a great extent, the gravity dam can be considered to be in the elastic stage under the seismic wave. When the peak ground acceleration is 0.37g, the failure phenomenon is mainly dam head failure, and individual phenomenon are dam heel failure and combination failure. With the increase of peak ground acceleration, the dam head failure alone is less and less, and the dam heel failure and the combination failure are proportional to the acceleration. In addition, it is noted that there is a serious failure like the combination failure at low peak ground acceleration, and also there is a slight damage at higher peak accelerations, this is because the uncertainty of the parameters of the concrete material was took into account during the analysis process. In general, the seismic damage degree of concrete gravity dam is exacerbated with the increase of peak ground acceleration. In comparison with Table 2 and Table 3, considering the effect of the concrete strain rate effect, it is found that the number of dam crest damage and minor damage is increased, but the number of dam heel failure and combination failure is reduced, the concrete tensile strength and elastic modulus are increased due to the effect of strain rate.

Tab. 2 - Probability of failure modes of dams without consideration of strain rate

	0.23g	0.37g	0.474g	0.60g	0.70g	0.80g	Total number	probability
Dam head failure	0	6	5	2	1	1	15	8.34%
Dam heel failure	0	1	3	6	10	11	31	17.22%
Combination failure	0	1	6	14	17	18	56	31.11%
Others	30	22	16	8	2	0	78	43.33%
Failure probability of crack penetration	0	26.67%	46.67%	73.33%	93.33%	100%		

Tab.3 - Probability of failure modes of dams considering strain rate

	0.23g	0.37g	0.474g	0.60g	0.70g	0.80g	Total number	probability
Dam head failure	0	5	5	4	3	3	20	11.11%
Dam heel failure	0	1	3	2	9	10	25	13.89%
Combination failure	0	0	4	13	15	17	49	27.22%
Others	30	24	18	11	3	0	86	47.78%
Failure probability of crack penetration	0	20.0%	40.0%	70.0%	90.0%	100%		

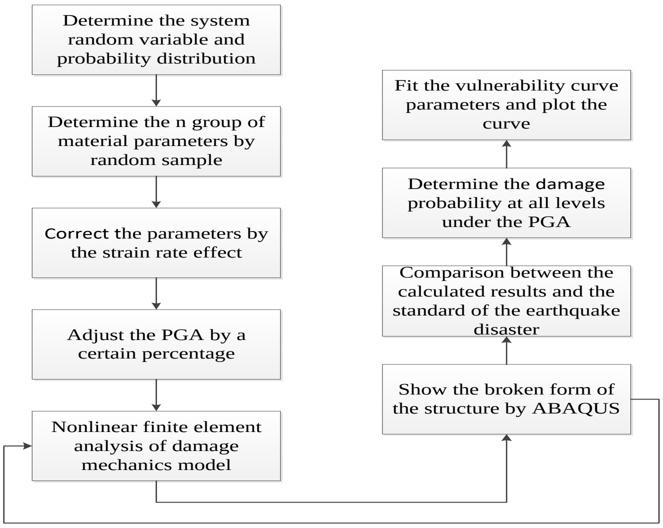

Fig. 5 - Procedure of seismic vulnerability analysis

According to the classification method of seismic damage level of concrete gravity dam proposed in Section 3, the simulated 360 groups of damage models are classified. According to the formula (16), the parameters m_{PGA}, σ_{PGA} are fitted and the results are shown in Table 4 and Table 5, respectively.

Tab. 4: Parameter values of fragility curves of the dam without consideration of strain rate

Damage level	m_{PGA}	σ_{PGA}
Minor damage	1.0956	0.2632
Medium damage	1.3609	0.1877
Serious damage	1.5184	0.2191
Dam break	1.8603	0.3573

Tab. 5: Parameter values of fragility curves of the dam consideration of strain rate

Damage level	m_{PGA}	σ_{PGA}
Minor damage	0.9577	0.3227
Medium damage	1.3960	0.1956
Serious damage	1.6460	0.2727
Dam break	1.9543	0.3778

The data in Table 4 and Table 5 are brought into the vulnerability curve formula (14), and two kinds of seismic vulnerability curves of gravity dam are obtained which acceleration ground peak and seismic damage exceeding probability is independent variables and dependent variables respectively, as shown in Figure 6 and Figure 7.

It can be seen from Figure 6 and Figure 7, due to the uncertainty of the material parameters of the concrete, when the peak ground acceleration is small, it may cause serious damage and dam break, and when the peak ground acceleration is large, the phenomenon of minor damage or basically intact might occur. But in general, the degree of seismic damage is aggravated with the increase of the value of peak ground acceleration. In addition, under the design value of peak ground acceleration (0.474g) and without considering the effect of concrete strain rate, the probability of dam breakage is 17.1%, the probability of serious damage and dam break is 37.6%. The probability of dam break is 12.5%, and the probability of serious damage and dam break is 31.4% when considering the effect of concrete strain rate. The probability of dam break is 56.4%, the probability of serious damage and dam break is 97.2% without considering the strain rate effect of concrete at 1.5 times the peak ground acceleration. Considering the strain rate effect of concrete, the probability of dam break is 50.7%, the probability of serious damage and dam break is as high as 86.9%. It can be seen that the probability of serious damage of gravity dam is reduced when considers the strain rate effect, and the reduction amplitude increases with the increase of peak ground acceleration.

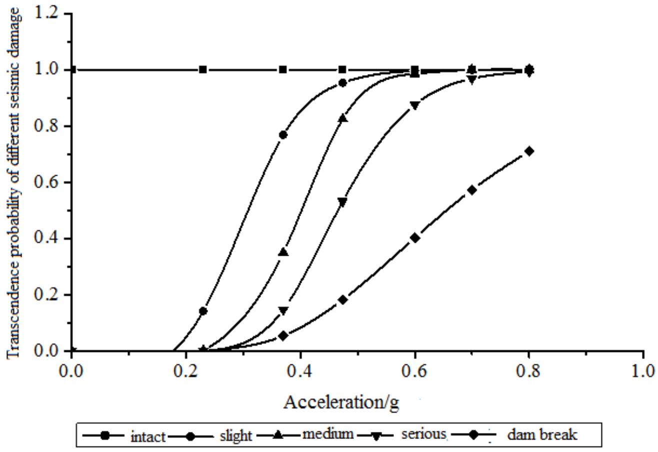

Fig. 6 - Seismic vulnerability curves of the Koyna dam without considering strain rate

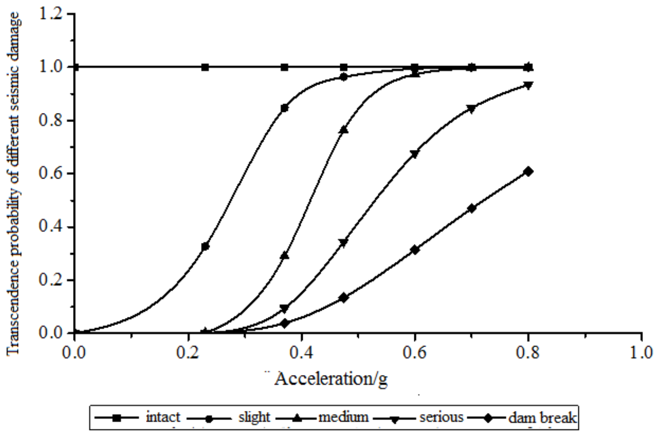

Fig. 7 - Seismic vulnerability curves of the Koyna dam considering strain rate

CONCLUSION

Considering the uncertainty of earthquake and the material parameters of concrete, the seismic vulnerability analysis of Koyna gravity dam is carried out with the strain rate effect of concrete, and the following conclusions are obtained.

According to the classification standard of seismic damage level of gravity dams proposed in this paper, and the vulnerability curve with the peak ground acceleration is obtained. Under the design value of peak ground acceleration (0.474g) and without the effect of strain rate, the probability of serious damage and dam break is 37.6%. And considering the effect of concrete strain rate effect, the probability of serious damage and dam break is 31.4%.The probability of serious damage and dam break is 97.2% without considering the strain rate effect of concrete at 1.5 times the peak ground acceleration. The probability of serious damage and dam break is 86.9% when the strain rate is considered. It can be seen that the probability of serious damage of gravity dam is reduced after considering the strain rate effect, but in order to meet the requirements of gravity dam, the vulnerable parts still need to be strengthen.

The earthquake magnitude is proportional to the seismic damage level of the gravity dam, considering the randomness of the parameters of concrete parameters; individual earthquake magnitude is inversely proportional to the damage degree of the gravity dam. Dam head break, dam heel crack and combination failure are the typical seismic damages of gravity dam, which is consistent with the actual damage. And with the increase of the earthquake magnitude, the damage degree is more and more obvious. Therefore, the dam head, dam heel and slope break are the need to focus on the site during the process of optimization design and maintenance of gravity dam.

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