SEISMIC FRAGILITY ASSESSMENT OF CONCRETE GRAVITY DAMS

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ABSTRACT

Concrete gravity dams are one of the most important infrastructures so maintaining of them in good conditions is an important concern for dam owners. They should able to continue their function after a disaster such as earthquake. But most of them are aged dams with some have been built near faults. Indeed, there are some concerns regarding the performance of these dams under the effect of seismic loads. In recent years some criteria about linear performance of these dams have been developed. But the same cannot be said about nonlinear performance of these dams, which seem to lack well-developed criteria. In this paper we shall try to devise a set of criteria concerning nonlinear performance of concrete gravity dams that have been affected by near field earthquakes. Having done that, we shall then apply these criteria in order to illustrate seismic fragility curves for Pine Flat dam. The fragility curves show the dam is very vulnerable when an earthquake strikes it with the peak ground motion more than 0.25g.

INTRODUCTION

In recent years, the growing knowledge of seismic hazard and improvement in designing techniques of dams have caused an increased awareness and concerns regarding the performance and reliability of aged concrete gravity dams under the effect of seismic loads. As a result, dam engineers seek to develop the most reliable methods of investigating safety issues affecting concrete gravity dams before beginning a rehabilitation process for these dams. Undoubtedly, one of the best methods of analyzing these dams is a nonlinear dynamic time history analysis. Nonetheless, there are always some uncertainties concerning the behavior of these dams under seismic loads. Some uncertainties are related to issues such as the material properties of dam and foundation, the differences between shape and height of dams and so on. Others go back to insufficiency of our knowledge regarding seismic hazards and earthquake characteristic. Because of these factors, the most promising method for analyzing concrete gravity dams seems to be a combination of nonlinear dynamic time history analysis topped by applying our knowledge of probabilities that could be inferred from seismic fragility curves.

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This paper attempts to introduce a methodology for illustrating seismic fragility curves of concrete gravity dams by concentrating on data on Pine Flat dam (Figure 1) that was built near Fresno, California in 1954.

FRAGILITY ANALYSIS

PROBABILISTIC SAFETY ASSESSMENT

For the purpose of dam safety, some limit states should be introduced in order to investigate performance levels of a dam. For example in frames, this limit state could be drift of stories, rotation of nodes, etc. For obtaining seismic fragility curves, the probability of exceeding to this structural limit state should be considered. In the equation (1), fragility is the probability of engineering demand parameter (EDP) that exceeds structural limit state (LS) at the defined PGA.

$$Fragility = P[EDP > LS \mid PGA] \tag{1}$$

This probability could be presented by lognormal distribution or some of the others distributions:

$$Fragility = P[EDP > LS \mid PGA] = 1 - P[EDP < LS \mid PGA] = 1 - \Phi\left[\frac{\ln(LS) - \mu}{\sigma}\right] \tag{2}$$

In the equation above Φ is standard normal probability integral, μ is mean of data and σ is logarithmic standard deviation.

STRUCTURAL MODELING OF DAM BEHAVIOR

Smeared Crack Model

In this research, smeared crack model was used for the purpose of analysis. The constitutive model for smeared fracture analysis defining (i) the pre-softening material behavior, (ii) the criterion for softening initiation, (iii) the fracture energy conservation, and (iv) the softening, closing and reopening of cracks [4].

Description of Model

With regard to the above-mentioned dam, an educational computer code, NSAG-DRI [3] was used to carry out the nonlinear analysis of the tallest monolith of Pine Flat Dam. This code was capable of carrying out coupled equation of dam-reservoir system. For modeling of tensile stress on dam's body smeared crack model was applied. The 4-node, quadrilateral, isoparametric finite element model of this monolith in plane stress has been illustrated in Figure 2. The model had 5664 nodes (3768 nodes at foundation) and 5512 elements. For modeling dam-foundation interaction, flexible massless foundation with fixed support at base and roller support for sides was used [8,9]. For this model, earthquake input applies at the lowest level of foundation (Figure 3). It was assumed that foundation has linear behavior. The length and depth of the foundation were 348m and 126m, respectively. It was assumed normal water level is 116.88 m. Sharan boundary condition was used for truncated far end of reservoir [6]. A 5 percent Rayleigh damping ratio was selected for the fundamental mode.

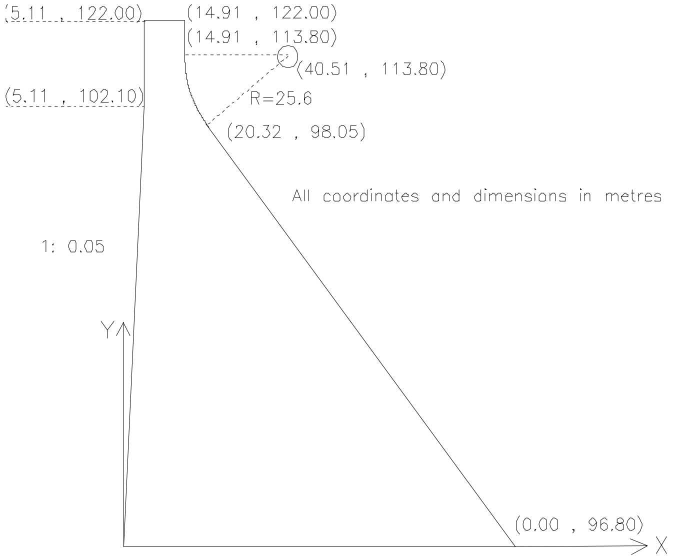

Figure 1. Dimensions of the tallest monolith of Pine Flat dam.

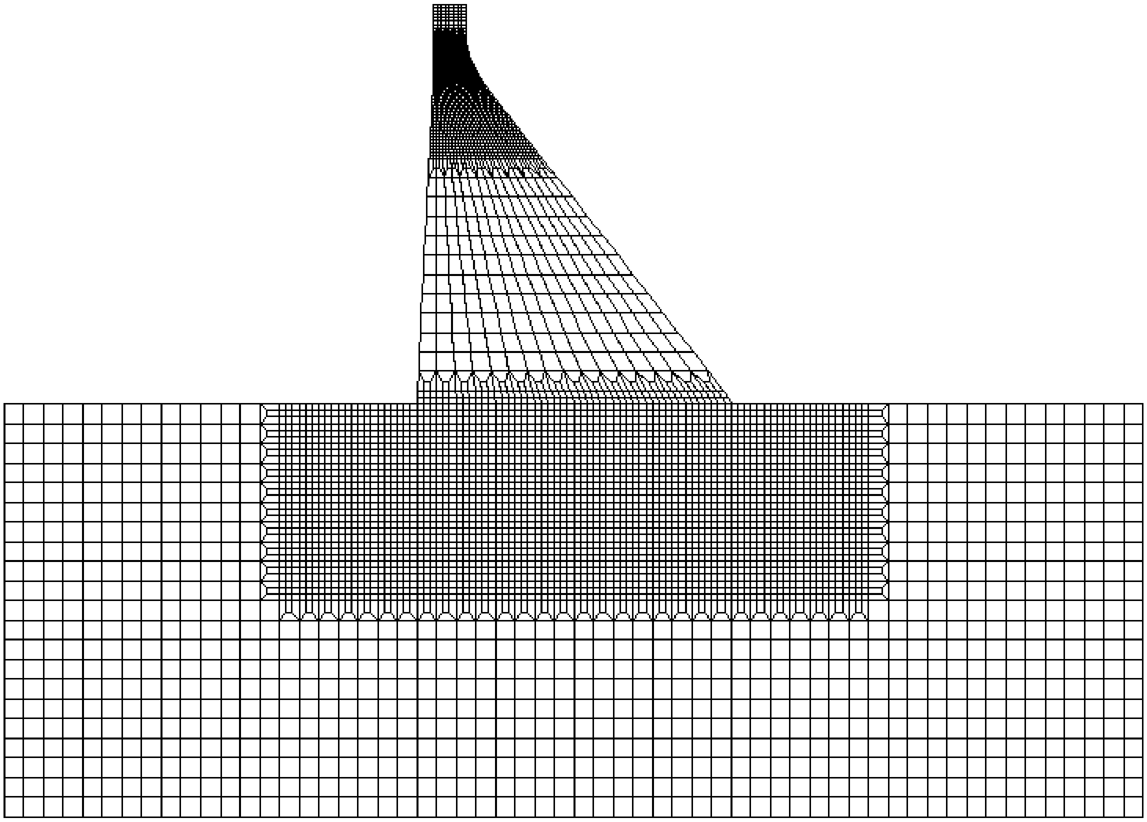

Figure 2. Finite element model of the tallest monolith of Pine Flat Dam.

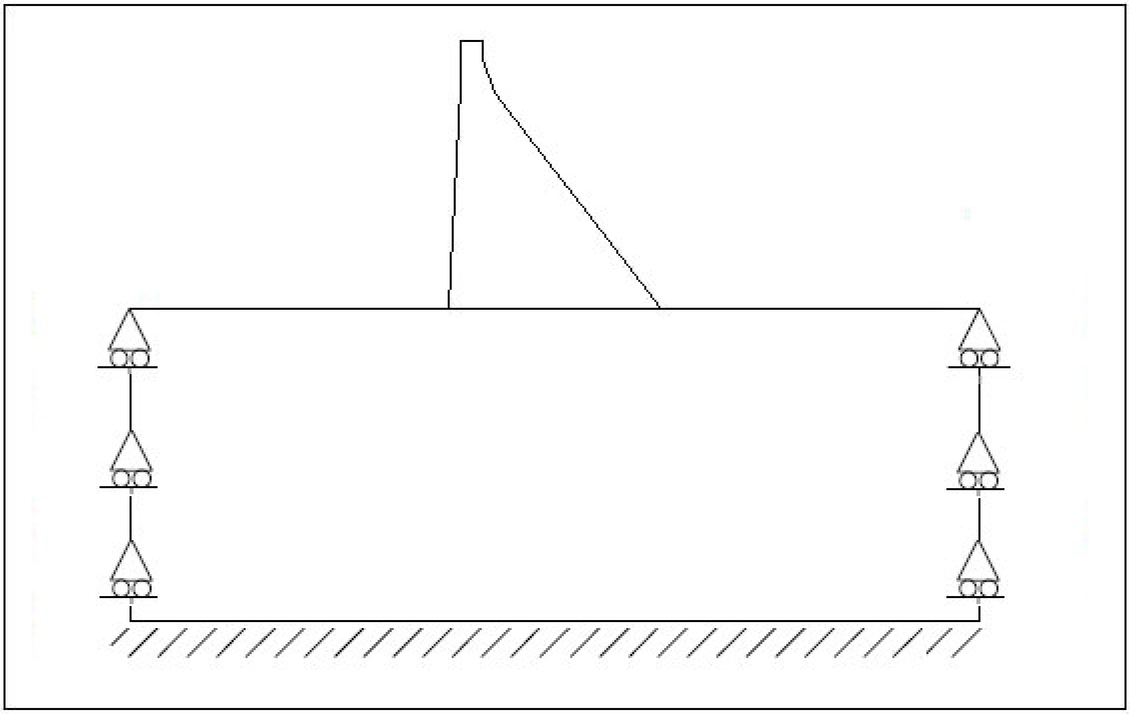

Figure 3. Boundary conditions in massless foundation model.

Material properties has been shown in Table 1 [2,4]. Tensile strength was selected conservatively based on point load strength index.

Table 1. Summary of selected parameters.

Concrete Material Properties	
Unit Weight	2483 Kg/m^3
Modulus of Elasticity	27.58 GPa
Static Tensile Strength	2.4 MPa
Poisson's Ratio	0.20
Fracture Energy (G_f)	300 N/m
Rock Material Properties	
Modulus of Elasticity	22.4 GPa
Poisson's Ratio	0.33
Wave Reflection Coefficient	$\alpha=0.82$

Earthquake Ground Motion

For evaluation of the earthquake damage, the dam was assumed to be located in the near field of earthquake event. Six selected natural acceleration time histories have been shown in Table 2. All these records have been scaled from 0.1g to 0.7g. Natural Periods of dam-reservoir-foundation system have been shown in Table 3.

Table 2. Ground Motion Records Used for Analysis [5].

Year	Earthquake	Record	Magnitude	R (km)
1989	LOMA PRIETA	Gilroy - Gavilan Coll	6.9	11.6
1994	NORTHRIDGE	Newhall, West Pico Canyon	6.7	8.0
1984	MORGAN HILL	Coyote Lake Dam	6.2	0.1
1971	SAN FERNANDO	Pacoima Dam, DS record	6.6	2.8
1992	CAPE MENDOCINO	Cape Mendocino	7.1	8.5
1994	NORTHRIDGE	Pacoima Dam, DS record	6.7	7.1

Table 3. Natural Periods (Sec).

Mode	Massless Foundation
1	0.3801
2	0.1838
3	0.1708
4	0.1095
5	0.0685
6	0.0636
7	0.0484
8	0.0456
9	0.0408
10	0.0381

RESULT FROM NONLINEAR DYNAMIC ANALYSIS AND INTRODUCING CRITERIA

Different horizontal earthquakes were applied to dam’s models to find out when the dam-reservoir-foundation system reaches to 5% energy balance error based on nonlinear dynamic time history analysis. The PGA that causes 5% energy balance error was determined by the accuracy of 0.05g.

The energy balance error is computed as equation (3). In this equation, EK is absolute kinetic energy. ED is viscous damping energy. ER is nonlinear resorting work. The work of preseismic applied force is EP, the absolute seismic input energy is EQ and the work done by hydrodynamic pressure is EH.

$$\text{Energy balance error} = \frac{(\mathrm{EP} + \mathrm{EQ} + \mathrm{EH}) - (\mathrm{EK} + \mathrm{ED} + \mathrm{ER})}{(\mathrm{EQ} + \mathrm{EH})} \times 100 \qquad (3)$$

After determining the maximum PGA that dam-reservoir-foundation can endure in every horizontal earthquakes (Figure 4), now we have to define limit states. For adopting a factor to determine limit state (LS), The factor should increase as PGA increases. As a result, tensile stress on dams' body cannot be a factor due to the fact that based on nonlinear dynamic analysis, tensile stress in cracked elements is equal to zero.

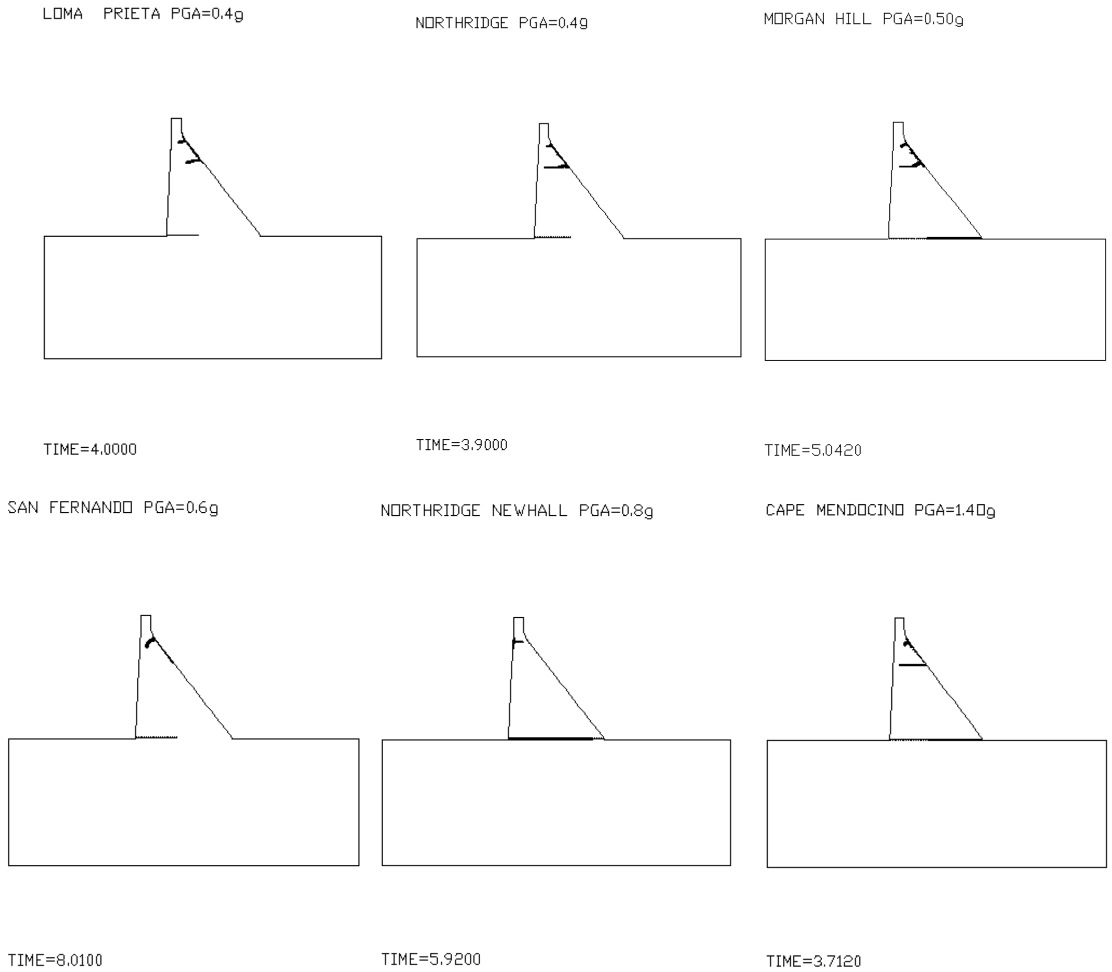

Figure 4. Propagation of cracks at the body of dam with massless foundation model.

Other factors such as deformation of crest relative to heel are somewhat inaccurate because this rotation is due to crack at the neck of dam [7]. In this research, two factors are considered for requiring criteria that enable us to develop fragility curves for concrete gravity dams. First limit state (LS1), is based on length of crack at the base. Outputs are organized in Table 4.

It is considered that, when the dam-foundation-reservoir system reaches to 5% energy balance error (Figure 4), the lowest length of crack at the toe and heel of the dam is 34m. So, for a performance level which can guarantee that the dam's structure is safe and can continue its operation, the length of crack is chosen at 75% of the lowest length of crack or 25.5 m. It means that it would be about 0.26 of dam's base length.

Second structural limit state (LS2) is introduced based on total areas of cracked elements in the body of dam. Outputs are organized in Table 5. The lowest areas of cracked elements happened for Loma Prieta earthquake when the PGA is 0.4g. For a safe performance level 75% of this area is chosen. It is about 112.5 m^2 or 0.0195 of the tallest monolith section.

Table 4. Length of crack at the toe and heel of dam for massless foundation

Earthquake record(s)	PGA	Number of cracked elements at the toe and heel	Length of crack At the toe and heel (m)	Areas of crack elements (m^2)
LOMA PRIETA	0.40g	17	34	68
NORTHRIDGE NEWHALL	0.80g	48	96	192
MORGAN HILL	0.50g	40	80	160
SAN FERNANDO	0.60g	12	42	84
CAPE MENDOCINO	1.40g	47	94	188
NORTHRIDGE	0.40g	20	40	80

Table 5. Areas of crack elements at the body of dam for massless foundation

Earthquake record(s)	PGA	Areas of cracked elements at the toe and heel of dam (m^2)	Areas of cracked elements at the neck of dam(m^2)	Total areas of crack elements(m^2)
LOMA PRIETA	0.40g	68	82.09	150.09
NORTHRIDGE NEWHALL	0.80g	192	41.04	233.04
MORGAN HILL	0.50g	160	56.78	216.78
SAN FERNANDO	0.60g	84	66.35	150.35
CAPE MENDOCINO	1.40g	188	68.41	256.41
NORTHRIDGE	0.40g	80	98.51	178.51

SEISMIC FRAGILITY CURVES

Performing nonlinear dynamic analysis, the crack length and the areas of cracked elements are determined for each 0.1g increased in PGA. By using these data, lognormal distribution and defined limit states described in the last section, seismic fragility curves have been illustrated in Figure 5 and Figure 6.

Based on a study in 2003 for raising height of Pine flat dam, seismic hazard potential at the site is low. Probabilistic seismic hazard analysis shows that the peak horizontal accelerations to be expected at the site is 0.13g with a 2,500-year return period, 0.17g with a 5,000-year return period, and 0.23g with a 10,000-year return period [1]. Two defined limit states are chosen by determining lowest amount of damage which can cause structural unreliability under effect of some powerful near field earthquakes. So the safety factor that is prepared by areas of cracked elements should be considered to be quite satisfactory.

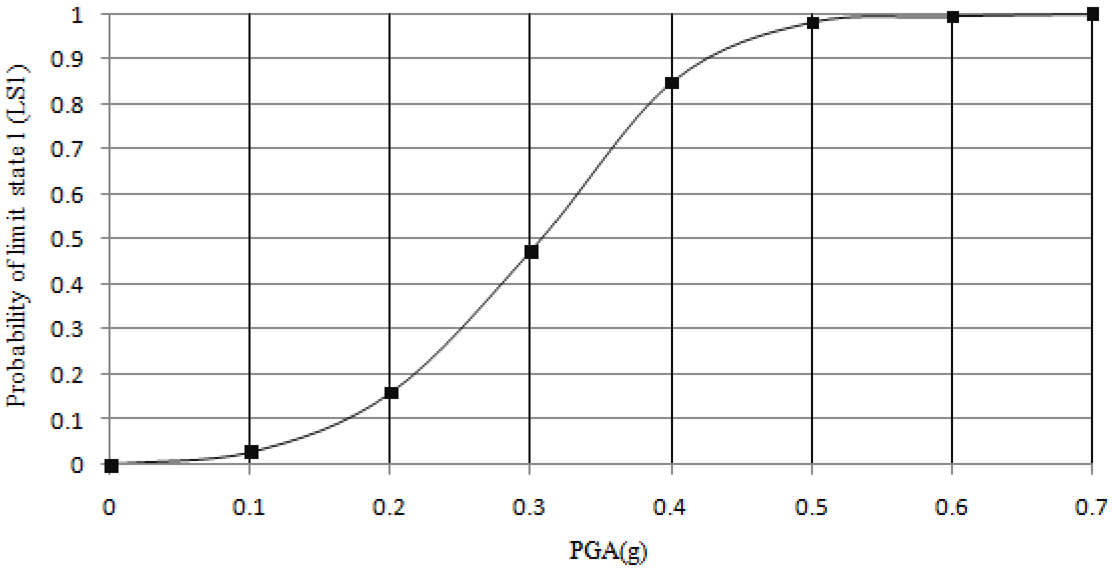

Figure 5. Seismic fragility curves based on length of crack at the base.

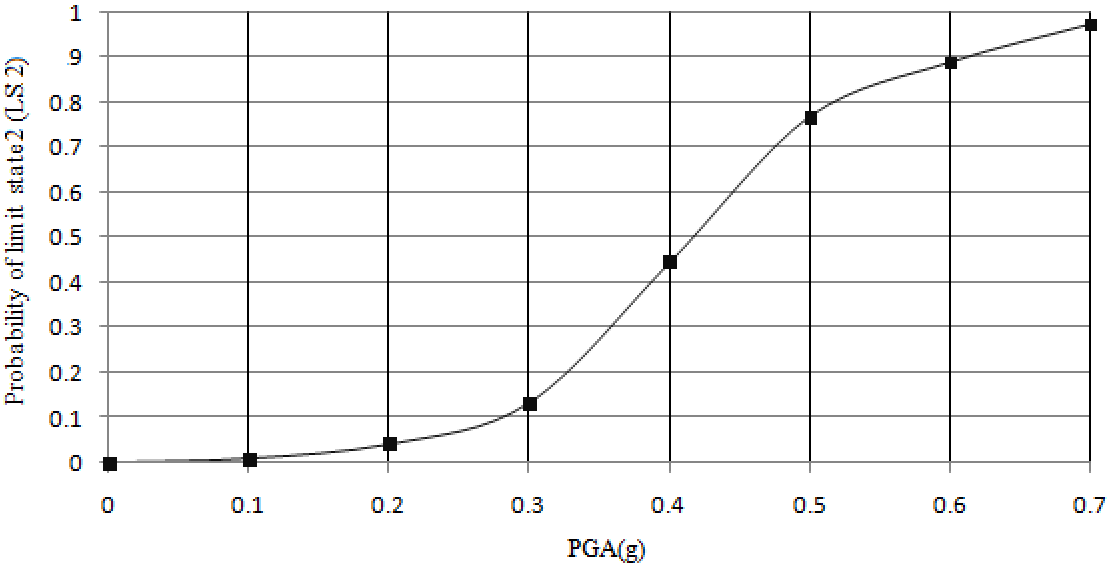

Figure 6. Seismic fragility curves based on areas of cracked elements.

SUMMARY

The seismic fragility curves that have been illustrated in this paper demonstrate that probability of occurrence of structural limit states are probable for massless foundation. Seismic fragility curves based on length of crack at the base show more probability when it compares with seismic fragility curves based on areas of cracked elements. In this respect, seismic fragility curves based on areas of cracked elements should be a more realistic approach.

The probability of occurrence of limit state 1 (length of crack) when the PGA is equal to 0.23g, is about 23 percent.

The probability of occurrence of limit state 2 (areas of cracked elements) when PGA is equal to 0.23g is lower than 6 percent. Consequently, the fragility curves based on this limit state should grant structural safety of dam even under effect of near field seismic loads.

The criterion of areas of cracked elements for drawing seismic fragility curves of concrete gravity dam should be regarded as a new approach. It means that it needs to be tested on other gravity dams' section such as Folsom. In this research the length of square elements at the base of dam's body was 2 m. By reducing this length to about 1 m the results can be more accurate.

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