On Sensitivity Analysis of a Nonlinear Gravity Dam Model

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Abstract

This paper investigates the sensitivity of the nonlinear responses in a gravity dam to the variability of the input parameters. For this purpose, the classical finite element analysis of coupled system is adopted. The coupled dynamic interaction of dam-foundation-reservoir system is modeled based on Lagrangian-Eulerian approach while the reservoir is modeled as a compressible medium and the foundation is assumed to be massless. The non-linearity in the concrete is originated from an adopted/extended rotating smeared crack model. The finite element model is excited using both the near-fault and far-field ground motions. The global parameters such as modulus of elasticity ratio, reservoir bottom absorption, reservoir length and height, earthquake intensity and etc. are assumed to be random variables. Finally, the sensitivity of the nonlinear responses in terms of crack propagation and crest displacement is assessed. Results of this research can be used in global uncertainty reduction and developing a robust probabilistic models.

Keywords: Concrete dam; seismic; crack; random variable; parametric study; probabilistic.

1. INTRODUCTION

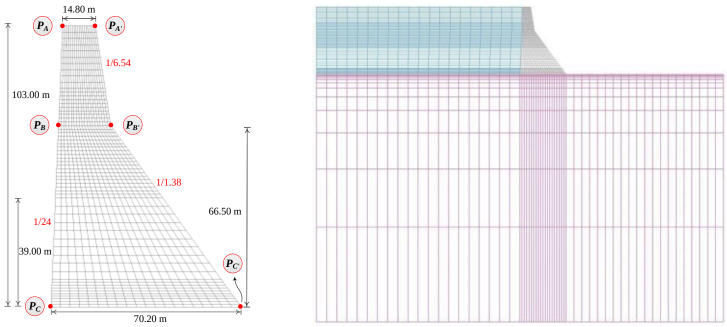
There are several important factors that influence the finite element analysis of concrete gravity dams [1]. These factors are the semi-unbounded size of the reservoir and foundation rock domains; dam-reservoir interaction; wave absorption at the reservoir boundary; water compressibility; dam-foundation rock interaction; spatial variations in ground motion at the dam-rock interface, complex nature of material and loads and also their interaction in dam-reservoir-foundation coupled system. However, it is worthy to mention that the integrative seismic analysis of a dam is combination of all these aspects which are required for realistic assessment of a coupled system [2].

In the present paper only the potential failure modes due to earthquake shaking on gravity dams are investigated. The major potential failure modes in gravity dams are due to overstressing, sliding along cracked surfaces in the dam or planes of weakness within the foundation, and sliding accompanied by rotation in the downstream direction. The consequence of cracking, if extended through the dam section, may lead to sliding or rotational instability of the separated block [3].

In the following sections, parametric finite element analysis of a concrete gravity dam is performed. The main contribution of the authors is to investigate crack behavior of the coupled system under different types of input excitations. Different finite element models are provided for this purpose taking into account both the internal and external effects. The paper discusses on each parameter individually and investigates the relative importance of each one. Finally, results are compared in terms of displacement and crack profile and an optimum numerical model is recommended. This conference paper is, in fact, a short summery of a peer-reviewed journal paper [4] already published by the authors.

2. MODELS AND MATERIALS

Koyna dam in India is selected as the case study in this investigation. The existing Koyna dam is rubble concrete gravity dam of 853 m length and 103 m height, its thickness at the base and at the crest are 70.2 m and 12.1 m, respectively for the central non-overflow monoliths. Usually due to large dimension of gravity dams in cross-stream direction the assumption of plane strain is acceptable and so gravity dams are analyzed as 2D structures [5]. In the present study one of the non-overflow blocks is modeled. The finite element model of 2D dam and its dimensions is shown in Fig. 1a. Furthermore, Fig. 1b shows the coupled dam-reservoir-foundation system. Fluid and solid elements are in interaction with each other at the interface of dam and reservoir as well as reservoir and foundation. Table 1 represents the mechanical and strength properties of the mass concrete and foundation rock. These properties are used for analysis of the base model and they may change during the parametric analyses.



(a) (b)

Figure 1: Numerical model of Koyna dam (a) 2D mesh, (b) coupled system

Table 1: Mechanical properties of mass concrete and foundation rock

	E_c (GPa)	ρ_c (kg/m^3)	υ_c	f'_t (MPa)	f_c (MPa)	G_f (N/m)	E_f (GPa)	ρ_f (kg/m^3)	υ_f
Static	31.0	2643	0.2	2.4	24	-	16.9	2700	0.33
Dynamic	35.7		0.14	3.6	36	200			

Applied loads on the system are dam body self-weight, hydrostatic pressure and seismic loads. In the case of bi-directional seismic analysis, both components are applied simultaneously to the system. The excitations are applied at the base of the foundation model. It is noteworthy that the nonlinearity of the system is originated from a co-axial rotating smeared crack approach for the concrete. This model has already been developed and tested on a gravity dam by the authors [6]. The five-parameter Willam-Warnke [7] failure criterion is used in this model.

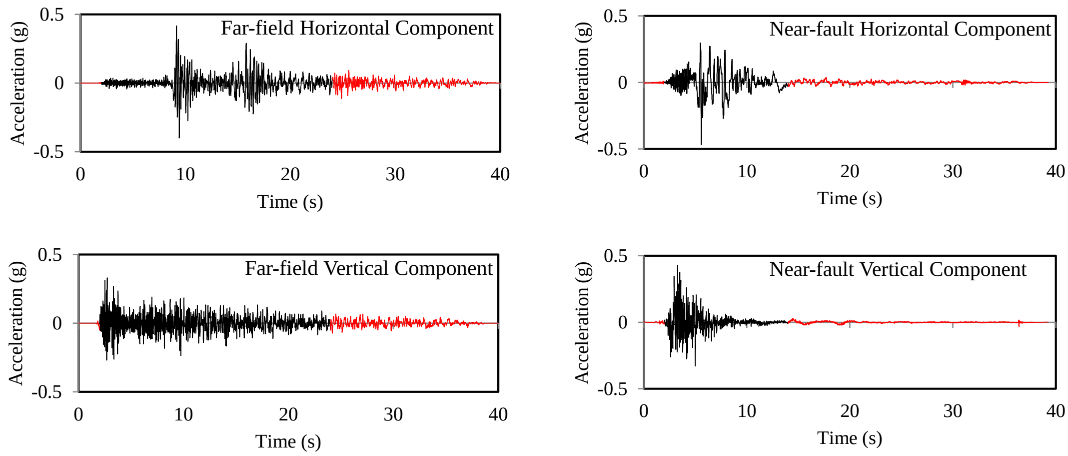
3. LOADS AND METHODS

Considering that in this paper a set of ground motions other than the original Koyna ground motion is used, hence, the smoothed response spectrum of the Koyna ground motion is used as the target one. The other ground motions are scaled in such a way to match the target spectra reasonably.

The Pacific Earthquake Engineering Research (PEER) Center ground motion database (version beta) was used for preliminary selection of two appropriate ground motions (far-field and near-fault) based on the general site characteristics of the Koyna dam [8]. Imperial Valley-06 ground motion recorded at the Victoria Station was chosen as far-field motion. Its magnitude, Mw, closest distance to co-seismic rupture, R_{rup}, and fault mechanism, Fmech, are 6.53, 31.9 km, and strike-slip, respectively. On the other hand, the Imperial Valley-06 event recorded at El Centro Array#5 Station was selected as near-fault motion. Its M_w, R_{rup}, F_{mech}, and the predominant period, T_p, are 6.53, 4.0 km, strike-slip, 4.0 s, respectively. Figs. 2a and 2b show the scaled acceleration time histories of the selected motion. In order to reduce the computational efforts in nonlinear analyses only the strong ground motion part of the records were selected (which includes at least 90% of the Arias intensity of the motion).

4. RESULTS

In this section the importance of the different parameters on nonlinear seismic response of a typical gravity dam-reservoir-foundation system is investigated. Changes in response due to changes made in the considered parameter are studied. In assessing the effects of the considered parameter, all other parameters are kept unchanged. The Newmark-β time integration method is utilized to solve the coupled nonlinear problem of dam-reservoir-foundation system. The displacement and flow characteristics are chosen as the convergence criteria in each load step of the dynamic analysis.



(a) (b)

Figure 2: Truncated ground motion time histories (a) far-field; (b) near-fault`

Based on the extensive literature survey explained in the first section and also the authors' experiences in seismic analysis of concrete dams, a base (pilot) model is chosen first. The responses of different parametric models are evaluated with respect to the base model. Considering total height of the gravity dam to be H_0, the length of the reservoir finite element model is assumed to be $3H_0$ and the water level is $0.95H_0$. The massless foundation model is assumed and the material properties are used based on Table 1. Wave reflection coefficient at the reservoir bottom is assumed 0.8. A $\xi = 5\%$ damping ratio is used in dynamic analyses. Table 2 is summarized different models used for parametric-sensitivity studies. The varying parameter in each group is highlighted.

Considering that the continuum crack model is used in the present paper, the failure of the dam is judged based on the following two criteria: (1) having at least one unstable crack through (upstream-downstream) within the dam, and (2) exceeding the maximum displacement, u_{max}, of the cracked segment from the unacceptable ultimate displacement, u_{ult}. The value of the u_{ult} was suggested to be 0.1% of H_0 in [9]. This value for Koyna dam is about 100 mm. It means that in nonlinear analysis of Koyna dam, if there is a through crack in dam body and the crest displacement (as an index point) exceeds u_{ult} = 100 mm, the case is judged to be failed.

Table 2: Summary of models used for parametric study

Group ID	1	2	3	4	5	6	7	8
Reservoir length	Varying	$3H_0$	$3H_0$	$3H_0$	$3H_0$	$3H_0$	$3H_0$	$3H_0$
Reservoir level	$0.95H_0$	Varying	$0.95H_0$	$0.95H_0$	$0.95H_0$	$0.95H_0$	$0.95H_0$	$0.95H_0$
Reservoir absorption	0.80	0.8	Varying	0.8	0.8	0.8	0.8	0.8
Foundation model	Massless	Massless	Massless	Varying	Massless	Massless	Massless	Massless
Foundation flexibility	~ 0.5	~ 0.5	~ 0.5	~ 0.5	Varying	~ 0.5	~ 0.5	~ 0.5
Damping ratio	5%	5%	5%	5%	5%	Varying	5%	5%
GM components	H+V	H+V	H+V	H+V	H+V	H+V	Varying	H+V
GM intensity	Spectrum-based	Spectrum-based	Spectrum-based	Spectrum-based	Spectrum-based	Spectrum-based	Spectrum-based	Varying

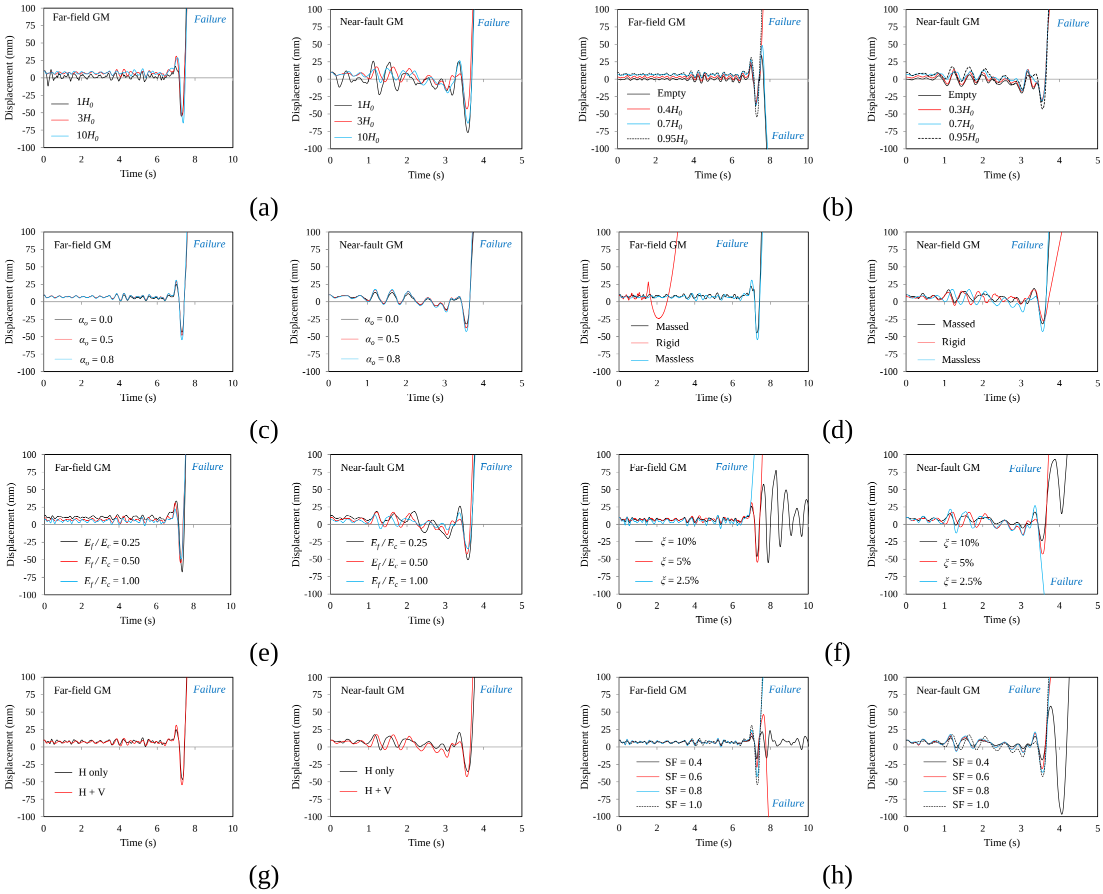


Figure 3: Impact of variable parameter on horizontal displacement time history of crest, (a) reservoir length, (b) water level, (c) reservoir bottom absorption, (d) foundation model, (e) foundation flexibility, (f) damping ratio, (g) GM component, (h) GM intensity

4.1. RESERVOIR WATER LENGTH

The length of the reservoir finite element model is assumed to be $1H_0$, $3H_0$, and $10H_0$. Fig. 3a shows the time history of crest (P_A) displacement in stream direction for the three cases. As seen, modeling the reservoir length equal to the reservoir height leads to a slightly different crest displacement than two other models. Both models with the length 3H0 and 10H0 lead to almost the same drift response. Thus, the reservoir with the length 3H0 can be the computationally optimal model. Similar conclusions derived by Bayraktar et al. [10] and Attarnejad and Lohrasbi [11]. Fig. 4a shows the crack propagation for all models. In all cases the cracks start at the slope discontinuity of the downstream face and propagate toward upstream. Under the near-fault ground motion, cracks are also propagating on the lower parts of the body in downstream face. It seems that increasing the reservoir length leads to increasing the cracked lengths; however, the crack profile of the model with the reservoir length $3H_0$ is similar to that obtained from the model with $10H_0$.

4.2. RESERVOIR WATER LEVEL

Four cases are considered for the water level, i.e. $0H_0$ (empty reservoir), $0.4H_0$, $0.7H_0$, and $0.95H_0$. Fig. 3b shows the displacement time history of the crest (P_A) point for different water levels. Increasing water level increases the initial displacement of the dam due to hydrostatic pressure. Higher water level leads to higher displacement during the seismic excitation. One cycle prior to failure, the model with $0.95H_0$ has a considerably larger displacement than the others. Fig. 4b shows the crack propagation in which reduction of water level reduces the cracked length at the dam-foundation interface. This also changes the crack profile of the neck area.

4.3. RESERVOIR BOTTOM ABSORPTION

Three cases are considered for the reservoir bottom absorption. The wave reflection coefficient, α_0, is assumed to be 0, 0.5, and 0.8. Based on Fig. 3c, the bottom wave reflection coefficient does not have a meaningful effect on displacement response of the dam. However, increasing the wave reflection coefficient increases the hydrodynamic pressure and consequently increases the displacement one cycle before failure, especially for near-fault ground motion. The results of this study are in agreement to those by Gupta and Pattanur [12]. Fig. 4c shows the crack profiles for three models. Under the far-field ground motion, the amount of the cracked elements at the neck area is almost the same; however, increasing the wave reflection coefficient increases the base cracking.

4.4. FOUNDATION MODEL

Three types of foundation models are assumed for the system, i.e. rigid, massless, and massed foundation with infinite elements. Fig. 3d shows the displacement time history. Comparing the massless and massed foundation models reveals that they have almost the same trend; however, considering the radiation damping (massed foundation) decreases the response values compared to standard massless model. A similar response was observed by Hariri-Ardebili and Saouma [13]. Seismic response of the dam under far-field ground motion and using rigid foundation model has a substantial difference with the two others. In this condition, dam fails earlier than the others. Fig. 4d shows the crack profile of the dam body. Again, comparing the massless and massed foundation models shows less cracked elements for the massed foundation. Rigid foundation model leads to extensive cracking at the base of the dam. Under the far-field ground motion, there is a large cracked area around the heel of the dam; however, under the near-fault motion a through crack is generated at the dam-foundation interface.

4.5. FOUNDATION FLEXIBILITY

Three different foundation flexibilities are tested. Ratio of the foundation modulus of elasticity to the concrete is assumed to be 0.25, 0.50 and 1.0. Fig. 3e shows the displacement time history. Increasing the modulus of elasticity of foundation leads to decreasing both the initial static displacement due to hydrostatic pressure and dynamic displacement of the dam. This observation is similar to those reported by Hall [14]. Fig. 4e shows the crack profile of the dam. As seen, in general, increasing the modulus of elasticity of the foundation leads to increasing the number of cracked elements at the lower parts of the dam especially at dam-foundation interface. However, crack profile of the neck is decreased slightly. In the case of E_f equal to E_c, almost the entire dam-foundation interface is cracked. This observation matches well with the research by Motamedi et al. [15] on seismic response of PineFlat gravity dam.

4.6. DAMPING RATIO

Three different structural damping ratios are taken into account, i.e. ξ = 2.5%, ξ = 5% and ξ = 10%. Considering that the bounded Rayleigh damping formulation is used in the present study, three different pairs of α_M and β_K are computed. Fig. 3f shows the displacement time history of the crest point for different values of the damping. It can be concluded that using higher damping ratio decreases the displacement response almost during whole range of dynamic excitation. Using ξ = 2.5% leads to early failure of the model at least one cycle prior to the model with ξ = 5% fails. This observation satisfies well with those reported by Chuhan et al. [16] for arch dams. Fig. 4f shows the crack profile resulted from different damping ratios. As seen, increasing the damping ratio leads to decreasing the damaged area and reduces the crack profile of the dam. The reduction in number of cracked elements is perspicuous in the neck area for far-field ground motion and in the dam-foundation interface for the near-fault ground motion.

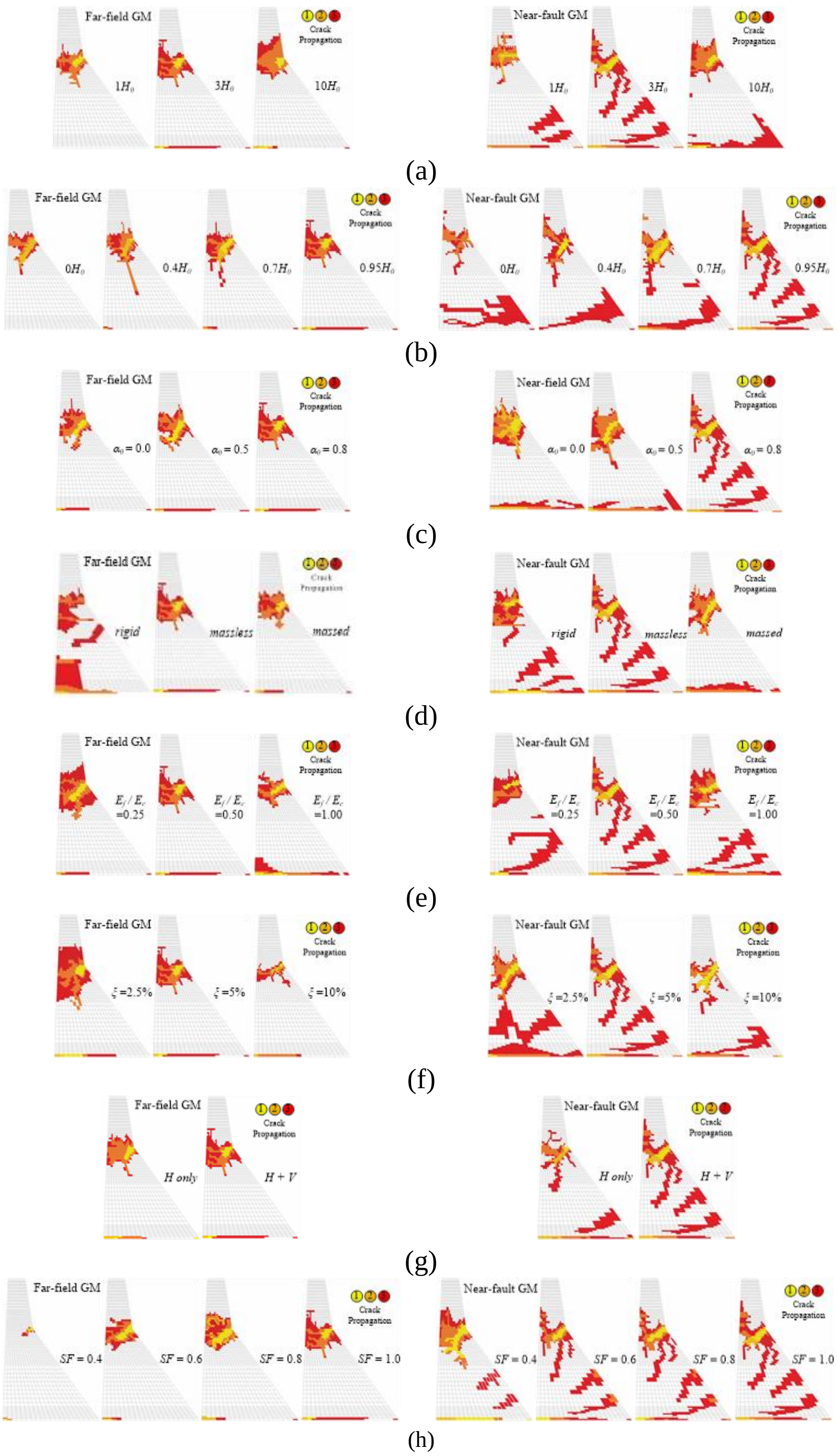


Figure 4: Impact of variable parameter on crack propagation in dam, (a) reservoir length, (b) water level, (c) reservoir bottom absorption, (d) foundation model, (e) foundation flexibility, (f) damping ratio, (g) GM component, (h) GM intensity

4.7. GROUND MOTION COMPONENTS

In this case, the finite element model is kept unchanged and only the input ground motion is changed. In the first model, only the horizontal component is used. In the second model, both the horizontal and vertical components are applied simultaneously. Fig. 3g shows the comparison between the displacement time histories.

As seen, there is a small difference between two models. The difference is much clear for the far-field ground motion. It seems that the effect of vertical component intensifies the crack process. These observations match well with those reported by Lee and Fenves [17]. Fig. 4g shows the crack profile of the dam subjected to different ground motion components. In the case of far-field ground motion, the final crack profiles are close together; however, applying only the horizontal ground motion leads to slightly less cracked elements especially in the dam-foundation interface. In the case of near-fault ground motion, applying the horizontal and vertical components increases cracked elements.

4.8. GROUND MOTION INTENSITY

The original scaled ground motions are assumed to have the scale factor (SF) of unity. Consequently, other pairs of ground motions are generated using a linear SF of 0.8, 0.6, and 0.4. Equal SF is used for both the horizontal and vertical components in each case. Fig. 3h shows the displacement time history. In the linear (pre-cracking) region, the displacement has a direct relation with the intensity of the applied load. Higher intensity motions lead to higher displacement response. The far-field ground motion with SF = 0.4 leads to some small cracking in the crack area; however, no failure occurred in this case (Fig. 4h). The ground motion with SF = 0.6 leads to failure of the model one cycle after the base model (SF = 1.0). Based on Fig. 4h, increasing the seismic intensity level under far-field ground motion does not have a considerable effect on final crack profile of the neck area (because in the case of Koyna dam, this section of the dam is most vulnerable); however, increases cracking in the dam-foundation interface.

5. CONCLUSIONS

This paper studies the parametric finite element analysis of a concrete gravity dam. Nonlinear behavior of the dam is originated from concrete smeared crack. The following conclusions can be drawn from this research:

- Increasing the water level leads to increasing the vibration period.
- Increasing the reservoir water length from $1H_0$ to $3H_0$, leads to increasing the crack profile; however, any further increase in reservoir length does not have considerable effect on crack profile and displacement response.
- Increasing the reservoir water level leads to increase in both the static and dynamic displacements. Crack profile especially in the dam-foundation interface also increases.
- Increasing the wave reflection coefficient leads to increase in both the hydrodynamic pressure and the displacement one cycle prior to failure, especially for near-fault ground motion.
- Using the standard massless foundation model increases the displacement and cracked area.
- Rigid foundation model leads to extensive cracking at the dam-foundation interface.
- Increasing the flexibility of the foundation leads to reduction in both the initial static and dynamic displacement of the dam.
- A flexible foundation increases the number of cracked elements at the dam-foundation interface; however, crack profile of the neck reduces slightly.
- Increasing the damping ratio leads to reduction in the displacement almost during the entire range of dynamic excitation. Also it leads to reduction of both the damaged area and the crack profile of the dam.
- Impact of vertical component of ground motion is almost negligible in the linear elastic range; however, cracking of concrete intensifies the effect of vertical component.
- High intensity motions usually dominant the neck cracking, however, the low intensity motions usually dominant heel cracking.
- In most cases, near-fault excitation leads to a different crack profile than the far-field motion. Pulse-like motion leads to additional cracks at the lower parts of the body which starts at the downstream face and proceeds in an almost inclined line toward upstream.

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