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Concrete Gravity Dams and Traveling Wave Effect along Reservoir Bottom

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***Abstract*—** In the present article, effect of non-uniform excitation of reservoir bottom on nonlinear response of concrete gravity dams is considered. Anisotropic damage mechanics approach is used to model nonlinear behavior of mass concrete in 2D space. The tallest monolith of Pine Flat dam is selected as a case study. The horizontal and vertical components of 1967 Koyna earthquake is used to excite the system. It is found that crest response and stresses within the dam body decrease significantly when the reservoir is excited non-uniformly. In addition, the crack profiles within the dam body and in vicinity of the neck decreases.

***Keywords*—**Concrete gravity dam, dam-reservoir-foundation interaction, traveling wave, damage mechanics.

I. INTRODUCTION

GENERALLY, in seismic behavior evaluation of dams, it is assumed that the system is excited uniformly. However, in infrastructures with extended interface with the earth such as concrete dams and their reservoirs, the seismic excitation is non-uniform due to limited velocity of earthquake waves and coherency effects. Due to finite speed of travelling wave, its amplitude changes and the travelled wave arrives at different points in various times.

Several researchers have worked on the nonlinear behavior of concrete gravity dams under the static and dynamic excitation using various numerical models, as in [1], [2] and Calayir and Karaton [3]. However, there is not many works considering effects of asynchronous on nonlinear seismic behavior of dams. In 1998, Bayraktar and Dumanoglu [4] considered effects of asynchronous ground motion on hydrodynamic pressures in concrete gravity dams. They found that hydrodynamic pressures decrease when the earthquake wave velocity decreases. Ghobarah and Ghemian [5] investigated travelling wave effect on the linear response of concrete gravity dams. They resulted that hydrodynamic pressures decrease when non-uniform excitation is used for exciting the reservoir bottom. Alves [6] and Alves and Hall [7] considered effects of spatially variation on the nonlinear seismic response of Pacoima dam.

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In the present paper, the bottom of the reservoir is excited non-uniformly and the nonlinear behavior of the mass concrete in 2D space is modeled using Damage mechanics approach. This nonlinear approach has been introduced and verified by the authors in Mirzabozorg et al. [8].

II. ASYNCHRONOUS INPUTS

When interface of earth with various components of the considered system are extended, the direction of wave propagation and its velocity can affect on the seismic response of the system. Reservoir medium in concrete dams is too long in the upstream direction and therefore, it is expected having different excitations in various points under the reservoir at the same time. The following sections illustrate the finite element modeling of the reservoir and numerical conditions applied on the boundaries of the reservoir medium.

III. RESERVOIR GOVERNING EQUATION AND BOUNDARY CONDITIONS

The governing equation in the reservoir medium is Helmoltz given in equation (1) extracted from the Euler's equation.

$$\nabla^2 p = \frac{1}{C^2} \frac{\partial^2 p}{\partial t^2} \tag{1}$$

where p, C and t are the hydrodynamic pressure, pressure wave velocity in the liquid and time, respectively. Boundary conditions required to apply on the reservoir medium to solve equation (1) are shown in Fig. 1, schematically.

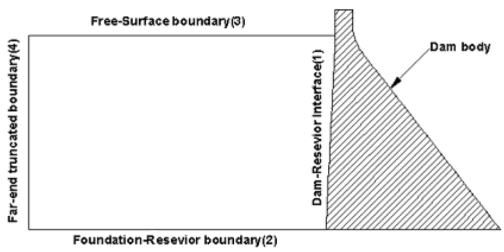


Fig. 1 Reservoir boundary conditions

IV. MATERIAL NONLINEARITY

The main aspects of the utilized anisotropic damage mechanics model in the current study are:

- Softening initiation criterion
- Concrete strain softening due to cracking
- Fracture energy conservation
- Closing/reopening crack criterion
- Co-axial rotating crack band model

The uni-axial strain energy which is the area under the stress-strain curve up to the peak stress (apparent tensile stress) is used as softening initiation index. The strain rate effect under dynamic loads is applied on the crack initiation criterion as demonstrated in Fig.2.

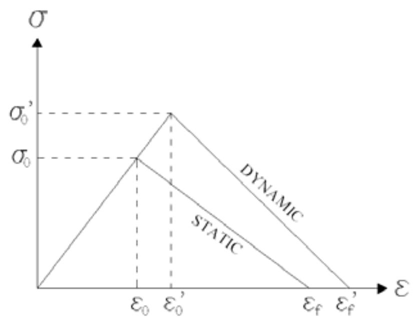


Fig. 2 Strain rate effect on apparent stress-strain curve

During the softening phase, the elastic stress-strain relationship is replaced with the damage modulus matrix. Using the secant modulus stiffness approach (SMS) shown in Fig. 3, the constitutive law relating the total stresses and total strains is given by:

$$[D]_d = \frac{E}{1-v^2}\begin{bmatrix} (1-d_1)^2 & (1-d_1)(1-d_2) & 0 \\ (1-d_1)(1-d_2) & (1-d_2)^2 & 0 \\ 0 & 0 & \frac{(1-v)(1-d_1)^2(1-d_2)^2}{(1-d_1)^2+(1-d_2)^2} \end{bmatrix} \quad (2)$$

$$d_i = 1-\sqrt{\frac{\varepsilon_0}{\varepsilon_i}-\left(\frac{\varepsilon_i-\varepsilon_0}{\varepsilon_f-\varepsilon_0}\right)\frac{\varepsilon_0}{\varepsilon_i}} \quad (3)$$

Where, d_i is the damage variable in the i -th local principal strain direction.

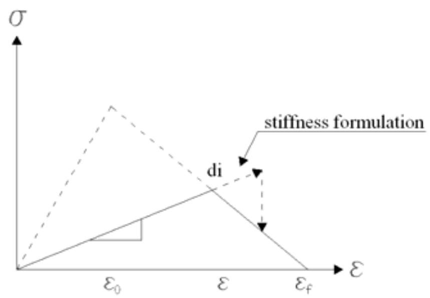


Fig. 3 Constitutive law-SMS formulation

Converting the local damage modulus matrix which is co-axial with principal strain directions to global coordinate results in:

$$[D]_{dG} = [T]^T [D]_d [T] \quad (4)$$

$$[T] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & \sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -\sin\theta\cos\theta \\ -2\sin\theta\cos\theta & 2\sin\theta\cos\theta & \cos^2\theta-\sin^2\theta \end{bmatrix} \quad (5)$$

in which θ is inclination of the normal to the cracked plane. Any change in principal strains or their directions leads to update requirement of the global constitutive matrix $[D]_{dG}$.

The crack closing/reopening criterion is based on the state of principal strain and its history within the element. Decomposing the average strain of the element into the elastic and inelastic components, the crack is assumed open if the maximum principal strain is greater than the inelastic strain, ε^{in}.

$$\varepsilon = \varepsilon^e + \varepsilon^{in} = \varepsilon^e + \lambda\varepsilon_{max} \quad (6)$$

Where ε_{max} is the maximum principal strain in the element during history of cyclic loads, λ is the ratio of the residual strain in the closed element and the maximum principal strain ε_{max} which is usually assumed 0.2.

V. MASSED FOUNDATION

The equations governing the P and S wave propagation within a massed foundation medium are given as:

$$\frac{\partial^2\bar{\varepsilon}}{\partial t^2} = V_p^2\nabla^2\bar{\varepsilon} \quad (7)$$

$$\frac{\partial^2\bar{\varpi}_y}{\partial t^2} = V_S^2\nabla^2\bar{\varpi}_y \quad (8)$$

In which VP and Vs are the primary and secondary wave propagation velocity within foundation medium and are given as:

$$V_p = \sqrt{\frac{E_r(1-\nu_r)}{\rho_r(1+\nu_r)(1-2\nu_r)}} \quad (9)$$

$$V_S = \sqrt{\frac{G_r}{\rho_r}} = \sqrt{\frac{E_r}{2\left(1+\nu_r\right)\rho_r}} \tag{10}$$

where subscript r indicates the parameters pertinent to the foundation rock. One of the main aspects in the seismic loading and wave propagation within the semi-infinite medium such as foundation rock underlying structures is preventing the wave reflection from the artificial boundary of the infinite medium in finite element analysis. In this study, the viscous boundary, which is a non-consistent boundary (called local boundary) is applied on the far-end boundary of the foundation in 2D space expressed as:

$$\sigma = a\rho_r V_P \dot{u} \tag{11}$$

$$\tau = b\rho_r V_S \dot{v} \tag{12}$$

where σ and ε are the normal and shear stresses, and u and v are the normal and tangential displacements, respectively. It is found that taking both a and b equal to unity, leads to the highest efficiency in absorbing the outgoing seismic waves. It is worth noting that the used boundary condition is frequency independent and can absorb both harmonic and non-harmonic waves [2].

Radiation damping derived from equations (11) and (12) applied on the far-end boundary of the foundation is made up of dashpots which are added to the global damping matrix of the structure, [C]. In the present research, these lumped dashpots are determined:

$$C_{11}^{i} = V_P \rho_r \int_{l_e} N_j \, dl \tag{13}$$

$$C_{22}^{i} = V_s \rho_r \int_{l_e} N_j \, dl \tag{14}$$

where C_{11}^{i} and C_{22}^{i} are the components of the lumped damping in the normal and tangential directions, respectively and N_j is the shape function of the j[th] node in the i[th] line element on the far-end boundary of the foundation.

VI. Coupled structure-reservoir problem

In the present study, the staggered displacement method, which is an unconditionally stable approach, is utilized to solve the coupled problem [8]. Equations of the dam-foundation structure and the reservoir are:

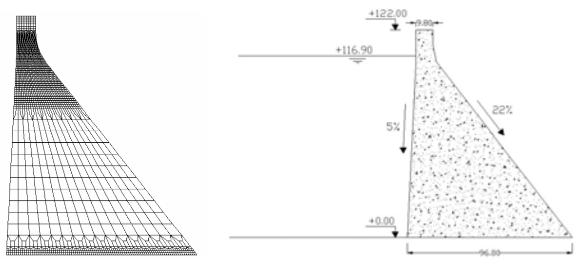
$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{f_1\}-[M]\{\ddot{U}_g\}+[Q]\{P\}=\{F_1\}+[Q]\{P\}$$
$$[G]\{\ddot{P}\}+[C']\{\dot{P}\}+[K']\{P\}=\{F\}-\rho[Q]^T\left(\{\ddot{U}\}+\{\ddot{U}_g\}\right)=\{F_2\}-\rho[Q]^T\{\ddot{U}\} \tag{15}$$

Where, $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices of the structure including the dam body and its foundation medium and $[G]$, $[C']$ and $[K']$ are matrices representing the mass, damping and stiffness equivalent matrices of the reservoir, respectively. The matrix $[Q]$ is the coupling matrix; $\{f_1\}$ is the vector including both the body and hydrostatic force; and $\{P\}$ and $\{U\}$ are the vectors of hydrodynamic pressures and displacements, respectively and $\{\ddot{U}_g\}$ is the ground acceleration vector.

VII. Seismic behavior of Pine Flat dam

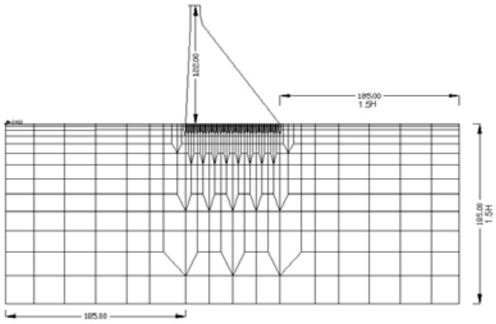
The tallest monolith of Pine Flat dam is selected for considering the effect of travelling waves along the reservoir bottom on the nonlinear seismic response of the system. The crest of the dam is 560 m long and the height of the tallest monolith is 122 m. The modulus of elasticity, the unit weight and Poisson's ratio of the concrete are taken as 27580 MPa, 2400 kg/m3 and 0.2, respectively. The tensile strength of the concrete is assumed 2.7 MPa which is 10% of the compressive strength. An elasto-brittle damping model is utilized in which cracked elements do not contribute to the damping matrix. The stiffness pro¬portional damping equivalent to 10% of critical damping based on the first and second natural vibration modes of the dam-foundation system is applied on the structure. The structure is modeled using 1984 4-node iso-parametric plane stress elements and 552 4-node elements produce the finite element model of the foundation. It is worth noting that the foundation is modeled up to 1.5 times of the dam body height in each direction to eliminate the effect of finite modeling of semi infinite medium. Figs. 4 and 5 illustrate the finite element models of the dam body and its foundation, respectively. To model the radiation damping on the far-end boundary of the massed foundation, 2-node elements as boundary elements are used to apply the lumped dashpot on the far-end nodes of the model, as shown in Fig. 5.

Finally, 1121 4-node elements are used to model the reservoir. The length of FEM of the reservoir is about 6.3 times of the dam body height and the depth of the reservoir is 116.88 m. For the reservoir, pressure wave velocity and mass density are taken as 1438.66 m/s and 1000 kg/m3, respectively and no absorption is considered at the reservoir bottom (the wave reflection coefficient according to the reservoir bottom is assumed unity).

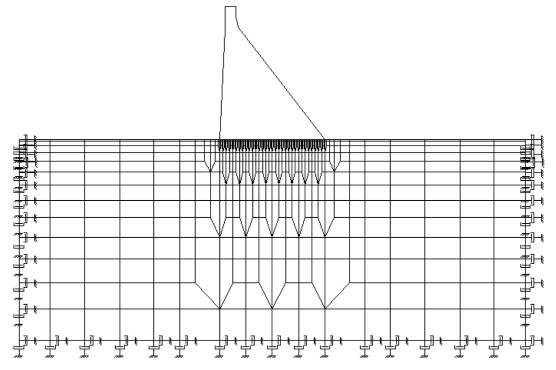


(a) (b)

Fig. 4 Dimensions and FE model of the dam body-Pine Flat dam



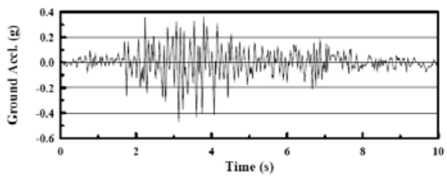
(a)



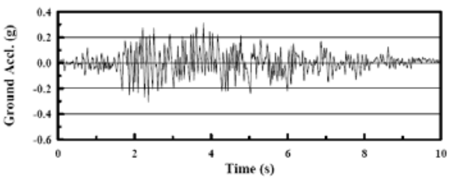
(b)

Fig. 5 Dimensions and finite element model of the dam body and its foundation media

The first 10 s of the earthquake components recorded in the Koyna Dam for the 1967 Koyna earthquake in Fig. 6 is used to excite the system. The direct integration method used in Ghaemian and Ghobareh [10] is utilized to solve the problem. The integration parameters of α, β and γ are taken -0.2, 0.36 and 0.7, respectively. The time integration step is 0.001s and the time step of the earthquake record is 0.01s. At the first step, the self-weight and the hydrostatic loads are applied on the model. No cracked point is observed at the end of this stage. At the next step, the dynamic analysis of the model is conducted applying the earthquake components.



(a)



(b)

Fig. 6 Ground motion recorded at the Koyna Dam for the 1967 Koyna earthquake: (a) the stream component; (b) the vertical component

A. Dam-reservoir system with rigid foundation

The time history of the crest displacement in the stream direction for non-uniform and uniform excitation is shown in Figs. 7 and 8. In the uniform excitation case, all nodes on the bottom of the reservoir are excited uniformly.

Based on the conducted analyses, the analysis is terminated at 4.48 s due to energy balance error when both the reservoir and the structure are excited uniformly. However, there is not any numerical instability during the dynamic analysis when the non-uniform excitation is applied on the bottom of the reservoir. As shown, non-uniform excitation decreases the crest displacements in the stream directions in comparison with the case exciting the reservoir bottom uniformly.

Based on obtained results, absolute maximum crest displacements are 33 mm and 60 mm in the non-uniform and uniform excitations, respectively. In addition, the frequency content of the crest response is completely different in the two compared cases.

As shown in Fig. 8, when the dam body is excited and there is not any excitation on the bottom of the reservoir, the absolute maximum of the crest displacement is 28 mm, in comparison with the case of non-uniform excitation in which the corresponding value is obtained 33 mm. In addition, there is an agreement between the frequency contents of the two series of the results.

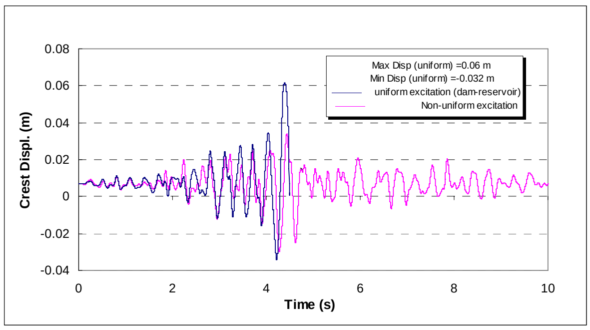


Fig. 7 Crest displacement in the stream direction, non-uniform and uniform excitation

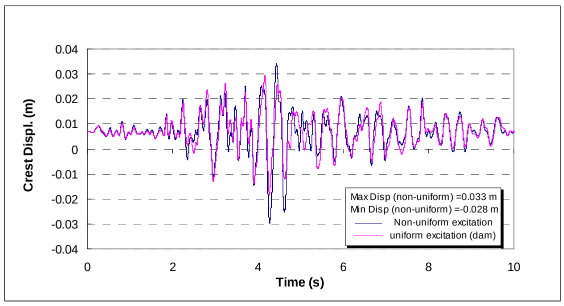
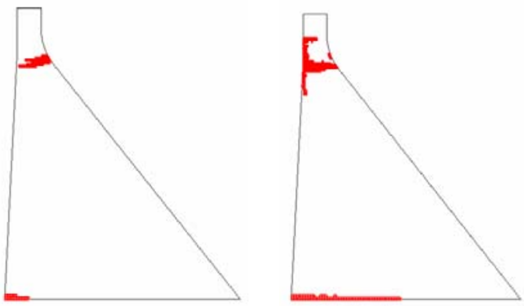


Fig. 8 Crest displacement in the stream direction, non-uniform excitation and uniform excitation of the dam body (without excitation of the reservoir bottom)

The obtained crack profiles for the cases of uniform and non-uniform excitations are shown in Fig. 9 and Fig. 10

shows the crack profiles resulted from the analysis when the dam body is excited without any excitation on the bottom of the reservoir. Clearly, both the extension and the number of cracked elements within the neck region and near the base of the dam body increase intensely when the system is excited uniformly.

As shown in Figs. 9 and 10, there is an agreement between the cases of non-uniform excitation and the excitation of the dam body without any excitation on the reservoir bottom. Based on the investigations presented in the dam engineering field, numerical models generally lead to larger response in comparison with the real behavior of the system and results shown in the current section shows that the non-uniform excitation of the system can lead to more real response. In fact, the uniform excitation of the system including the reservoir bottom leads to increasing the response intensely.



(a) (b)

Fig. 9 Crack profiles in dam body; (a) non-uniform excitation (b) uniform excitation

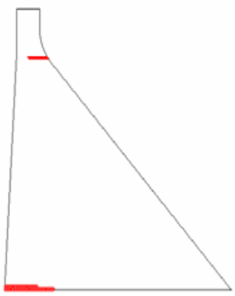


Fig. 10 Crack profiles; uniform excitation of the structure without any excitation on the bottom of the reservoir

B. *Dam-reservoir-foundation system*

In the current section, the analyzed systems include the massed foundation and its corresponding radiation on the far-end truncated boundary. The time histories of the crest displacement in the stream direction for non-uniform and uniform excitation are shown in Fig. 11. As can be seen, the nonlinear analysis of the model is terminated at 5.53 s due to energy balance error when the both the reservoir and the structure are excited uniformly and there is not any numerical instability during the dynamic analysis when the reservoir bottom is excited non-uniformly. The maximum absolute value of the crest displacement is 33 mm in the case of non-uniform excitation and its corresponding value in the case of uniform reservoir bottom excitation is 60 mm.

Crack profiles for the cases of uniform and non-uniform excitation are shown in Fig. 12. Fig. 13 shows the crack profiles resulting from the excitation of the structure without any excitation of the reservoir. As can be seen, there is only a cracked element in the case of non-uniform excitation of the reservoir. Both the extension and the number of cracked elements within the neck region and near the base of the dam body increase intensely when the system is excited uniformly.

Comparing the results shown in Figs. 9 and 12, in the model with the massed foundation, the number of cracked elements within the heel and neck region is less than the case with the rigid foundation in the conducted analyses.

Based on the conducted analyses, it can be found that the results obtained from the model with the rigid foundation are too conservative and modeling the non-uniform excitation with the massed foundation including the radiation damping leads to more real response due to accounting for more real assumptions governing on the system of the dam-reservoir-foundation media.

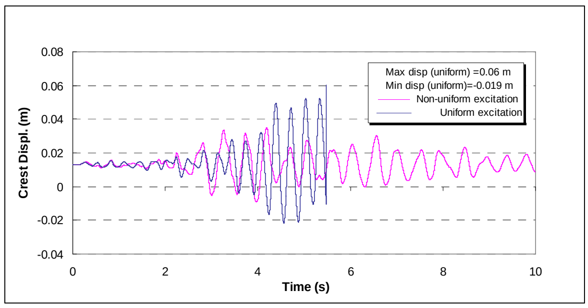
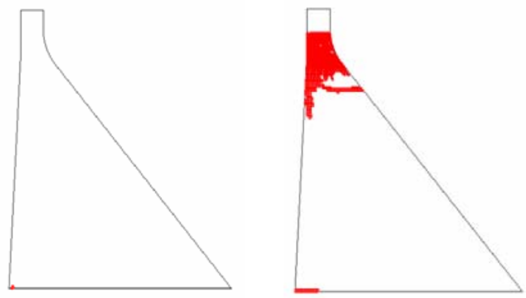


Fig. 11 Crest displacement in the stream direction, comparison of non-uniform and uniform excitation



(a) (b)

Fig. 12 Crack profiles within the dam body; (a) non-uniform excitation (b) uniform excitation

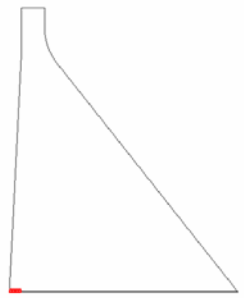


Fig. 13 Crack profiles within the dam body; uniform excitation of the structure without any excitation of the reservoir bottom

VIII. Conclusion

A nonlinear seismic analysis of concrete gravity dams with spatially variation ground motion under the reservoir bottom including dam-reservoir-foundation interaction is conducted. The reservoir-structure interaction is accounted for using finite element method assuming the reservoir is compressible. Damage mechanics approach is applied for modeling the nonlinear behavior of mass concrete in 2D space. Foundation is assumed massed and the radiation absorption on its far-end truncated boundary is modeled using the viscous boundary. The system of the structure including the dam body and its foundation is excited uniformly and the effect of finite propagation velocity of seismic waves is applied on the excitation of the long reservoir bottom in the upstream of the structure. Two sets of wave propagation velocities are used in the conducted analyses which are 650m/sec and infinity. Pine Flat dam is chosen as the case study and the system is excited using the two components of the earthquake recorded in Koyna 1967.

Generally, when the reservoir bottom is excited uniformly, the crack profiles within the neck region increases and are more diffused. In addition, the crest displacement increases in comparison with the case under the non-uniform excitation along the reservoir bottom.

Finally, the obtained results show that the non-uniform excitation can lead to crack profiles which are different from those obtained under the uniform excitation and modeling the non-uniform excitation with the massed foundation including the radiation damping leads to more real response due to accounting for more real assumptions governing on the system of the dam-reservoir-foundation media.

Appendixes, if needed, appear before the acknowledgment.

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