Structural Engineering and Mechanics, Vol. 35, No. 3 (2010) 365-377

DOI: http://dx.doi.org/10.12989/sem.2010.35.3.365

Nonlinear behavior of concrete gravity dams and effect of input spatially variation

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(Received September 16, 2008, Accepted February 5, 2010)

Abstract. In the present article, effect of non-uniform excitation due to spatially variation of seismic input on nonlinear response of concrete gravity dams is considered. The reservoir is assumed compressible. Isotropic damage mechanics approach is used to model static and dynamic nonlinear behavior of mass concrete in 2D space. The validity of utilized nonlinear model is considered using available theoretical results under static and dynamic conditions. The tallest monolith of Pine Flat dam is selected as a case study. Two cases are analyzed for considering the effect of limited wave propagation velocity on seismic behavior of the dam-reservoir system in which travelling velocities are chosen as 2000 m/s and infinity. It is found that tensile damage in neck and toe regions and also, in the vicinity of the base increase when the system is excited non-uniformly.

Keywords: concrete gravity dam; damage mechanics; fluid-structure interaction; spatial variation; seismic nonlinear response.

1. Introduction

In infrastructures with extended foundations such as concrete dams, seismic excitation is non-uniform due to limited velocity of earthquake waves and coherency effects. Seismic safety evaluation of dams is a major task in dam engineering and assessment of nonlinear response of dams in seismic safety evaluation of existing dams can lead to important results and decision making about future of existing structures.

Several researchers have worked on nonlinear behavior of concrete gravity dams in static and dynamic load conditions using various numerical models (Mirzabozorg *et al.* 2007). However, there is little information available considering effects of asynchronous on nonlinear seismic behavior of dams. Bilici *et al.* (2009) performed a stochastic dynamic analysis for studying a dam-reservoir-foundation system subjected to spatially varying earthquake motion. Based on their results, displacements and stresses within the dam body were generally dominated by quasi-static component resulted from spatially varying earthquake ground motion. Hacıefendioğlu *et al.* (2009) considered the effect of ice cover on stochastic response of concrete gravity dams to multi-support seismic excitations. Bayraktar *et al.* (1996) investigated asynchronous dynamic response of dam-

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reservoir-foundation systems using lagrangian approach. Dumanoglu and Severn (1984) obtained solutions for various finite velocities and also, for infinite velocity of seismic wave and showed that response of the dam body is increased due to reducing wave passage velocity. In addition, seismic response of concrete-faced rock-fill (CFR) dams subjected to asynchronous base excitation was studied by Bayraktar *et al.* (2005). They concluded that stresses obtained along concrete face slab considerably increase for empty and full reservoir cases with decreasing wave velocity. Zhang and Mai (1987) obtained response of an arch dam due to harmonic excitation with time-lag between abutments.

Alves (2004) and Alves and Hall (2006) considered effects of spatially variation on nonlinear seismic response of Pacoima arch dam using SCADA in which joint and material nonlinearity was modeled using smeared crack approach. In their study, they calculated non-uniform earthquake input at each node at dam-foundation interface using extrapolation and interpolation applied on data recorded in the three stations on the dam body and abutments. According to the results, extension of cracking was less severe if the time delay was omitted. Both the number and size of cracks decreased when the system was excited uniformly.

In the present paper, non-uniform excitation due to limited wave passage velocity is considered using the modeled dam-reservoir system. Nonlinear behavior of mass concrete in 2D space is modeled using damage mechanics approach and validity of numerical solution method is considered using available academic programs. It is worth noting that the novelty of the present study is considering material nonlinearity in the conducted asynchronous dynamic analyses.

2. Asynchronous input

In the current study, it is assumed that the heel of the dam body is excited first, as shown in Fig. 1 and wave propagation is towards downstream. Therefore, different points along the base of

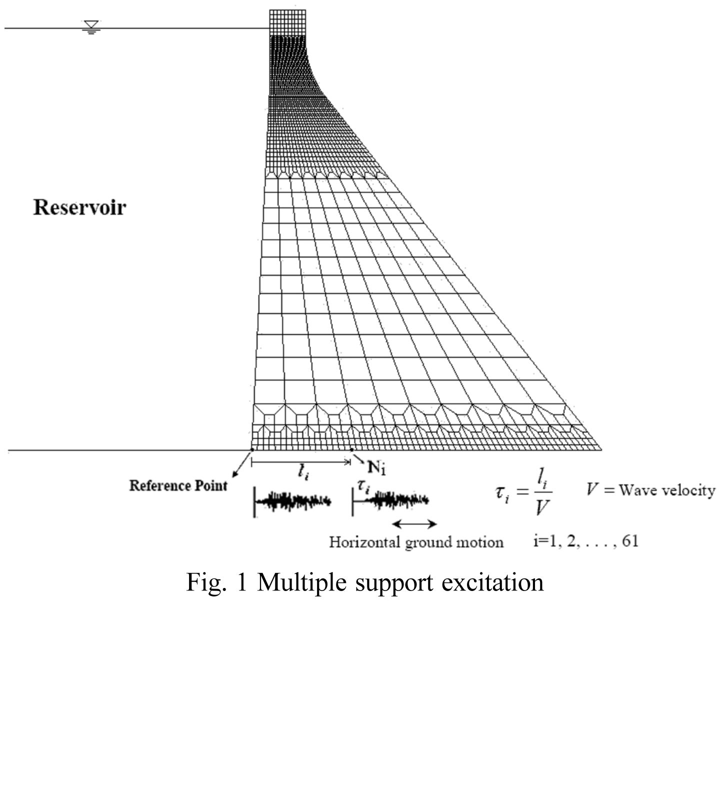


Fig. 1 Multiple support excitation

the dam body are excited using various acceleration values at the same time which depend on the velocity of travelling seismic waves and the distance of the considered node and the heel of the dam body. The lag time corresponding to each node at the base of the dam is computed as

$$\tau_i = \frac{l_i}{V} \tag{1}$$

In Eq. (1), τ_i is arrival time of the ground motion at specific support node, N_i; l_i is the distance of the reference node and the considered one indexed using i; and V is the travelling wave velocity which is taken 2000 m/s and infinity, in the conducted analyses. Finally, the accelerations are obtained at each node using interpolation based on the calculated lag time.

In the finite element formulation, the earthquake effect is represented by a set of forces that is obtained from multiplying the mass matrix of structure (including base nodes) to the influence matrix. This describes the influence of support displacement on structural displacement, to input ground motion acceleration, which is obtained from interpolation at each node. Detailed formulation can be found in Wilson (2002).

3. Damage mechanics

The damage mechanics concept is based on thermodynamics of irreversible process. In iso-thermal conditions, internal damage is defined using an internal variable called damage variable. Physically, internal damage is cumulative of micro-cracks in a representative volume. The concrete damaged plasticity model in ABAQUS (Hibbitt *et al.* 2004) is defined as:

- Provides a general capability for modeling concrete and other quasi-brittle materials in all types of structures (beams, trusses, shells, and solids)
- Uses concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete
- Can be used for plain concrete, even though it is intended primarily for the analysis of reinforced concrete structures
- Is designed for applications in which concrete is subjected to monotonic, cyclic, and/or dynamic loading under low confining pressures
- Consists of the combination of non-associated multi-hardening plasticity and scalar (isotropic) damaged elasticity to describe the irreversible damage that occurs during the fracturing process
- Allows user control of stiffness recovery effects during cyclic load reversals
- Can be defined to be sensitive to the rate of straining

Stiffness recovery is an important aspect of the mechanical response of concrete under cyclic loading. ABAQUS (Hibbitt *et al.* 2004a, b), allows direct user specification of the stiffness recovery factors w_t and w_c. The experimental observation in most quasi-brittle materials, including concrete, is that the compressive stiffness is recovered upon crack closure as the load changes from tension to compression. On the other hand, the tensile stiffness is not recovered as the load changes from compression to tension once crushing micro-cracks have developed. This behavior, which corresponds to $w_t = 0$ and $w_c = 1$, is the default used by ABAQUS. Fig. 2 illustrates a uni-axial load cycle assuming the default behavior (Hillerborg *et al.* 1976, Lee and Fenves 1998).

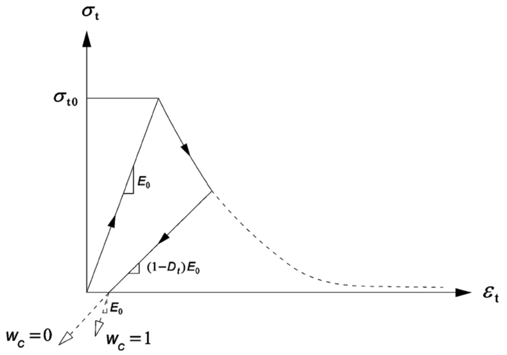


Fig. 2 Effect of the compression stiffness recovery parameter w_c

4. Fluid-structure interaction

4.1 Reservoir governing equation of motion

The governing equation in reservoir medium is Helmoltz equation (resulted from Euler's equation) given as Hibbitt *et al.* (2004)

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

where, p, C and t are hydrodynamic pressure, pressure wave velocity in liquid and time, respectively. Boundary conditions required to apply on reservoir medium to solve Eq. (2) are explained in the following sections. These boundaries are demonstrated in Fig. 3, schematically.

4.2 Dam-reservoir interface

At the interface of fluid-structure, there is no flow through the wet face of the dam body. Using Euler's equation and some mathematical operations, the following equation is resulted

$$\frac{\partial p}{\partial n} = -\rho n^T \ddot{u}_s \tag{3}$$

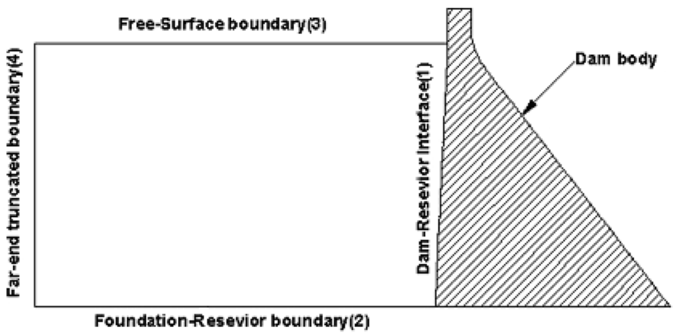


Fig. 3 Finite reservoir boundary condition

where, ρ and n are liquid density and normal vector to the surface, respectively; and $\ddot{u}_s$ is normal acceleration of the dam face at the interface.

4.3 Foundation-reservoir boundary

On this boundary no absorption is considered (wave reflection coefficient according to reservoir bottom is assumed unity) and therefore, boundary condition shown in Eq. (3) is applied on reservoir bottom.

4.4 Free surface boundary

To model surface wave with negligible surface tension, the following boundary condition is applied on free surface of the reservoir medium

$$\frac{\partial P}{\partial n} = -\frac{1}{g}\ddot{p} \tag{4}$$

where, g is gravitational acceleration; $\dot{p}$ and $\ddot{p}$ are the first and second derivatives of hydrodynamic pressure with respect to time.

4.5 Far-end truncated boundary

Sommerfeld boundary condition is applied on far-end truncation boundary of the reservoir medium for modeling complete absorption of propagating waves in upstream direction. This boundary condition is the most common one which is based on assumption that at long distance from the dam face, pressure wave is propagated as plane (Hibbitt *et al.* 2004)

$$\frac{\partial p}{\partial n} = -\frac{1}{C}\frac{\partial p}{\partial t} \tag{5}$$

5. Case study-pine flat dam

The tallest monolith of Pine Flat dam is selected for considering effects of spatially variation on seismic response of concrete gravity dams. Crest length of the dam body is 560 m long and the height of the tallest monolith is 122 m. Modulus of elasticity, unit weight and Poisson's ratio of mass concrete are taken as 27580 MPa, 2400 kg/m^3 and 0.2, respectively. Tensile strength of mass concrete is assumed 2.7 MPa which is about 10% of its compressive strength.

An elasto-brittle damping model in which cracked elements do not contribute to the damping matrix is utilized for nonlinear analyses. The stiffness proportional damping equivalent to 10% of critical damping based on the first and second natural vibration modes of the dam-reservoir system is applied to the structure. The structure is modeled using 2040 4-node iso-parametric plane stress elements and 3774 4-node elements produce finite element model of the reservoir medium. Figs. 4 and 5 show dimensions and finite element models of the dam body and its reservoir, respectively.

The length of FE model of the reservoir is about 2.6 times of the dam body depth. The depth of the reservoir is 116.88 m. Pressure wave velocity and mass density within the reservoir medium are taken as 1438 m/s and 1000 kg/m^3, respectively and no absorption is considered at the reservoir bottom.

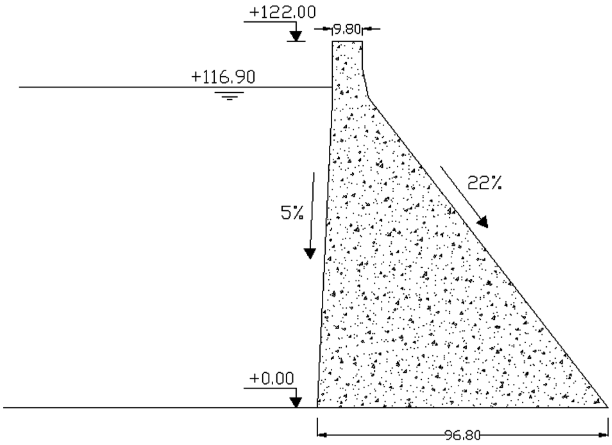


Fig. 4 Geometric properties of the dam body-Pine Flat dam

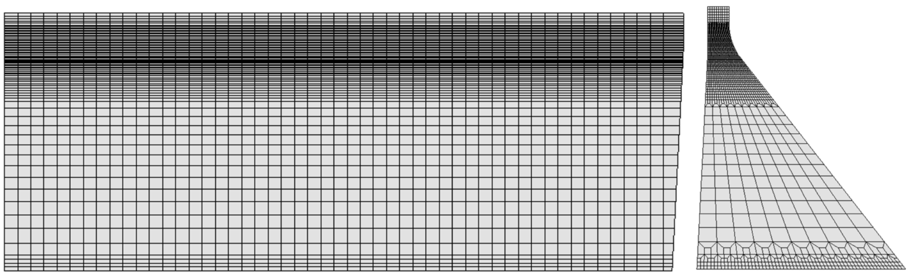


Fig. 5 Finite element model of the dam body and its reservoir

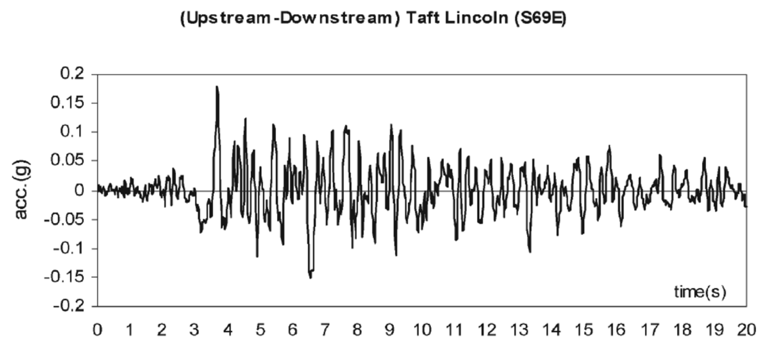
The first 20s of earthquake components recorded in Kern County site due to Taft Lincoln earthquake on 21 July 1952 depicted in Fig. 6 is used to excite the system. This recorded earthquake has PGA equal to 0.179 g and 0.155 g in horizontal and vertical directions, respectively.

5.1 Validity of nonlinear numerical approach

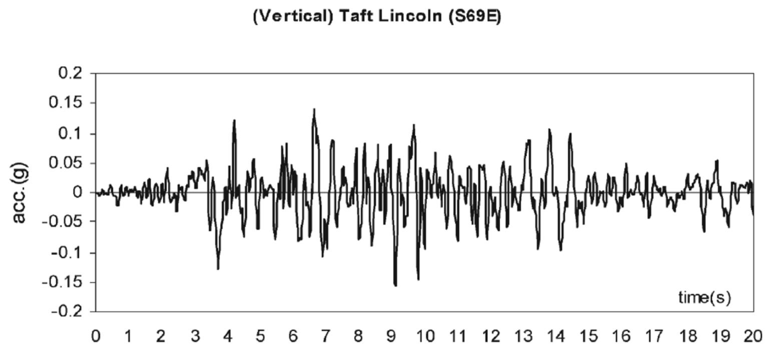
To investigate validity of utilized numerical model, the results obtained from analysis are compared with those obtained using NSAG-DRI (Mirzabozorg *et al.* 2007). It is worth noting that NSAG-DRI is an academic program which is able to analyze concrete gravity dams accounting for reservoir interaction effects and also is capable to analyze the nonlinear behavior of mass concrete using the damage mechanics approach proposed by the first and second authors (Mirzabozorg *et al.* 2004).

5.1.1 Nonlinear behavior of dam body with empty reservoir

Fig. 7 shows the crest displacement time history resulted from analyzing the dam body with empty reservoir using ABAQUS in comparison with those obtained from NSAG-DRI. As shown, the results are in excellent agreement. It is worth noting that there is not any crack profile within the dam body during the seismic analysis when the reservoir is assumed empty.



(a) Stream component



(b) Vertical component

Fig. 6 Upstream-downstream (S69E) and vertical components-Taft Lincoln earthquake

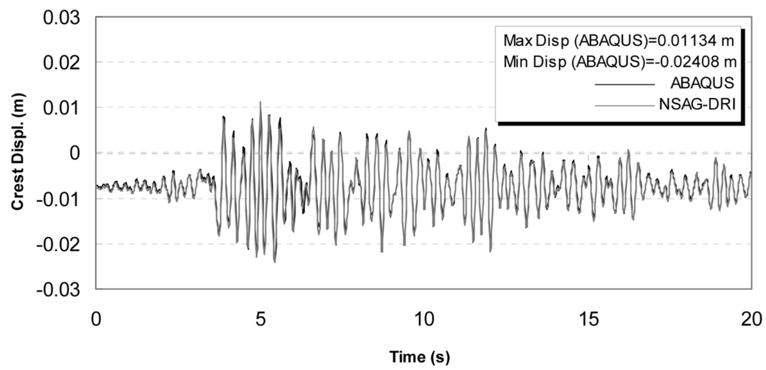


Fig. 7 Crest displacement in the stream direction-dam body with empty reservoir

5.1.2 Nonlinear behavior of dam body with full reservoir

Fig. 8 shows crest displacement in horizontal direction, when reservoir is full. As shown, results are in excellent agreement in spite of different nonlinear models utilized in the two utilized softwares.

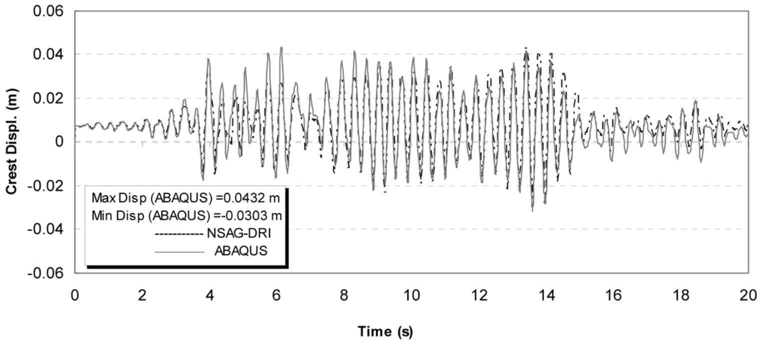
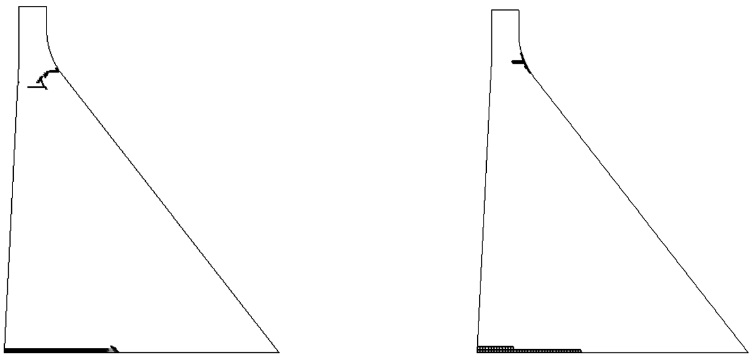


Fig. 8 Crest displacement in the stream direction-dam body with full reservoir



(a) ABAQUS (b) NSAG-DRI

Fig. 9 Tensile damage; dam body with full reservoir

Fig. 9 shows crack profiles within the dam body during seismic excitation of the considered system resulting from the two utilized numerical models. As shown, there is excellent agreement between nonlinear response of the dam body in spite of two different numerical approaches and different nonlinear models adopted in the two utilized programs.

5.2 Non-uniform excitation using stream and vertical components

Time history of the crest displacement in stream and vertical directions for both cases of uniform and non-uniform excitation are given in Figs. 10 and 11 and corresponding tensile damages are shown in Fig. 12 when the reservoir is assumed to be full. Comparing the resulted displacement time histories, it can be seen that there are differences between extreme values and frequency content of the responses. In fact, taking into account the limited wave passage velocity can lead to different response of the dam body. As can be seen from Fig. 12, when the dam body is excited non-uniformly, there are more cracked elements within the neck region of the dam body. In addition, the dam body is cracked at its toe, the phenomenon which is not observed when the system is excited uniformly.

Fig. 13 shows tensile damage resulting from the system with empty reservoir exciting the dam

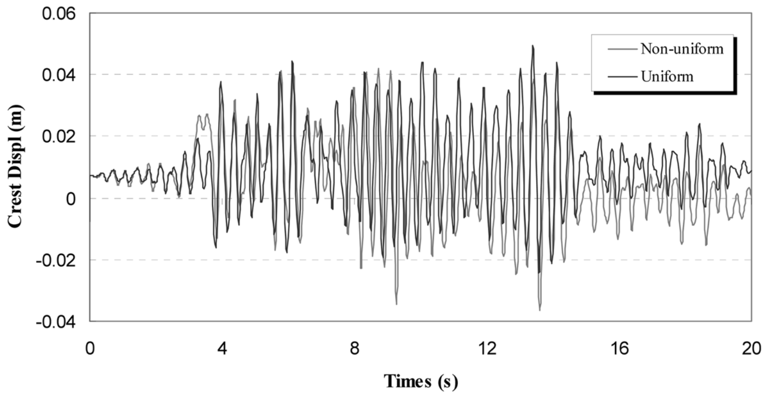


Fig. 10 Crest displacement in the stream direction

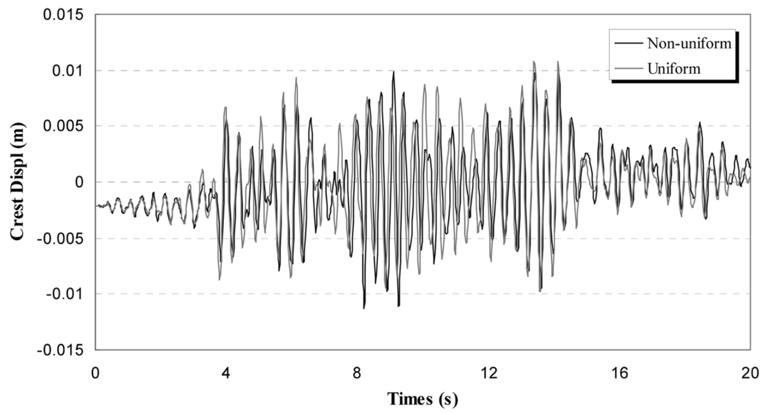
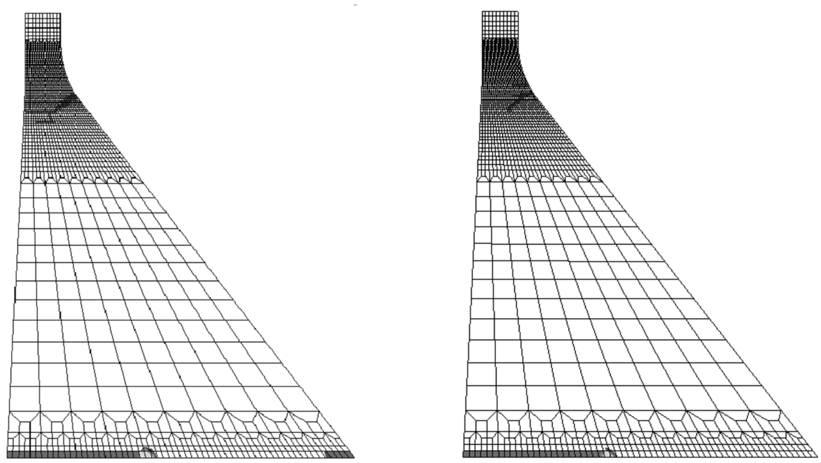


Fig. 11 Crest displacement in the vertical direction



(a) (b)

Fig. 12 Tensile damage profiles-full reservoir; (a) non-uniform excitation (b) uniform excitation

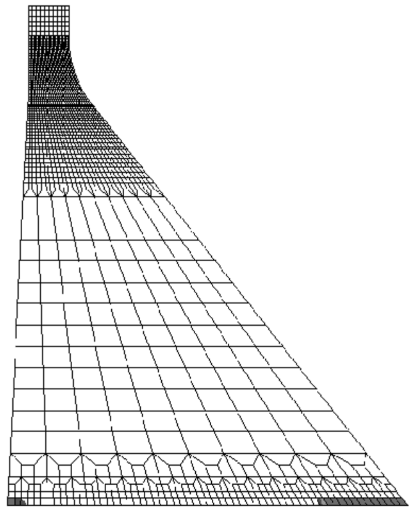


Fig. 13 Tensile damage profiles-empty reservoir

body non-uniformly. As mentioned previously, there is not any damage within the dam body when the reservoir is empty and the excitation is uniform. However, under non-uniform condition, the concrete experience some damage.

Clearly, both the extension and the number of cracked elements within the neck region and near toe of the dam body increase intensely, when the structure is excited non-uniformly with seismic wave propagation velocity of 2000 m/s. It is realized that asynchronous excitation due to wave passage, creates quasi-static displacements in addition to dynamic displacements. Quasi-static displacements occur because of relative motion of the base nodes along foundation-structure interface which cause all of the stresses in the dam body, especially near the base, increase noticeably in comparison with those of synchronous ground motion. It is worth noting that to obtain more reasonable results wave passage velocity used in dynamic analysis of dam-reservoir system should be obtained from evaluations conducted on the dam site (American Society of Civil Engineers 2000).

5.3 Non-uniform excitation using stream component

In this section, results of analyses due to exciting the dam-reservoir using only horizontal component are presented. Time history of the crest displacement in stream and vertical directions for the cases of uniform and non-uniform excitations are given in Figs. 14 and 15, respectively. Fig. 16 shows contours of tensile damage within the dam body, when reservoir is full. In addition, contour of tensile damage in the case with empty reservoir is shown in Fig. 17. There is not any crack profile within the dam body when the reservoir is empty and excitation of the dam body is uniform (as discussed previously).

As can be seen from Figs. 14 and 15, when the system is excited using horizontal component of ground motion, the extreme values are the same approximately and there is not any difference in frequency content of the responses resulted from the two cases of uniform and non-uniform excitation of the dam body. In addition, as concluded in section 5.2, when the system is exited non-

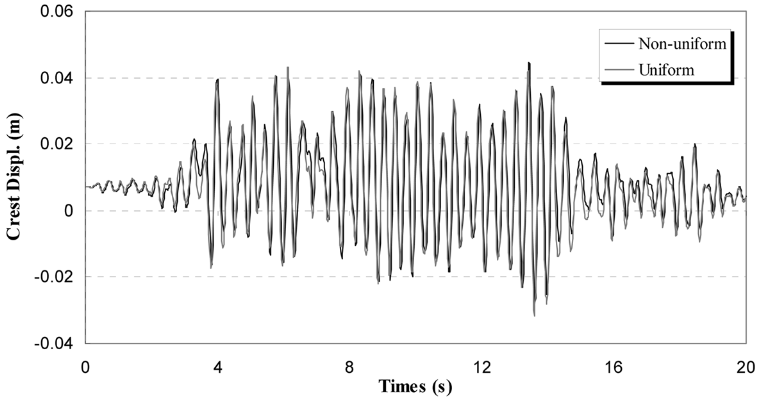


Fig. 14 Crest displacement in the stream direction due to horizontal excitation

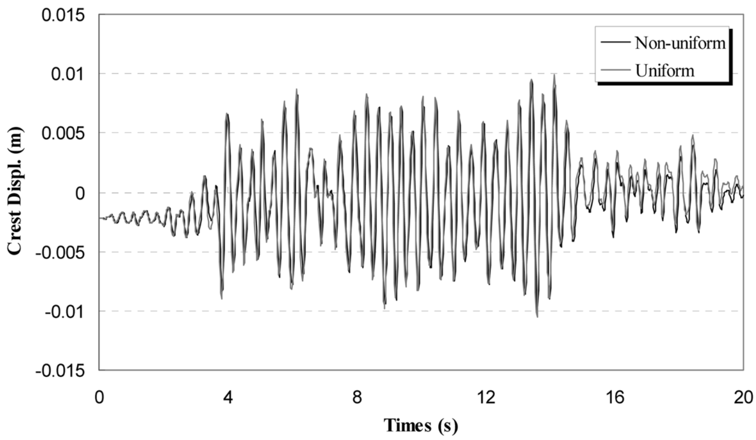
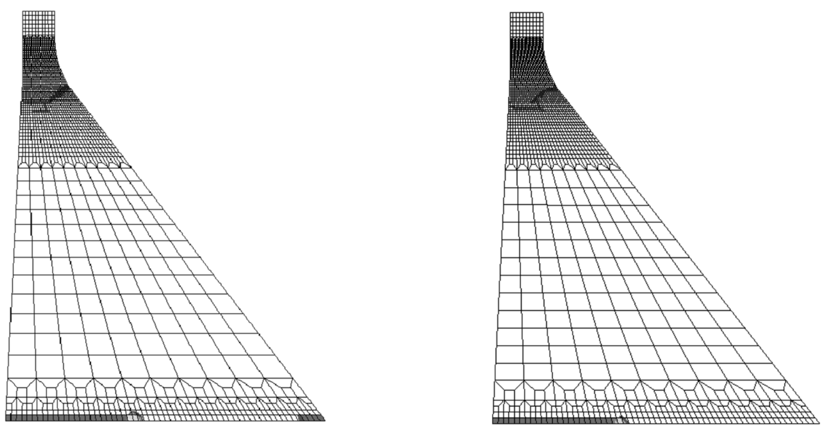


Fig. 15 Crest displacement in the vertical direction due to horizontal excitation



(a) (b)

Fig. 16 Contour of tensile damage-full reservoir (a) non-uniform (b) uniform

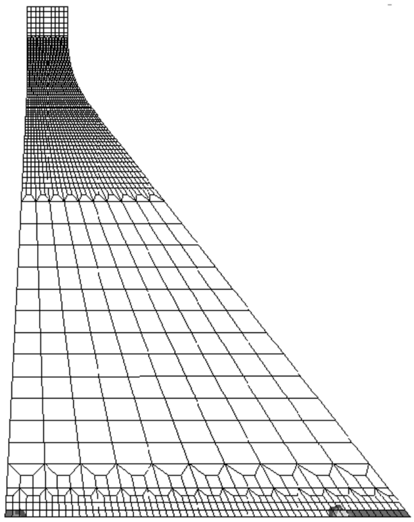


Fig. 17 Contour of tensile damage-empty reservoir and non-uniform excitation

uniformly, crack profiles increases within the neck region and in the toe of the dam body in both cases of full and empty reservoir.

6. Conclusions

Nonlinear seismic analysis of concrete gravity dams with spatially variation ground motions including dam-reservoir interaction is conducted. The reservoir-structure interaction is accounted for using finite element method assuming the reservoir is compressible. Isotropic damage mechanics approach is applied for modeling the nonlinear behavior of mass concrete in 2D space. The system of dam-reservoir is excited non-uniformly due to limited seismic wave propagation velocity. The two sets of wave propagation velocities used in the conducted analyses are taken as 2000 m/s and infinity. Pine Flat dam is chosen as the case study.

Generally, when the system of dam-reservoir is excited non-uniformly, there are some cracked elements at toe of the dam body. It must be noted that in common seismic analyses, there is not any cracked elements at toe of concrete gravity dams. In addition, crack profiles within the neck region of the dam body increase due to non-uniform excitation of the system.

Finally, the results show that the non-uniform excitation can lead to displacement time histories, stress contours and crack profiles which are different from those obtained under the uniform excitation. Therefore, dam design and dam safety evaluation should be considered based on the site and structure conditions.

It is worth noting that the authors conducted several analyses with various travelling wave velocities (from 1500 m/s to 4000 m/s) and concluded that there is negligible difference in results in the considered range, which is reasonable for rock foundations.

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