Input Spatially Variation Effect on
Linear Seismic Response of Concrete Gravity Dams

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Abstract

In the present paper, the effect of spatially variation of seismic input due to limited travelling velocity of exciting waves on linear response of concrete gravity dams is considered. The tallest monolith of the Pine Flat dam is selected as a case study. Hydrodynamic pressure distribution in the reservoir is governed by the pressure wave equation, assuming the water to be compressible. The first 20 seconds of the horizontal and vertical components of the 21 July 1952 Taft Lincoln earthquake is used as the stream and vertical excitations of the system, respectively. Two cases are analyzed for considering the effect of limited wave propagation velocity on seismic behavior of concrete dams in which the travelling velocities are chosen as 600 m/s and infinity. The results indicate that all components of the stresses increase intensely when non-uniform excitation is applied on the system. In this case, the stress contours are changed drastically in comparison with the case under the uniform excitation. Also, uniform and non-uniform excitation of the system affects the behavior of the dam body. It is concluded that the seismic safety evaluation of dams must be considered based on the site and structure conditions.

Keywords: Concrete gravity dam, Fluid-structure Interaction, Spatial variation, Seismic linear response

1 INTRODUCTION

Generally, in seismic safety evaluation of concrete dams, the system is excited uniformly. However, with extended foundations in such dams, the seismic excitation is non-uniform due to limited velocity of earthquake waves and coherency effects. Whether the effect of input variation is significant in the seismic response of the structure or not, clearly depends on the size of the structure-foundation interface. The lag time in the structure support excitation due to finite velocity of seismic wave is called asynchronous.

Several researchers have worked on the seismic behavior of concrete dams as referred in [1]. The effects of asynchronous and non-uniform support excitation on the response of large structures with an extended area of contact with the ground, such as suspension bridges [2] have been considered by many researchers However, there is not many works considering the effects of asynchronous on the seismic behavior of concrete dams [3]. The effect of non-uniform ground motion on response of rockfill dams has been considered by Haciefendioglu [4]. Bayraktar et al.[5] investigated asynchronous dynamic response of dam-reservoir-foundation systems using lagrangian approach. Altinisik [6] indicated that more stresses occur near the base of the dam because of the pseudo-static displacements resulted from modeling traveling wave effects. Dumanoglu and Severn [7] obtained solutions for various finite velocities and also, for infinite velocity of seismic wave and showed that the response of the dam body is increased due to reducing the wave velocity. Seismic response of concrete-faced rock-fill (CFR) dams subjected to asynchronous base excitation is determined by Bayraktar et al. [8]. Zhang and Mai [9] obtained the response of an arch dam due to harmonic excitation with time-lag between abutments. Response of dams to asynchronous base excitation also has been studied by Maheri and Gaffer-zadeh. [10], Priscu et al. [11], Haroun and Abdel-Hafiz [12] and Harichandran and Chen [13].

The main object of this paper is to evaluate the asynchronous effects on linear response of concrete gravity dams. The reservoir is assumed compressible and the prepared model in ABAQUS [14 and 15] environment is calibrated using available academic programs.

2 ASYNCHRONOUS INPUT

In the conducted analysis, it is assumed that the heel of the dam body is excited first, as shown in Figure 1. The wave propagation is towards the downstream. Therefore, different points along the interface 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.

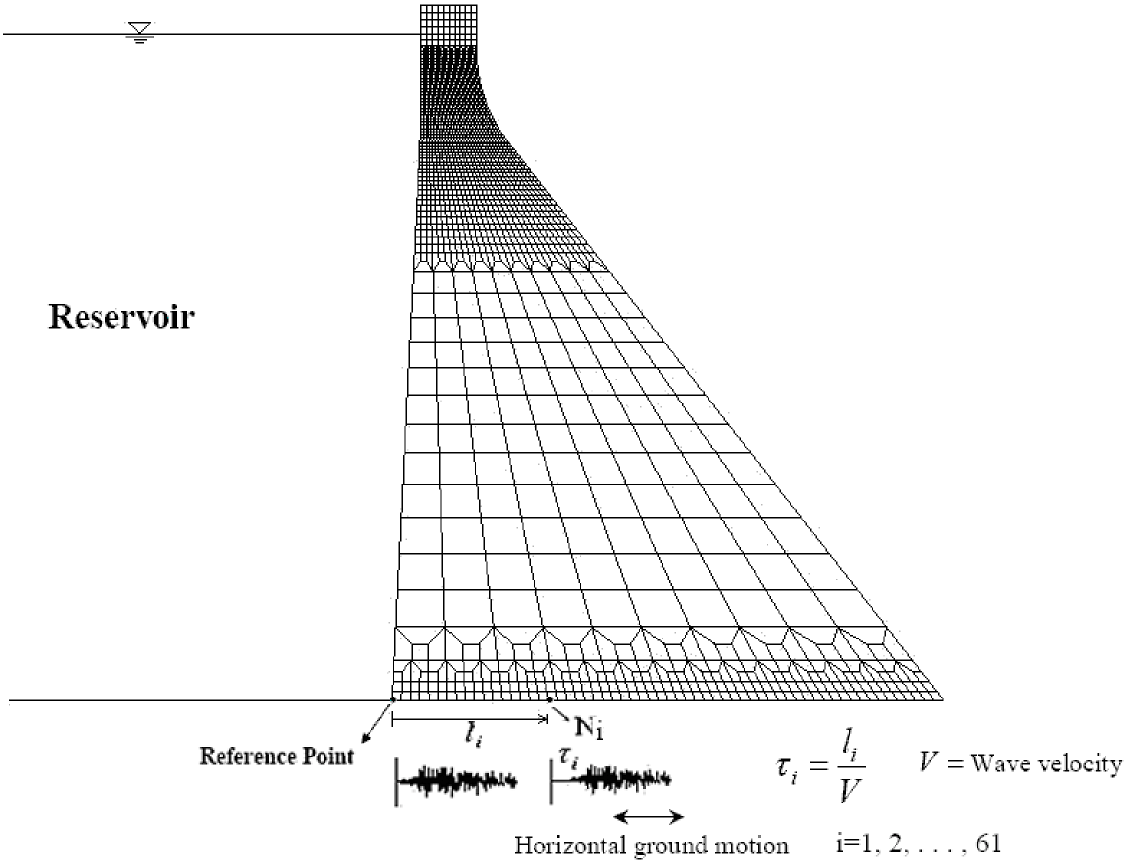

Figure 1: Multiple support excitation

As shown in Figure 1, τ_i is arrival time of the ground motion at specific support node, N_i; l_i is the distance of reference node and node N_i; and V is the travelling wave velocity which is taken as 600 m/s and infinity, in the conducted analyses.

3 FLUID-STRUCTURES INTERACTION

3.1 Reservoir Governing Equation of Motion

The governing equation in the reservoir media is Helmoltz equation obtained from Euler's equation given as [14]:

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

where, *p*, *C* and *t* are the hydrodynamic pressure, pressure wave velocity in the liquid and time, respectively. The boundary conditions required to apply on the reservoir media to solve equation (1) are explained in the following sections. These boundaries are demonstrated in Figure 2, schematically.

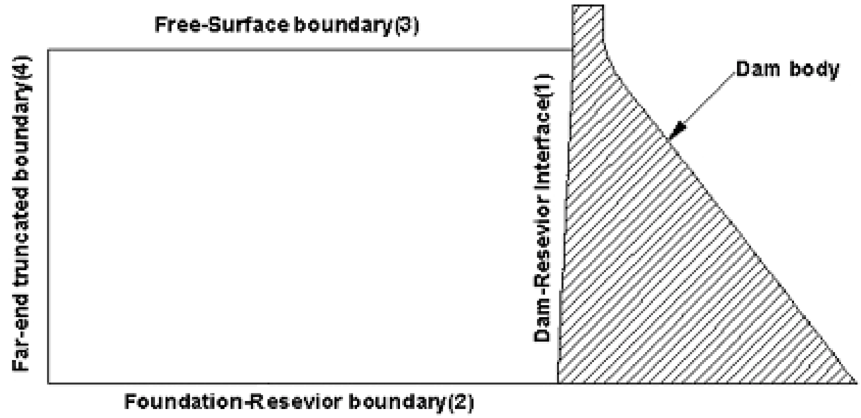

Figure 2**:** Finite reservoir boundary condition

3.2 Dam-Reservoir Interface- B.C. (1)

At the interface of fluid-structure, there is no flow across the interface. Using Euler’s equation and some mathematical operations, the following equation is resulted at the interface.

$$\frac{\partial p}{\partial n} = -\rho n^{T} \ddot{u}_{s} \tag{2}$$

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

3.3 Foundation-Reservoir Boundary- B.C. (2)

On this boundary no absorption is considered (the wave reflection coefficient according to the reservoir bottom is assumed unity) and therefore, the boundary condition shown in equation (2) is applied on the reservoir bottom.

3.4 Free Surface Boundary- B.C. (3)

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

$$\frac{\partial P}{\partial n} = -\frac{1}{g}\ddot{p} \tag{3}$$

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

3.5 Far-End Truncated Boundary- B.C. (4)

The Sommerfeld boundary condition is applied on the far-end truncation boundary of the reservoir for modeling the complete absorption of propagating waves in the upstream direction, as shown in Figure 1. This boundary condition is the most common one which is based on the assumption that at long distance from the dam face, the pressure wave is propagated as plane [15]:

$$\frac{\partial p}{\partial n} = -\frac{1}{C}\frac{\partial p}{\partial t} \tag{4}$$

4 CASE STUDY- PINE FLAT DAM

The tallest monolith of the Pine Flat dam is selected considering the effect of spatially variation on the seismic linear response of the system. The crest length of the dam body is 560m and the height of the tallest monolith is 122m. The modulus of elasticity, unit weight and Poisson's ratio of the concrete are taken as 27580MPa, 2400kg/m^3 and 0.2, respectively. The tensile strength of the concrete is assumed 2.7MPa 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 the analysis. The proportional damping equivalent to 10% of the critical damping based on the first and second natural vibration modes of the dam-reservoir system is applied on the equation of motion of the structure. The structure is modeled using 2040 4-node iso-parametric plane stress elements and 3774 4-node elements make the finite element model of the reservoir. Figures 3 and 4 show the geometric shape and the finite element models of the dam body and its reservoir, respectively.

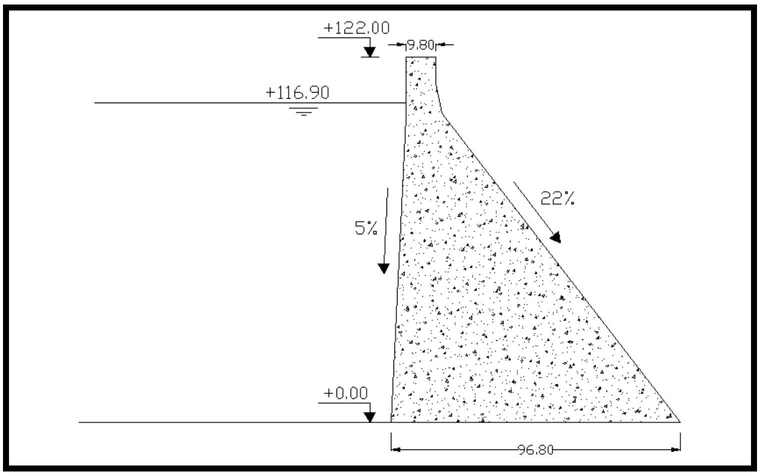

Figure 3: Dimensions of the dam body-Pine Flat Dam

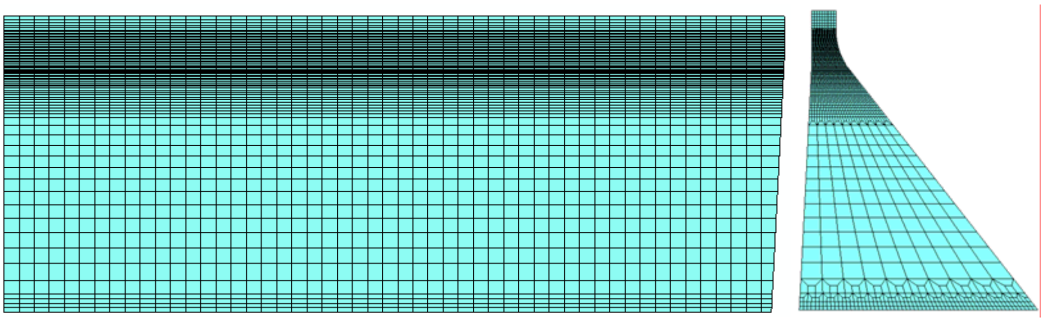

Figure 4**:** Finite element model of the dam body and the reservoir

The length of the FE model of the reservoir is about 2.6 times of the dam body depth. The depth of the reservoir is 116.88m. The pressure wave velocity and the mass density are taken as 1438.66m/sec and 1000kg/m3 within the fluid environment, respectively and no absorption is considered at the reservoir bottom (the wave reflection coefficient according to the reservoir bottom is assumed unity).

The first 20 sec. of the earthquake components recorded in Kern County site due to Taft Lincoln earthquake on 21 July 1952 depicted in Figure 5 is used to excite the dam. The components have the PGA equal to 0.179g and 0.155g in horizontal and vertical directions, respectively. The time step of the records is 0.02sec., which is equivalent to the time step used in seismic analysis.

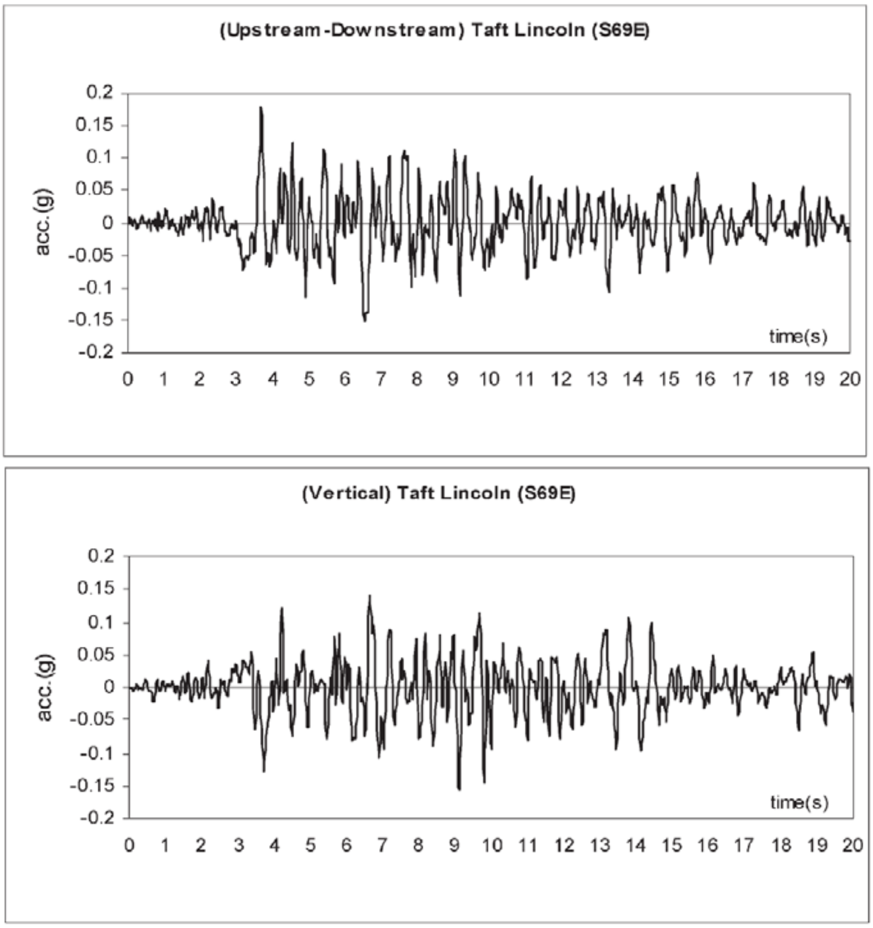

Figure 5: Upstream -downstream (S69E) and vertical components-Taft Lincoln earthquake

4.1 Verification of Numerical Model

The prepared model in ABAQUS [15, 16] environment and the performance of the numerical algorithm of the used software is verified using academic program called NSAG-DRI[1] [16]. It is worth noting that NSAG-DRI is able to analyze concrete dams in 2D space including dam-reservoir interaction and the smeared crack approach is used to simulate the nonlinear behavior of mass concrete in tension.

Figure 6 shows the time history of the crest displacement resulted from ABAQUS and NSAG-DRI when the reservoir is empty. As shown, the results are in excellent agreement.

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[1] **N**onlinear **S**eismic **A**nalysis of **G**ravity Dams Including **D**am-**R**eservoir **I**nteraction

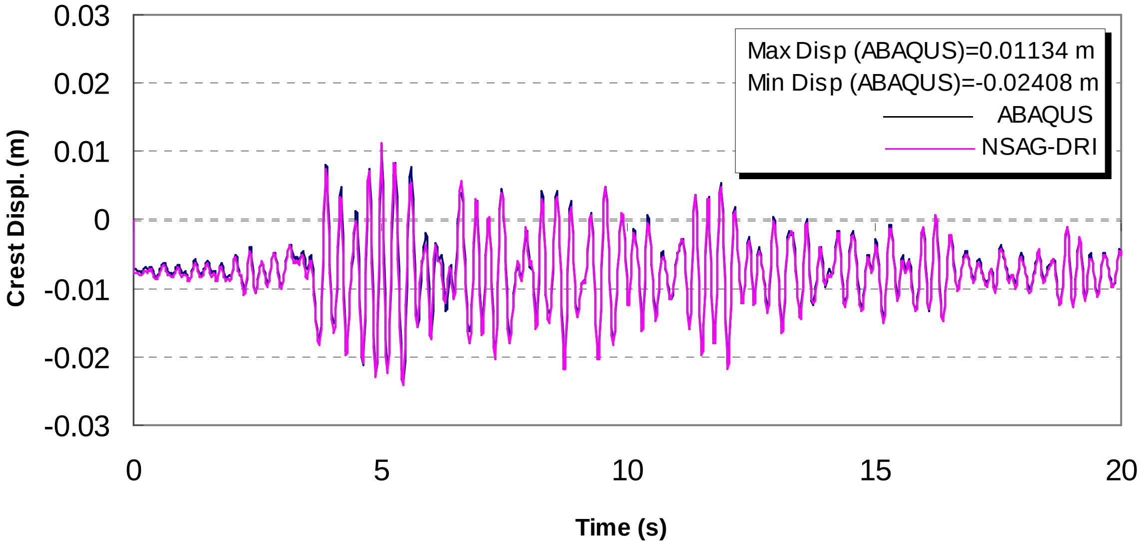


Figure 6**:** Crest displacement in stream direction, comparison of results obtained from ABAQUS with NSAG-DRI; dam body and empty reservoir

Figures 7 shows a comparison of the time history of crest displacement resulted from ABAQUS with those obtained form NSAG-DRI program when the reservoir is full. It is found that the obtained results are in excellent agreement in spite of various numerical algorithms used in the two utilized programs for solving the coupled problem of dam-reservoir interaction.

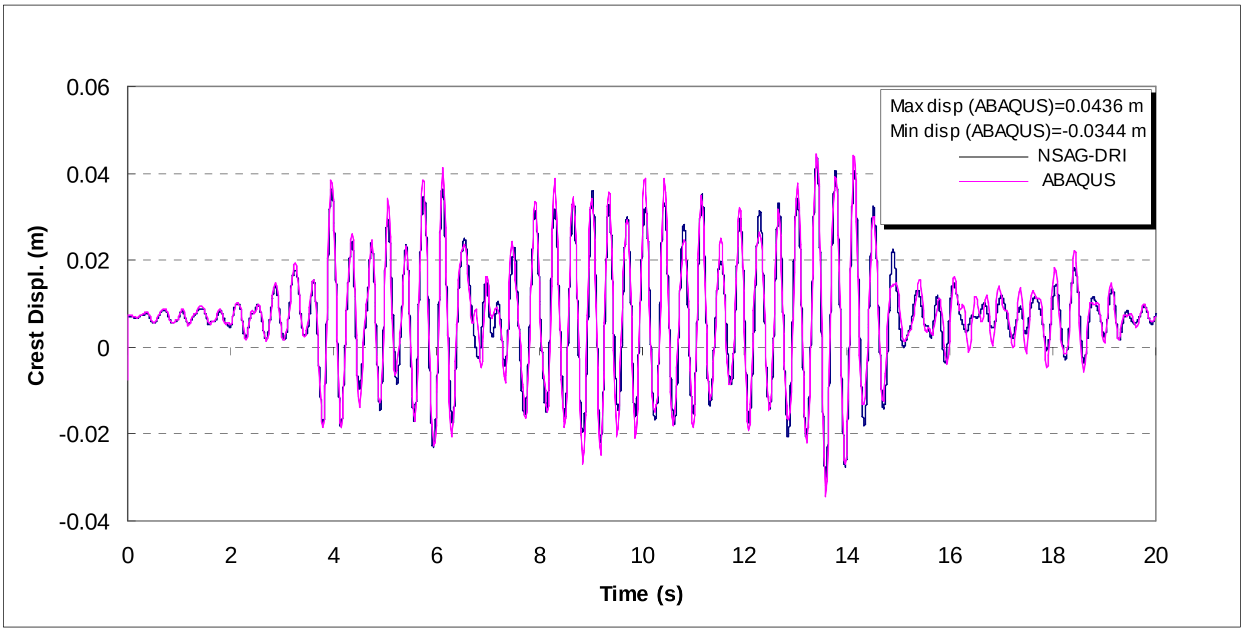


Figure 7**:** Crest displacement in stream direction, comparison of results obtained from ABAQUS with NSAG-DRI; dam body and full reservoir

4.2 Calibration of Finite Element Model under Non-Uniform Excitation

To calibrate the model subjected to non-uniform excitation, dynamic analyses are conducted assuming a high value for wave propagation velocity, such as 10000m/s, for modeling the uniform excitation of the dam body base. Two different analyses are performed assuming the reservoir is empty and full. The results are compared with those obtained when the system is excited uniformly. Figures 8 and 9 show that, the obtained results are in excellent agreement.

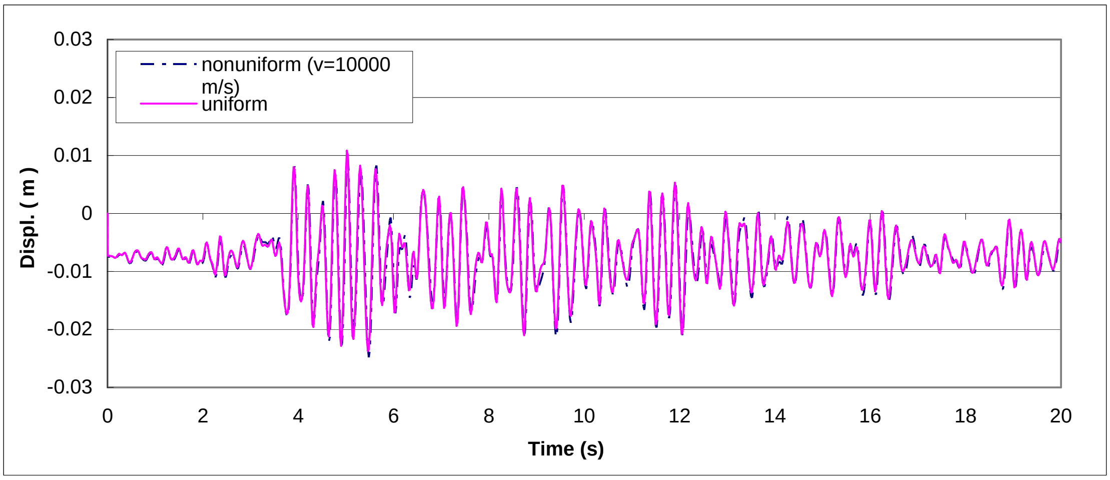


Figure 8: Crest displacement in the stream direction; dam body with empty reservoir

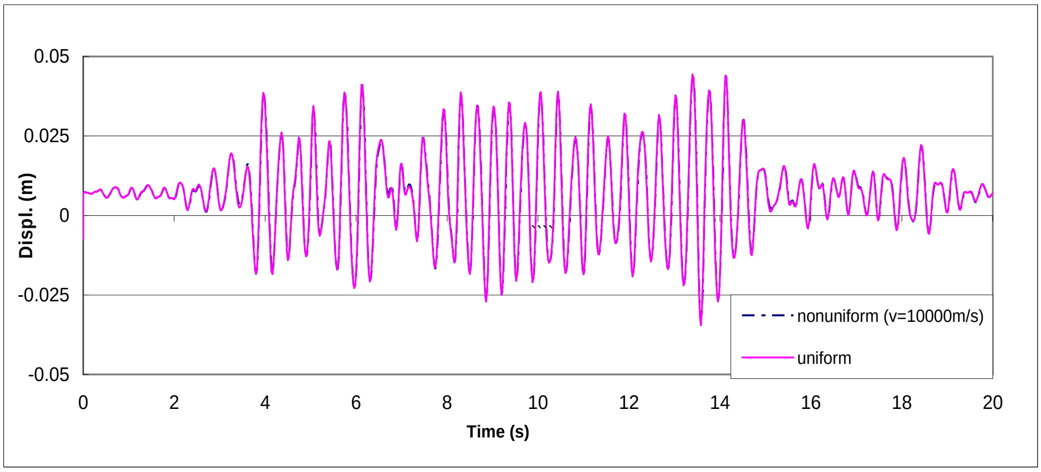


Figure 9: Crest displacement in the stream direction; dam body and full reservoir

4.3 Non-Uniform Excitation Using Stream and Vertical Components

The dam-reservoir system is excited using stream and vertical components of the earthquake record. The velocity of the seismic travelling wave is assumed 600m/sec., when the system is excited non-uniformly. The time history of the crest displacement in stream and vertical directions for the cases of uniform and non-uniform excitations are given in Figures 10 and 11, respectively. As can be found, non-uniform excitation increases the crest displacements.

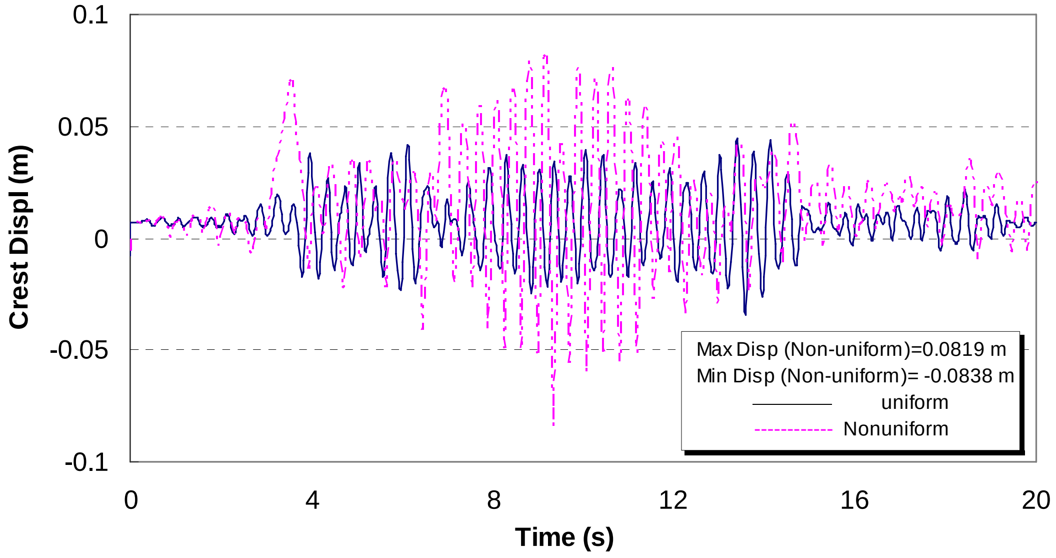


Figure 10: Crest displacement in the stream direction; dam body and full reservoir; non-uniform excitation (V=600m/sec.)

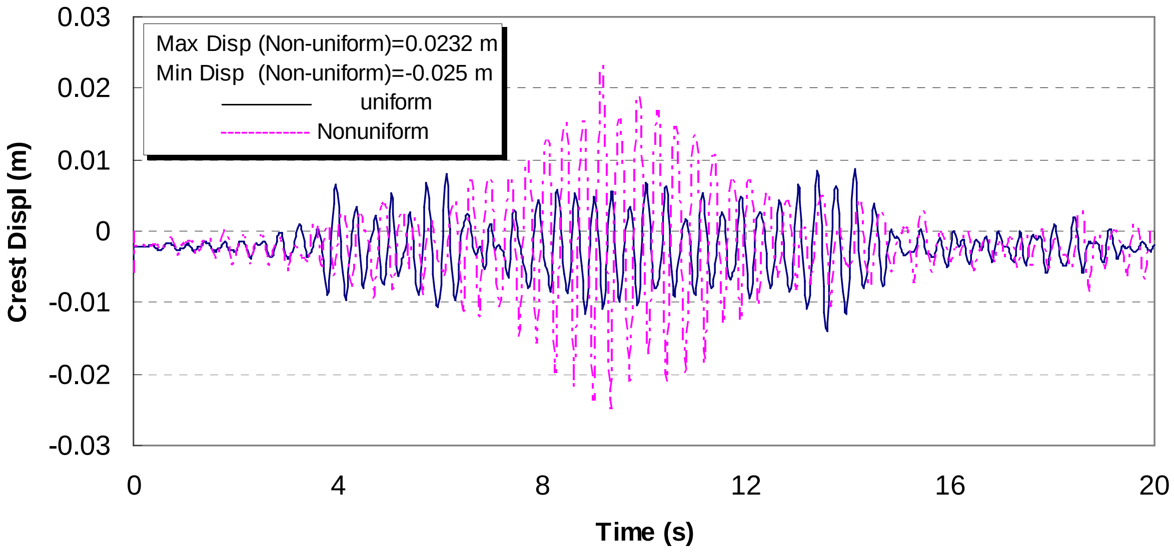
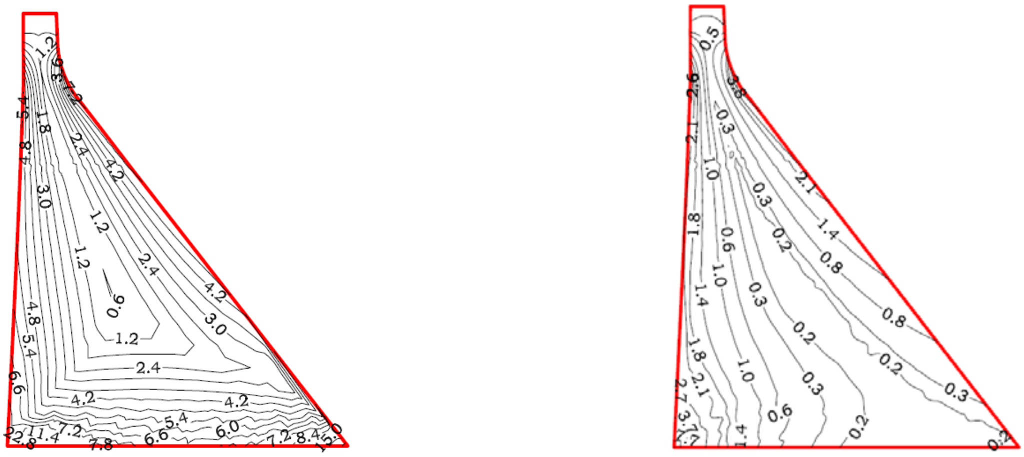


Figure 11: Crest displacement in the vertical direction; dam body and full reservoir; non-uniform excitation (V=600m/sec.)

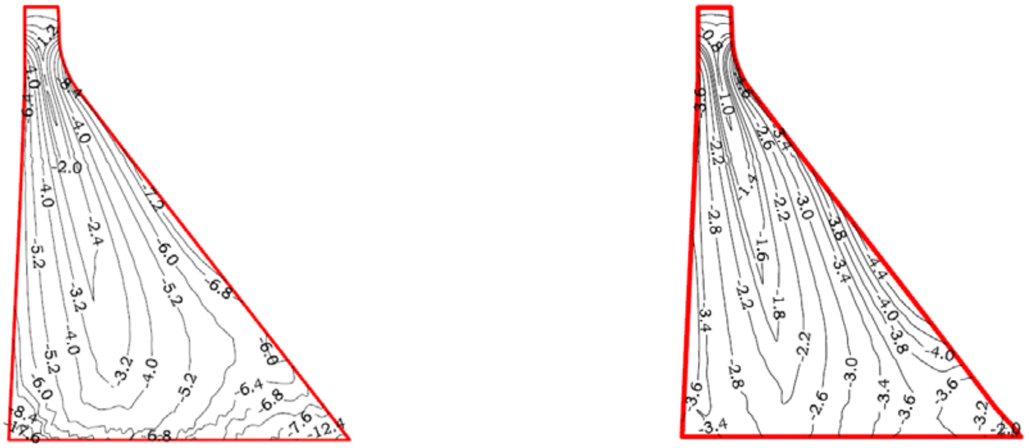
As shown, non-uniform excitation of the dam body leads to completely different crest response in value and in frequency content of the time history in both stream and vertical directions. Figures 12 to 15 show the envelopes of maximum principal stress, minimum principal stress, vertical and shear stresses within the dam body.



(a)

(b)

Figure 11: Maximum principal stresses; (a) non-uniform excitation (b) uniform excitation



(a)

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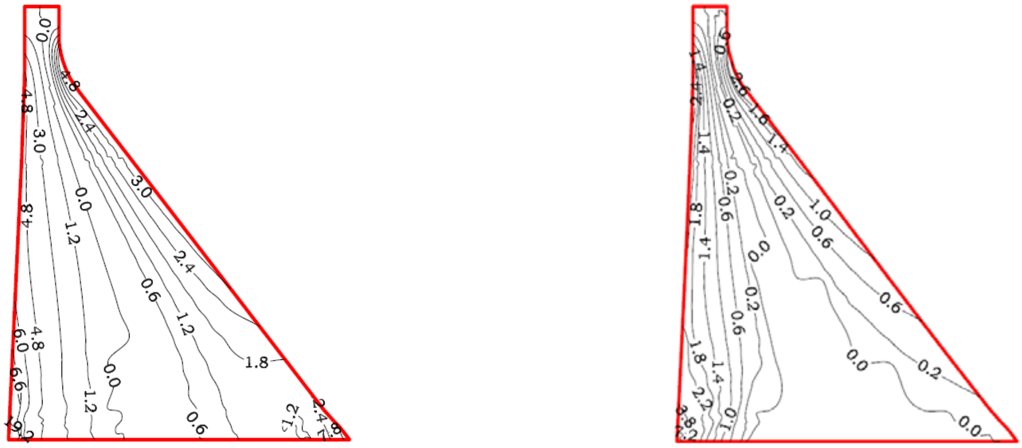
Figure 12: Minimum principal stresses; (a) non-uniform excitation (b) uniform excitation



(a)

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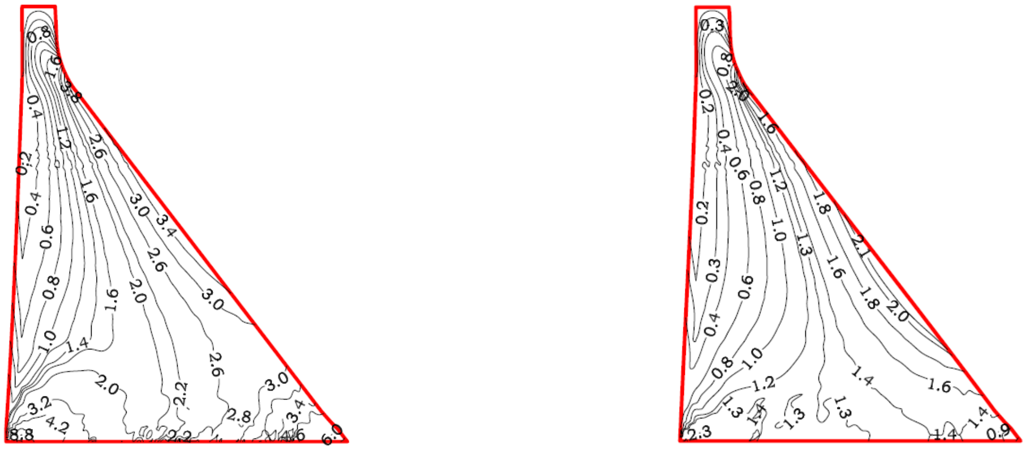
Figure 13: Vertical stresses; (a) non-uniform excitation (b) uniform excitation



(a)

(b)

Figure 14: Shear stresses; (a) non-uniform excitation (b) uniform excitation

All the stress components within the neck region and also, near the base of the dam body increase intensely due to limited velocity of seismic wave propagation. It is worth noting that, to obtain reasonable results in seismic behavior evaluation of concrete gravity dams, the shear wave velocity used in the dynamic analysis of the dam should be evaluated from experimental studies on the dam site. Table 1 presents a summary of the maximum stresses occurred within the dam body.

Table1**:** Maximum stresses within the dam body

Stress Component	**Excitation state**	Value (MPa)	Time (sec.)
Maximum principal	Uniform excitation	7.8	13.4
	Non-Uniform excitation	23.4	3.56
Minimum principal	Uniform excitation	-4.69	6.12
	Non-Uniform excitation	-17.8	9.72
Vertical	Uniform excitation	7.28	13.4
	Non-Uniform excitation	19.4	3.56
Shear	Uniform excitation	2.33	13.4
	Non-Uniform excitation	8.9	3.56

Based on the obtained results, peak values of the maximum and minimum principal stress; vertical and shear stresses in the case of non-uniform excitation are 3, 3.8, 2.7 and 3.8 times greater than those obtained when the system is excited uniformly. In fact, when the system is excited non-uniformly, value of stresses within the neck region and in vicinity of the based of the dam body increases.

Based on the plotted contours, the pattern of stress distribution within the dam body is completely different when the excitation of the structure is non-uniform.

4.4 Non-Uniform Excitation Using Stream Component

Figures 16 and 17 show the crest displacement time history in the stream and vertical directions when the system of dam body and its full reservoir is excited in the horizontal direction.

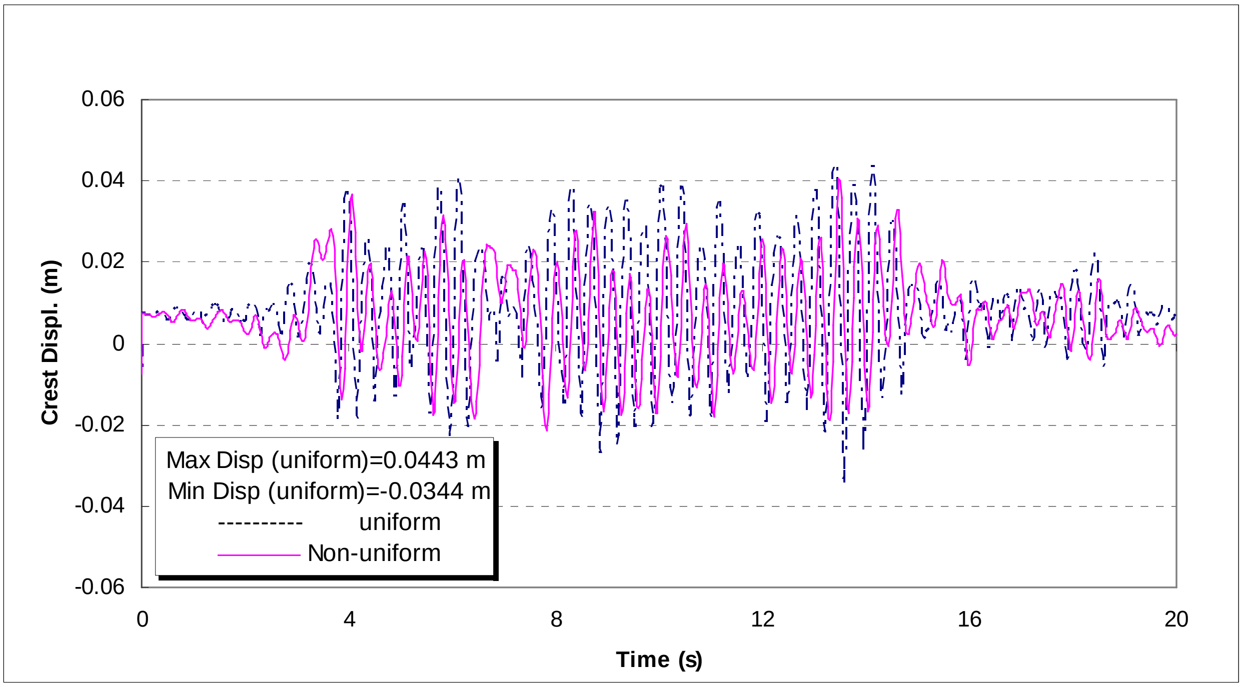


Figure 16: Crest displacement in the stream direction; dam body and full reservoir; non-uniform excitation (V=600m/sec.)

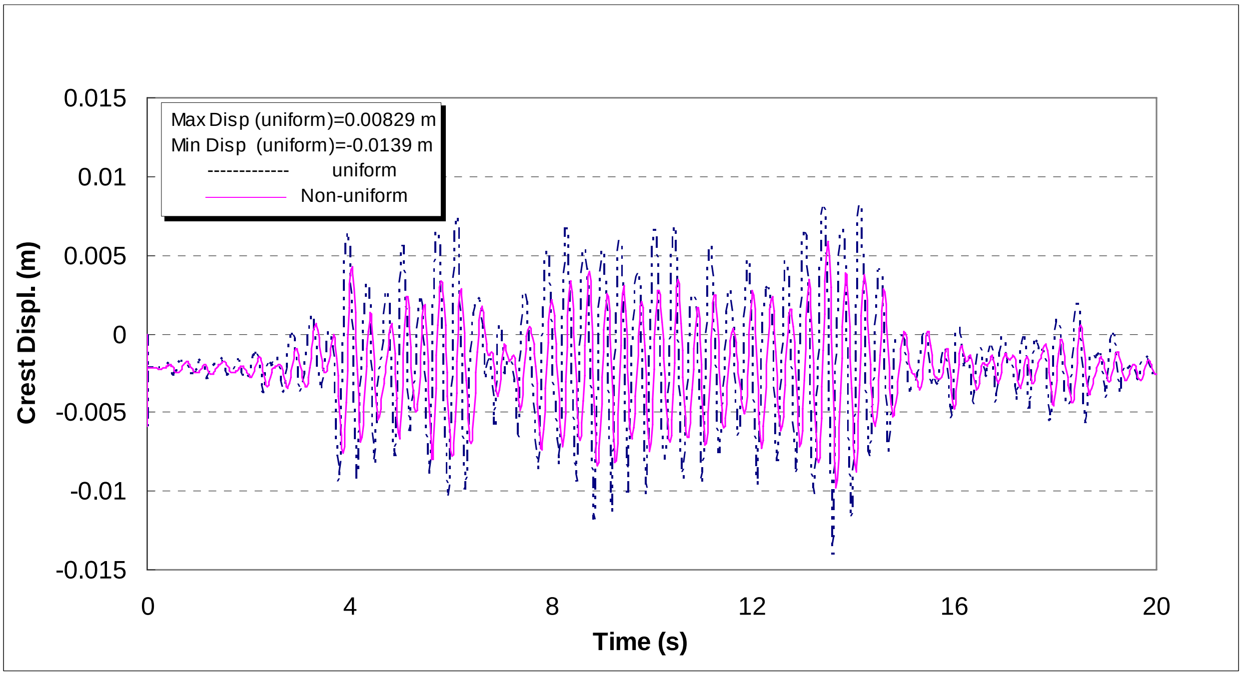
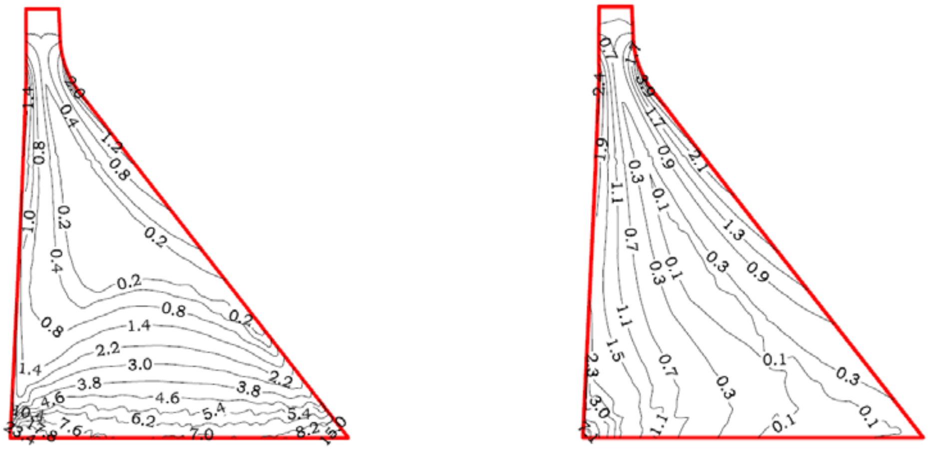


Figure 17: Crest displacement in the vertical direction; dam body and full reservoir; non-uniform excitation (V=600m/sec.)

In contrast to the case with excitation in both the two directions of stream and vertical, when the system is excited in the horizontal direction, the crest displacement is decreased in non-uniform excitation in comparison with the results obtained from the system under the uniform excitation. In addition, the frequency content of the crest response is completely different in the two conducted analyses.

Envelopes of the maximum and minimum principal stresses, vertical and shear stresses for the cases of uniform and non-uniform excitation are given in Figs. 18 to 21, respectively. As shown, all the stress components near the base of the dam increase considerably when the wave propagation velocity is taken as 600m/sec. However, in spite of the previous analyses (conducted using the two components of the earthquake record), non-uniform excitation of the system reduces the stress components within the neck region of the dam body which corresponds to the crest response shown in Figures 20 and 21.



(a)

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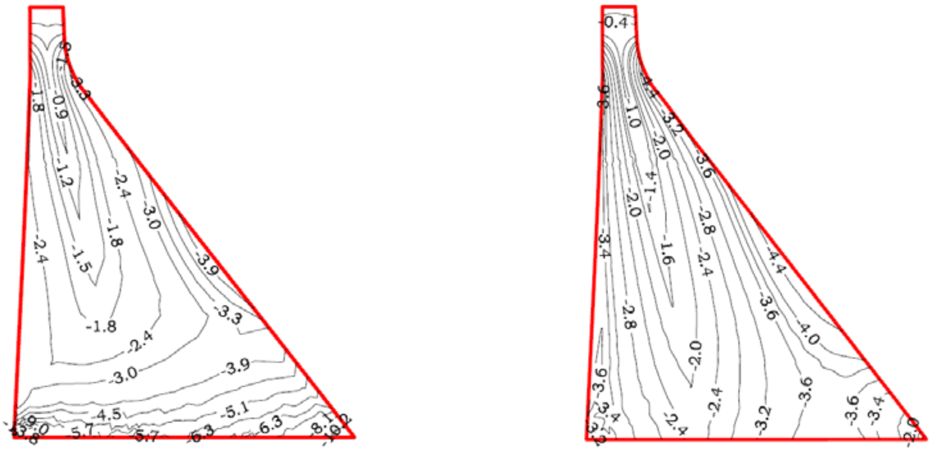
Figure 5: Maximum principal stresses; (a) non-uniform excitation (b) uniform excitation



(a)

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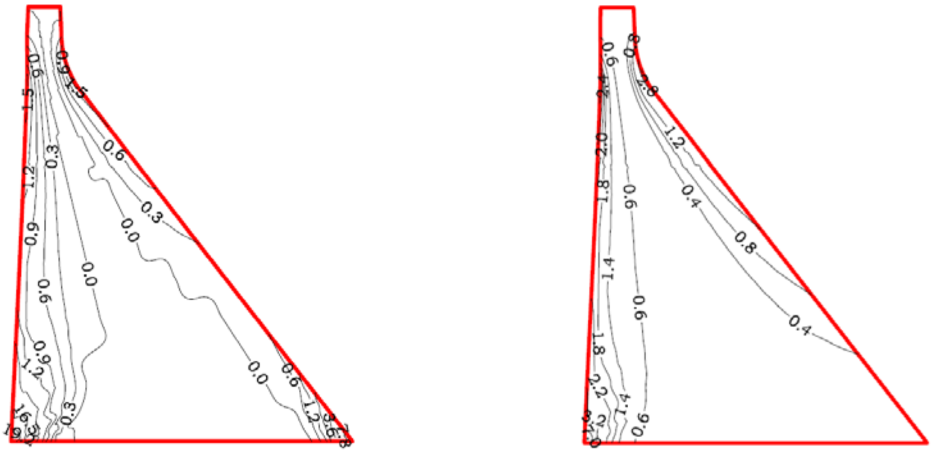
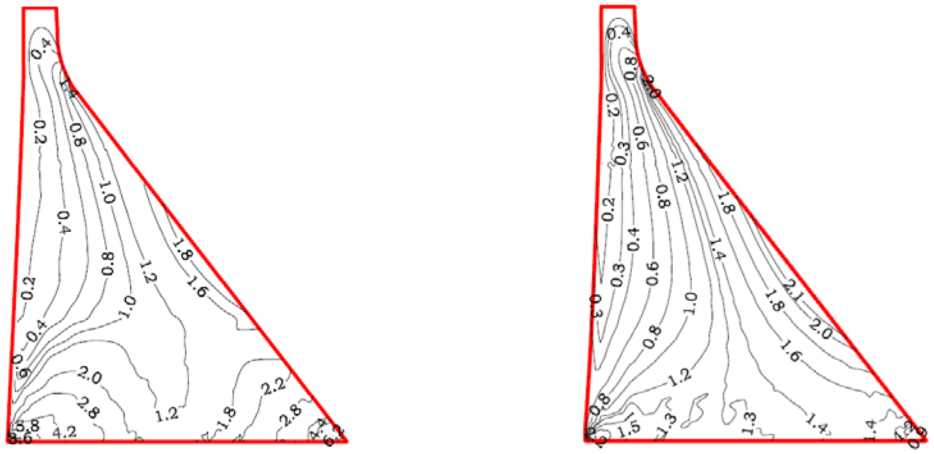
Figure 19: Minimum principal stresses; (a) non-uniform excitation (b) uniform excitation



(a) (b)

Figure 20: Vertical stress; (a) non-uniform excitation (b) uniform excitation



(a) (b)

Figure 21: shear stress; (a) non-uniform excitation (b) uniform excitation

Table (2) presents summary of the maximum stresses within the dam body under the horizontal excitation.

Table 2**:** Maximum stresses within the dam body under the horizontal excitation

Stress Component	**Excitation state**	Value (MPa)	Time (sec.)
Maximum principal	Uniform excitation	7.65	13.4
	Non-Uniform excitation	23.5	3.6
Minimum principal	Uniform excitation	-4.57	14.12
	Non-Uniform excitation	-14.1	6.46
Vertical	Uniform excitation	7.14	13.4
	Non-Uniform excitation	19.3	3.6
Shear	Uniform excitation	2.29	13.38
	Non-Uniform excitation	8.73	3.58

It is worth noting that, as expected, for the case using the non-uniform excitation, the maximum stresses occur in the vicinity of the base due to restriction of the nodes in the base of the dam body. However, under the horizontal excitation, the stresses within the neck region are lower than the case with uniform excitation.

5 CONCLUSIONS

Linear seismic analyses of a concrete gravity dam under non-uniform excitation including dam-reservoir interaction are conducted. The system of dam-reservoir is excited non-uniformly due to limited seismic wave propagation velocity. The reservoir is assumed compressible and the Pine Flat dam is chosen as a case study. The two sets of wave propagation velocities used in the conducted analyses are taken as 600m/sec. and infinity. Calibration and validity of the prepared model for non-uniform excitation is conducted comparing the results obtained from the uniform excitation of the system and the non-uniform excitation of the system when the seismic wave propagation velocity is assumed infinity. Based on the results, stress components near the base of the dam body are considerably increased when the system is under the non-uniform excitation with limited wave propagation velocity. In addition, unlike the case under the horizontal excitation, for the case under both horizontal and vertical excitation, the crest displacement and stresses within the neck region of the dam body resulting from the non-uniform excitation of the system with finite wave velocity, are larger than those obtained from the uniform excitation.

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