NONUNIFORM SEISMIC EXCITATION OF CONCRETE ARCH DAMS

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Abstract

In the present paper, effects of non-uniform excitation due to spatially variation of seismic waves under the reservoir bottom on the linear response of arch dams are studied. The foundation is assumed to be massed and infinite elements are utilized to model the semi infinite medium via the far-end boundary of the foundation FE model. The reservoir is assumed compressible and the coupled system is solved using the staggered method. As a case study, Amir-Kabir double curvature arch dam in Iran is selected to investigate the seismic behavior of the system. Two cases are analyzed in which wave travelling velocities are taken as 650m/sec and infinity. According to the results, comparison of the response due to non-uniform excitation with the response due to uniform input demonstrates the importance of accounting for spatial non-uniformity.

Keywords: Concrete arch dam, Dam-reservoir-foundation interaction, Infinite element, Linear behavior, Travelling wave

1 INTRODUCTION

Generally, in seismic analysis of concrete dams, it is assumed that the system is subjected to uniform ground motion. However, earthquake waves travel with specific finite speed depending on the wave shapes and geologic materials and it arrives at various locations at different times along the ground suface.

Several researchers have worked on seismic behavior of concrete arch dams as referred in [1-3]. Effect of asynchronous and multiple support input in analysis of beams [4] and bridge [5] have been considered by many researchers. However, there is not many works considering effects of asynchronous on the seismic behavior of concrete dams. Bayraktar et al. [6] investigated asynchronous dynamic analysis of dam-reservoir-foundation systems using lagrangian approach. Priscu et al. [7] studied response of dams to asynchronous base excitation. Dumanoglu and Severn [8] obtained solutions for various finite velocities and also, for infinite velocity of seismic wave. Seismic response of concrete-faced rock-fill (CFR) dams subjected to asynchronous base excitation is determined by Bayraktar et al. [9]. Zhang and Mai [10] obtained the response of an arch dam due to harmonic excitation with time-lag between abutments. Effect of non-uniform earthquake on response of arch dams has been considered by Szczesiak et al. [11] and Nowak and Hall [12]. Alves [13] considered effects of spatially variation on nonlinear seismic response of concrete arch dams. In 1998, Bayraktar and Dumanoglu [14] 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 [15] investigated travelling wave effect on the linear response of concrete gravity dams. They found that hydrodynamic pressures decrease when the non-uniform excitation is used for excitation of the reservoir bottom.

Main object of the present paper is considering effects of non-uniform excitation due to spatially variation of seismic wave under the reservoir bottom on linear response of concrete arch dams. In conducted analyses, foundation is assumed to be massed and infinite elements are utilized to model the semi-infinite medium via the far-end boundary of the foundation numerical model. In addition, the reservoir is assumed compressible and behavior of the system is linear.

2 FLUID DOMAIN AND TRAVELLING WAVE

The governing equation in the reservoir medium is Helmoltz equation given in eqn. (1) extracted from the Euler's equation [16].

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

where, p, C and t are the hydrodynamic pressure, pressure wave velocity in liquid and time, respectively. Boundary conditions required to apply on the reservoir medium to solve eqn. (1) are explained in [16] and are not represented herein.

When interface of the earth and the components of the problem are extended, the direction of wave propagation and its velocity can affect on the seismic response of the problem. Reservoir medium in concrete dams is too long in the upstream direction and therefore, it is expected to have different excitations in various points under the reservoir.

When the travelling wave propagation velocity is assumed infinite under the reservoir, the acceleration applied on the finite element nodes on the reservoir bottom boundary is assumed the same at a specific time. However, if the finite velocity is assumed for the seismic waves travelling under the reservoir, different nodes are excited using various accelerations at specific times which their amplitudes depend on the travelling wave velocity and the distance between the origin node (which is the first excited node) and the target node (which is the node to calculate the acceleration). In the present study, it is assumed that the first excited node is in the upstream node of the reservoir which is on the dam-reservoir interface and the seismic wave propagates in the upstream direction.

3 FOUNDATION DOMAIN AND RADIATION DAMPING

One of the main aspects in the seismic loading and wave propagation within the semi-infinite medium such as foundation rock is to prevent the wave reflection from the far-end artificial boundary of the finite medium. In the present study, infinite elements are utilized to model the semi-infinite medium effect via the far-end boundary of the foundation. The basic idea is to use elements with special shape functions for the geometry at the infinite boundary. Therefore, there will be two sets of shape functions, the standard shape function, N_i, and a growth shape function, M_i. The growth shape function, M_i, grows without limit as the coordinate of the i^{th} node approaches infinity, and is applied to the geometry. The standard shape functions N_i are applied to the field variables.

In the present article, to simulate the effect of semi-infinite medium via the near field medium of the foundation, 20-node solid elements with one face in infinity is utilized. The pertinent shape and growth functions and the procedure for the formation of the stiffness matrix is given in [18 bettes]

4 COUPLED STRUCTURE-RESERVOIR PROBLEM

In the present study, staggered displacement method, which is unconditionally stable, is utilized to solve the coupled problem [16]. Equations of the dam-foundation and the reservoir take the following form:

$$[\mathrm{M}]\{\ddot{\mathrm{U}}\}+[\mathrm{C}]\{\dot{\mathrm{U}}\}+[\mathrm{K}]\{\mathrm{U}\}=\{\mathrm{f}_1\}-[\mathrm{M}]\{\ddot{\mathrm{U}}_{\mathrm{g}}\}+[\mathrm{Q}]\{\mathrm{P}\}=\{\mathrm{F}_1\}+[\mathrm{Q}]\{\mathrm{P}\} \tag{6}$$

$$[\mathrm{G}]\{\ddot{\mathrm{P}}\}+[\mathrm{C}']\{\dot{\mathrm{P}}\}+[\mathrm{K}']\{\mathrm{P}\}=\{\mathrm{F}\}-\rho[\mathrm{Q}]^{\mathrm{T}}\left(\{\ddot{\mathrm{U}}\}+\{\ddot{\mathrm{U}}_{\mathrm{g}}\}\right)=\{\mathrm{F}_2\}-\rho[\mathrm{Q}]^{\mathrm{T}}\{\ddot{\mathrm{U}}\}$$

where, $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices of the structure including dam 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 [16].

5 ANALYSIS OF AMIR-KABIR DOUBLE CURVATURE ARCH DAM

Amir-Kabir arch dam, located in Iran, is selected to consider effect of travelling waves on the seismic response. This dam is a double curvature arch dam, which its crest length is 390m and its height above the foundation is 168m. The dam structure is modeled using 72 iso-parametric 20-node elements. Figure 1 shows the finite element model of the dam body and the near field model of the foundation.

Foundation is modeled using 980 20-node elements in a semispherical shape. The radius of the foundation region is taken to be 330m and semispherical body center is located on the middle of the crest of the dam body. The fluid is simulated using 8-node iso-parametric fluid elements including 1024 8-node elements. The finite element model of the fluid domain is modeled up to about twice of the height of the dam body in the upstream direction as shown in Figure 2.

The modulus of elasticity, the unit weight and Poisson’s ratio are taken as 26GPa, 24027N/m^3 and 0.17, respectively [19]. The static deformation modulus of the foundation is used for both the static and dynamic analysis [20]. The deformation modulus, the unit weight and Poisson’s ratio for the rock foundation are taken as

16.30GPa, 29400N/m^3 and 0.15, respectively [13]. The velocity of pressure wave propagation and the unit weight of water in the reservoir are assumed 1436m/sec and 9807N/m^3, respectively. Finally, wave reflection coefficient of the reservoir bottom and sides is assumed 0.8, conservatively [20].

The stiffness proportional damping is applied on the structure in which the damping ratio for the fundamental mode is selected as 10%. The fundamental frequency of the structure system and therefore, the coefficient of the stiffness matrix of the model are 2.3091HZ and 0.013832. The integration parameters of α, β and γ are taken -0.2, 0.36 and 0.7, respectively. [16].

Figure 3 demonstrates three components of the ground motion recorded at the Abbar station during Manjil-Iran earthquake on 20 June 1990 which is selected for dynamic analyses. This record is normalized and filtered for Amir-Kabir dam site. The horizontal and vertical PGA at MCE level of excitation is 0.43g and 0.33g at the dam site, respectively [19].

5.1 Validity of FE Model under Non-uniform Excitation

To consider validity of the numerical model subjected to non-uniform excitation, dynamic analyses are conducted assuming the high value for wave propagation velocity, such as 10000m/sec, for modeling the uniform excitation under the reservoir bottom and the results are compared with that obtained when the system is excited uniformly. Figures 4 shows the obtained results which are in excellent agreement.

5.2 Effect of Non-uniform Excitation on Reservoir Bottom

Figures 6 to 8 show crest displacements at quadrant midpoints in upstream-downstream, cross-stream and vertical directions, respectively.

In Figure 9, the crest displacement of the crown cantilever in upstream-downstream direction in various conditions of the excitation is depicted. It can be observed that considering non-uniform excitation under bottom of reservoir decrease the crest response of the system in comparison with the uniform excitation.

The crest displacements of the crown cantilever in cross-stream and vertical direction are presented in Figures 10 and 11. It can be realized that considering non-uniform excitation under reservoir bottom decrease the crest response of the system in comparison with the uniform excitation. In addition, the frequency content of the crest response are the same approximately, when there is uniform excitation under the reservoir bottom and the case without the reservoir excitation. however, when the reservoir bottom is excited non-uniformly, the frequency response of the crest changes. This phenomenon can be important in seismic safety evaluation of concrete dams and depending on the travelling wave velocity in the site, must be accounted for.

Figures 12 and 13 show the concurrent contours of cantilever and arch stresses in upstream and downstream faces of the dam body. As shown, pattern of stress distribution which is too important in opening and closing of vertical and lift joints, are completely different in the three conducted dynamic analyses. In addition, the arch and cantilever stresses resulted form non-uniform excitation of the system is less from the two other analyses which is in agreement with the results obtained from the crest displacement time histories.

Table 1 presents summary of maximum tensile stresses resulted from conducted analyses. Based on the obtained results:

- The effect of non-uniform excitation on arch stresses is much more than those on the cantilever stresses.
- When the reservoir bottom is excited uniformly, the results are the same as the case without any exitation under the reservoir.
- When the non-uniform excitation is applied under the reservoir bottom, the maximum arch and cantilever stresses are reduced 51.8% and 33.5% in comparison with the case with uniform excitation under the reservoir, respectively. These reductions reach to 23.3% and 1%, when there is not any excitation for the reservoir bottom.

As can be found from the results, the effect of non-uniform excitation along the reservoir is significant on the stress distribution within the dam body and therefore, based on the dam and reservoir site geometric and material conditions, must be included in seimicsafety evaluation of arch dams.

Conclusions

A linear seismic analysis of concrete dams in 3D space which includes the dam–reservoir-foundation interaction is conducted. The reservoir-structure interaction is accounted for using finite element method and the coupled equations of the system are solved utilizing the staggered displacement method. The foundation medium is assumed to be massed and the effect of semi-infinite medium via the far-end boundary of the massed foundation is modeled using the infinite elements. In addition, the effect of finite velocity of travelling wave along the reservoir is accounted for in the liquid domain.

Amir-kabir double curvature arch dam in Iran is used to consider the effect of non-uniform excitation along the reservoir bottom on the linear seismic response of the system. The two cases are analyzed in which the travelling velocities are chosen as 650m/sec (for instance) and infinity. Validity of the prepared model for non-uniform excitation of the liquid domain is controlled based on the conducted analyses, it is observed that the non-uniform excitation decreases the crest displacements in the stream directions in comparison with the cases exciting the system uniformly. In addition, it is found that the result obtained from the model with uniform excitation is too conservative and modeling non-uniform excitation leads to a reduction in stress levels within the dam body which is an important phenomenon in seismic safety assessment of existing dams.

Reference

1. Fok, K., Chopra, AK., 1986a. Earthquake analysis of arch dams including dam-water-interaction, reservoir boundary absorption and foundation flexibility. Journal of Earthquake Engineering & Structural Dynamics 14, 2, 155-184.
2. Fok, K., Chopra, A.K., 1986b. Frequency response functions for arch dams: Hydrodynamic and foundation flexibility effects. Journal of Earthquake Engineering & Structural Dynamics 14, 5, 769-795.
3. Tan, H., Chopra, AR., 1995. Earthquake analysis of arch dams including dam-water-interaction rock interaction. Earthquake Engineering & Structural Dynamics 24, 1453-1474.
4. Harichandran, R.S., Wang, W., 1990. Response of indeterminate two-span beam to spatially varying seismic excitation, Earthquake Engineering & Structural Dynamics. 19, 173-187.

5. Wu, R.W., Hussain, F.A., Liu, L.K., 1987. Seismic response analysis of structural system subjected to multiple support excitation. Journal of Nuclear Engineering and Design 47, 273-282.
6. Bayraktar, A., Dumanoglu, A.A., Calayir, Y., 1996. Asynchronous dynamic analysis of dam-reservoir-foundation systems by the lagrangian approach. Journal of Computers & Structures 58, 5, 925-935. (SCI).
7. Priscu, R., Popovici, A., Stematiu, D., Stere, C., 1985. Earthquake Engineering for Large Dams. John Wiley: 2nd ed, New York.
8. Dumanoglu, A.A., Severn, R.T., 1984. Dynamic response of dams and other structures to differential ground motions. Proceeding. Inst. Civil Engineering Part; 2, 77, pp.333-352.
9. Bayraktar, A., Haciefendioglu, K., Muvafik, M., 2005. Asynchronous seismic analysis of concrete-faced rockfill (CFR) dams including dam-reservoir interaction. Canadian Journal of Civil Engineering 32, 5, 940-947. (SCI).
10. Zhang, X., Mai, J., 1987. Vibration-Response of Arch Dams with Time-Lag between Abutments. Int. Symp. On Earthquakes and Dams, International Congress on Large Dams (ICOLD), Beijing, China, Vol. 1, pp. 619-632.
11. Szczesiak, T., Weber, B., Bachmann, H., 1999. Nonuniform earthquake input for arch dam-foundation interaction. Journal of Soil Dynamics and Earthquake Engineering 18, 487–493.
12. Nowak, P.S., Hall, J.F., 1990. Arch dam response nonuniform seismic input. Journal of engineering mechanics division. ASCE. 116, 125-132.
13. Alves, S.W., Hall, J.F., 2006. Generation of spatially non-uniform ground motion for nonlinear analysis of a concrete arch dam. Journal of Earthquake Engineering & Structural Dynamics 35, 11, 1339-1357.
14. Bayraktar, A., Dumanoglu, A.A., 1998. The effect of the asynchronous ground motion on hydrodynamic pressures. Journal of Computers and Structures 68, 271-282.
15. Ghobarah, A., Ghemian, M., 1999. Travelling wave effect on hydrodynamic forces on dams. Journal of the European Earthquake Engineering Vol. X111**,** 3, 22-34.
16. Mirzabozorg, H., Khaloo, A.R., Ghaemian, M., 2003. Staggered solution scheme for three-dimensional analysis of dam-reservoir interaction. Dam Engineering Journal 14, 3, 147-179.

17. Sharan, S., 1987. Time-Domain Analysis of Infinite Fluid Vibration. International Journal of Numerical Methods in Engineering 24, 945-958.
18. Mahab Gods, 1994. Overall Program for Stability Evaluation of Dams; Amir-Kabir Arch Dam, Report No.237061/1330/2000.
19. Engineering Guidelines for the Evaluation Hydropower Projects: Arch Dams, Federal Energy Regulatory Commission, Division of Dam Safety and Inspections, Washington, DC 20426, Chapter 11, [October 1999].

Table 1: Maximum tensile dynamic stresses

Stress	**Excitation state**	**Value (MPa)**
Arch	Uniform excitation under dam-reservoir	5.69
	No reservoir excitation	4.30
	Non-Uniform excitation	2.74
Cantilever	Uniform excitation under dam-reservoir	3.97
	No reservoir excitation	3.93
	Non-Uniform excitation	2.64

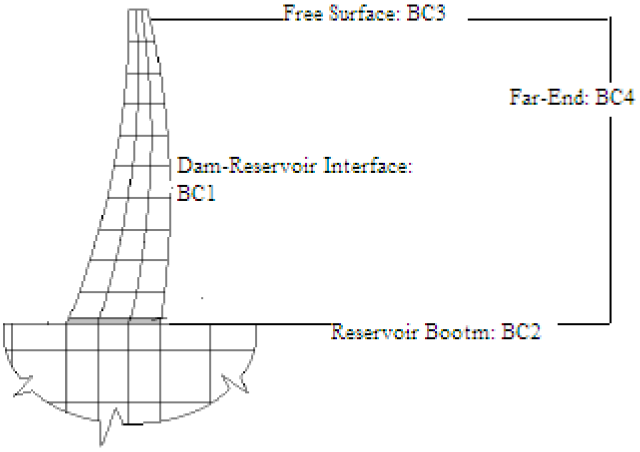


Figure 1: Reservoir boundaries

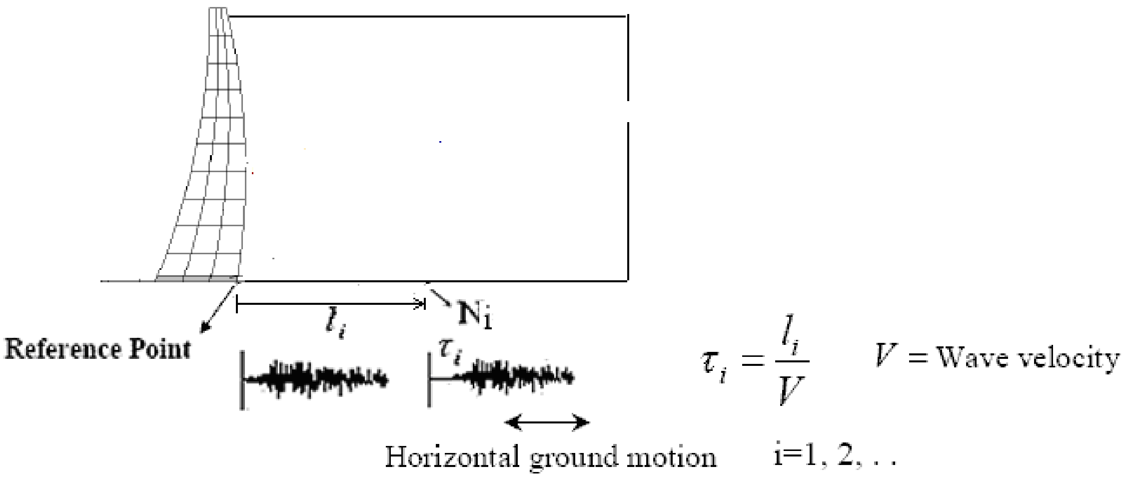


Figure 2: Travelling wave and excitation of reservoir bottom

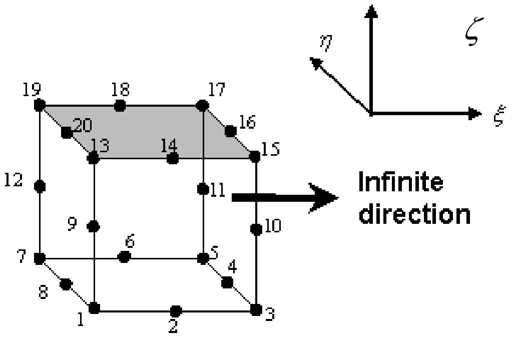


Figure 3: Solid element with one face in infinity

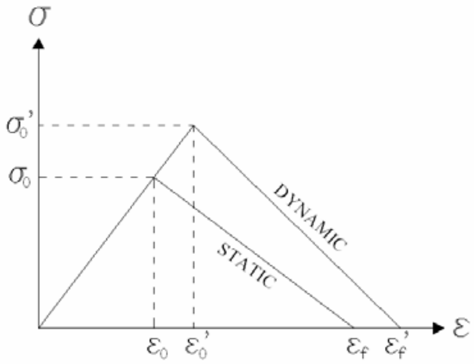


Figure 4: Strain rate effect on the apparent stress-strain curve

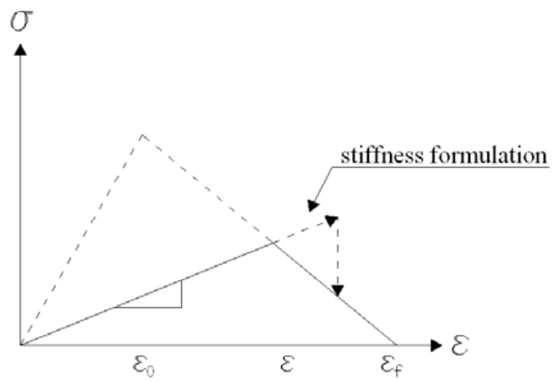


Figure 5: SMS formulation of the stiffness modulus matrix

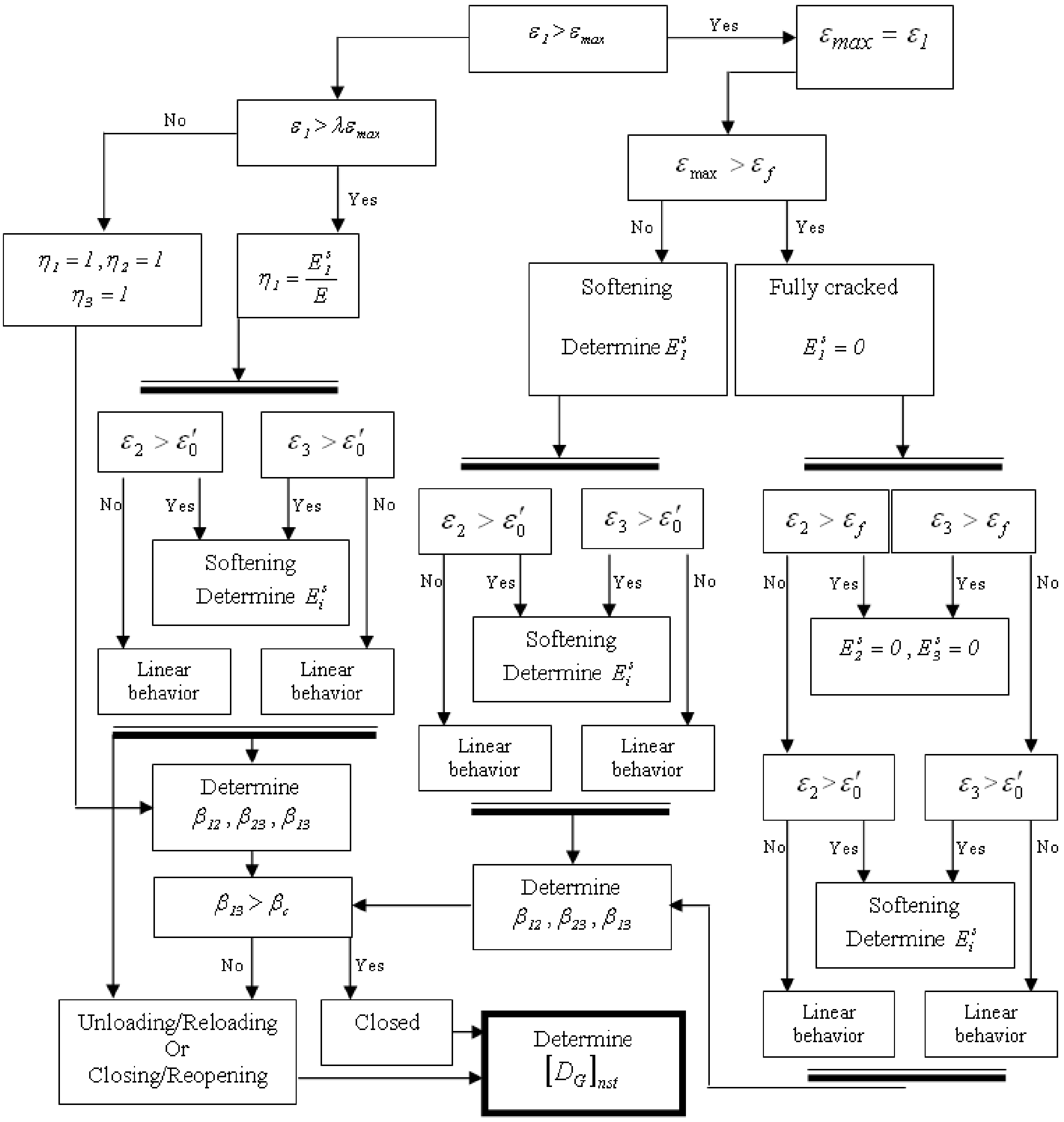


Figure 6: State determination of a Gaussian point, the closing/reopening algorithm and the fully cracked state

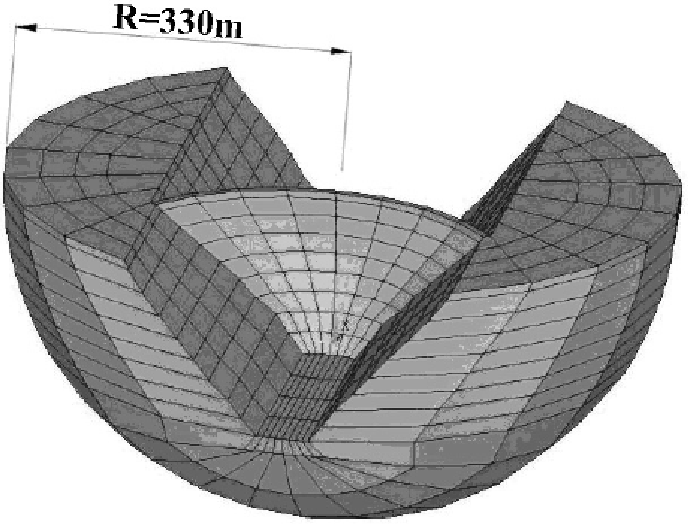


Figure 7: Dam-foundation FEM

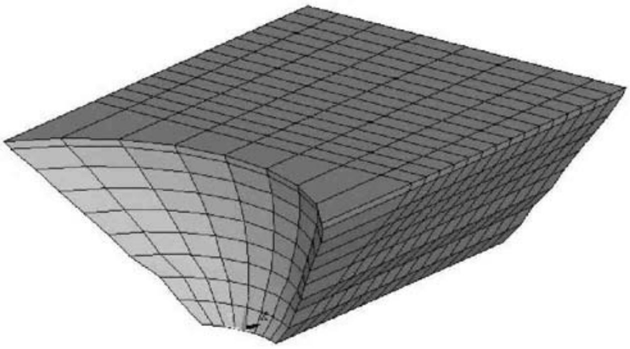
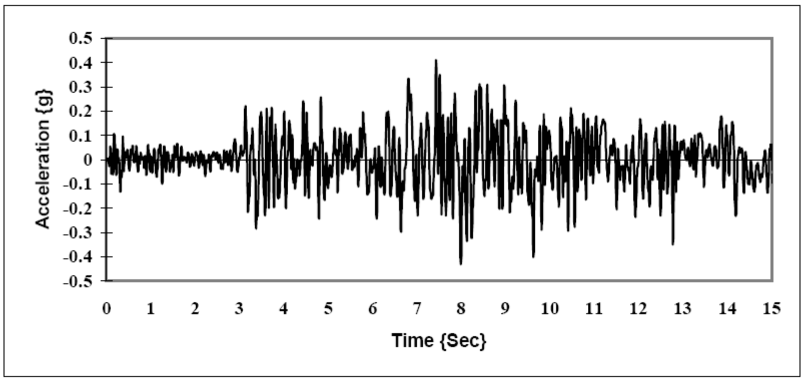
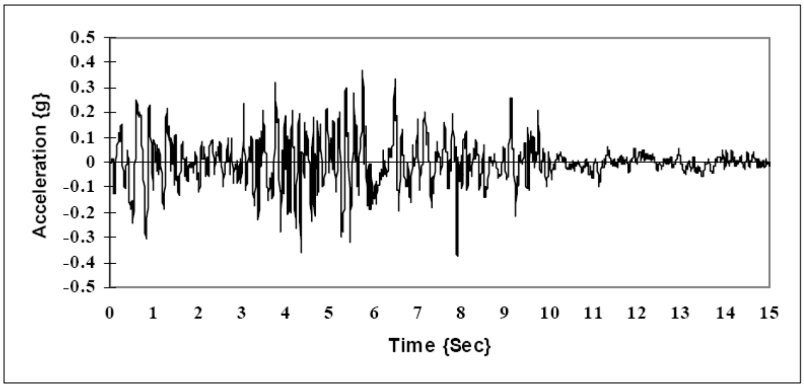


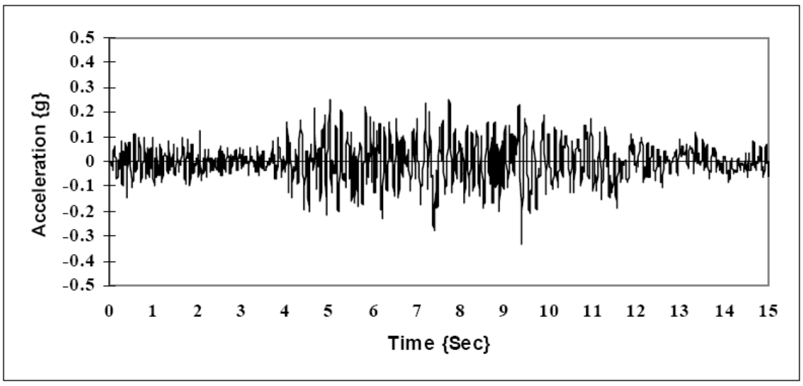
Figure 8: Reservoir finite element model



(a) Horizontal, upstream-downstream direction



(b) Horizontal, cross-stream direction



(c) Vertical direction

Figure 9: Components of the Manjil-Iran earthquake of June 20, 1990

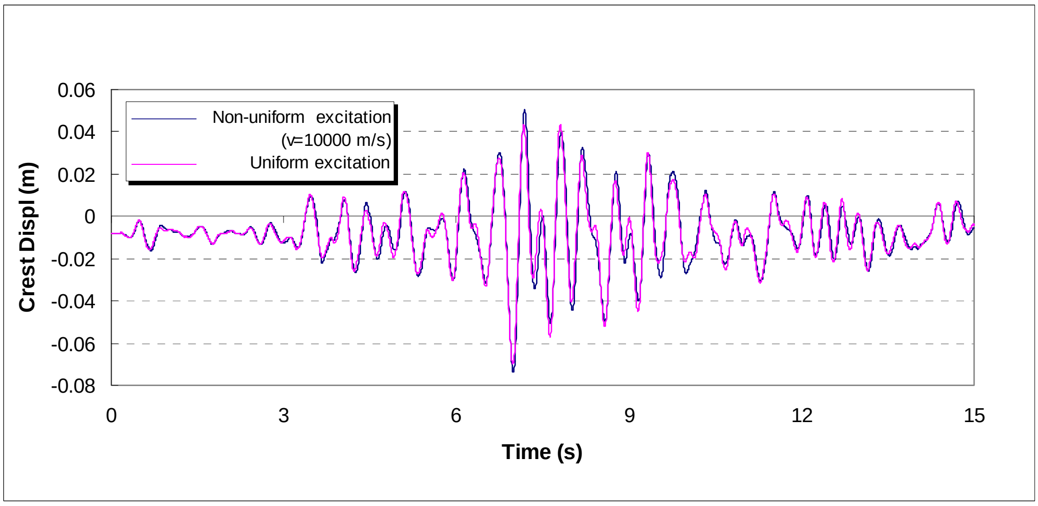


Figure 10: Crest displacement of the crown cantilever in upstream-downstream direction; comparing the cases of the non-uniform excitation (v=10000m/sec) and uniform excitation

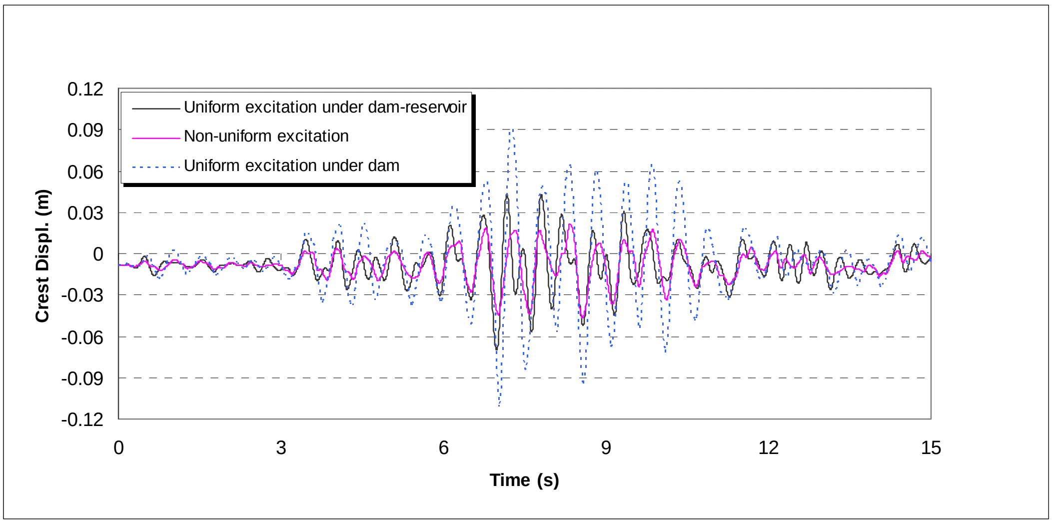


Figure 11: Crest displacement of the crown cantilever in upstream-downstream direction for various excitation conditions

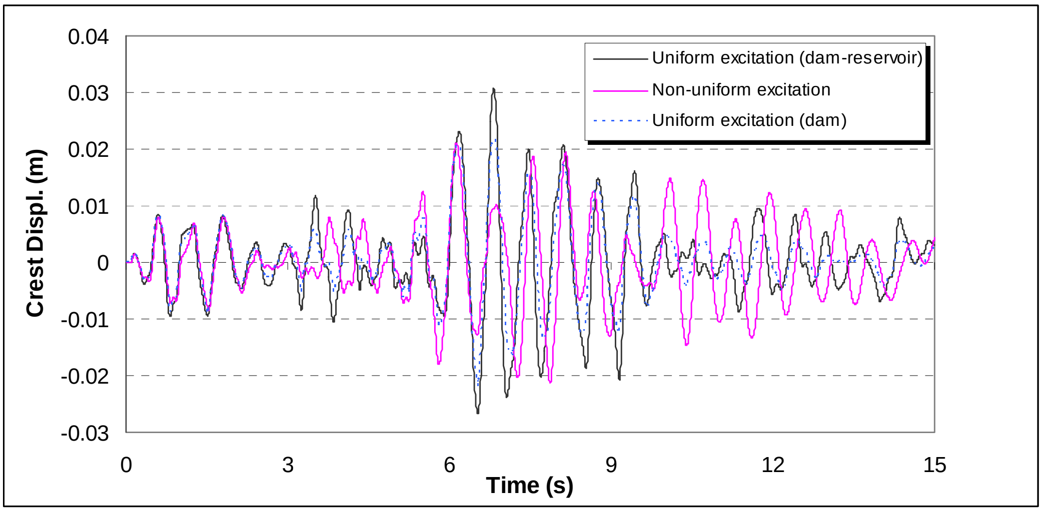


Figure 12: Crest displacement of the crown cantilever in cross-stream direction for various conditions of the excitation

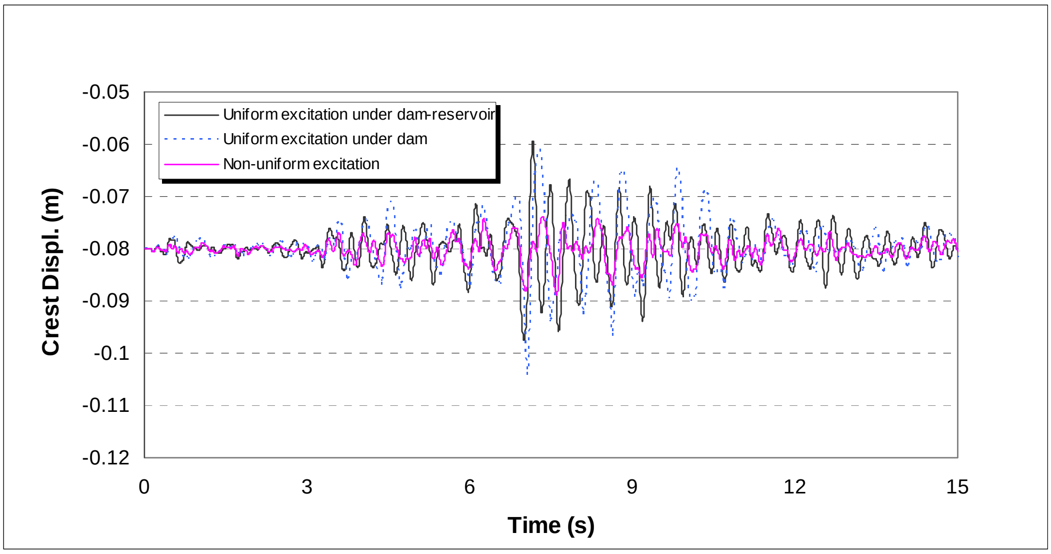


Figure 13: Crest displacement of the crown cantilever in vertical direction for various excitation conditions

(a) Upstream; no excitation under reservoir

(b) Downstream; no excitation under reservoir dam

(c) Upstream; Uniform (dam-reservoir)

(d) Downstream; Uniform (dam-reservoir)

(e) Upstream; Non-uniform excitation

(f) Downstream; Non-uniform excitation

Figure 14: concurrent contours of arch stresses in upstream and downstream faces of the dam body (MPa)

(a) Upstream; no excitation under reservoir (b) Downstream; no excitation under reservoir dam

(c) Upstream; Uniform (dam-reservoir) (d) Downstream; Uniform (dam-reservoir)

(e) Upstream; Non-uniform excitation (f) Downstream; Non-uniform excitation

Figure 15: concurrent contours of cantilever stresses in upstream and downstream faces of the dam body (MPa)

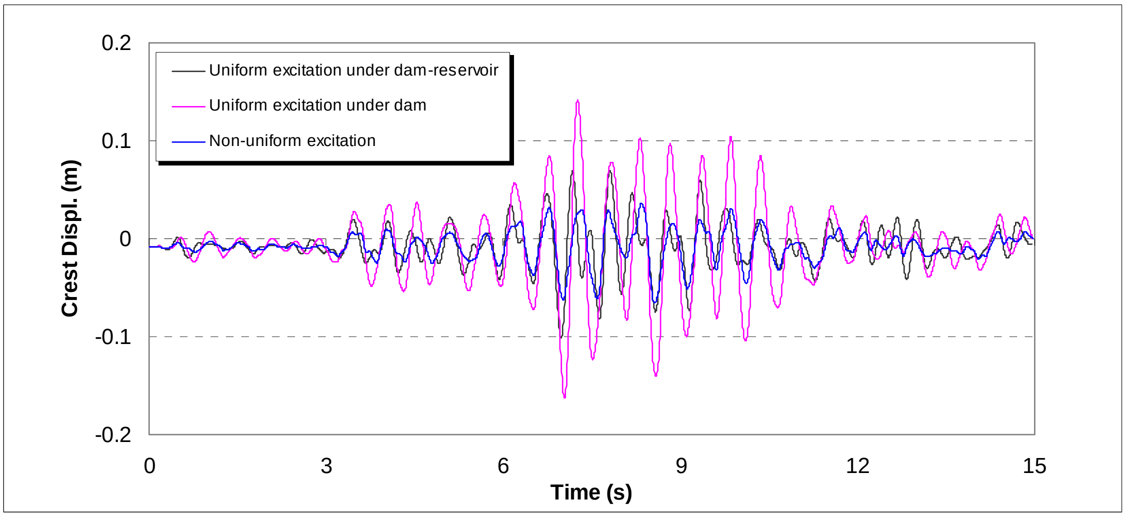


Figure 16: Crest displacement of the crown cantilever in upstream-downstream direction for various excitation conditions

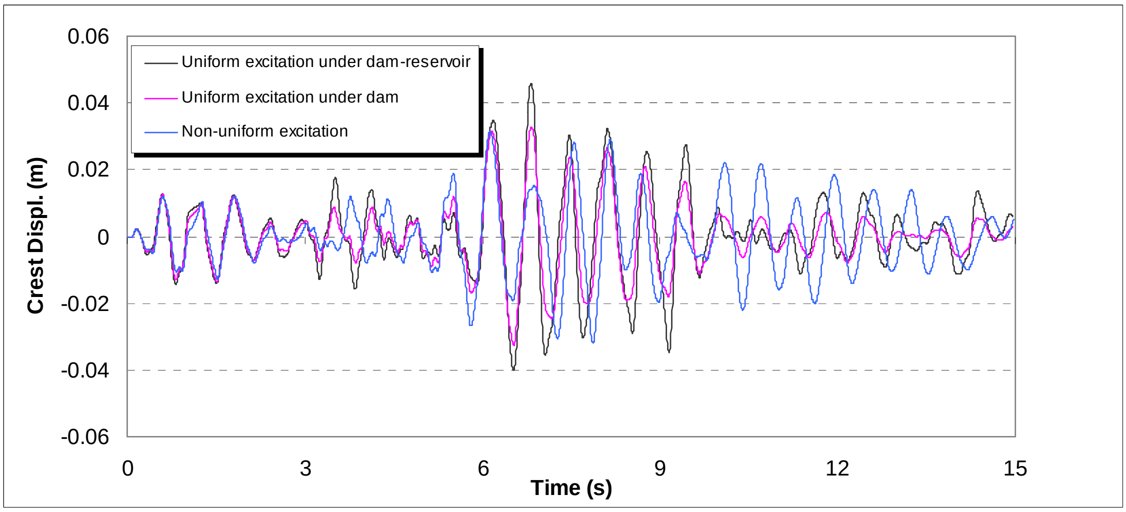


Figure 17: Crest displacement of the crown cantilever in cross-stream direction for various conditions of the excitation

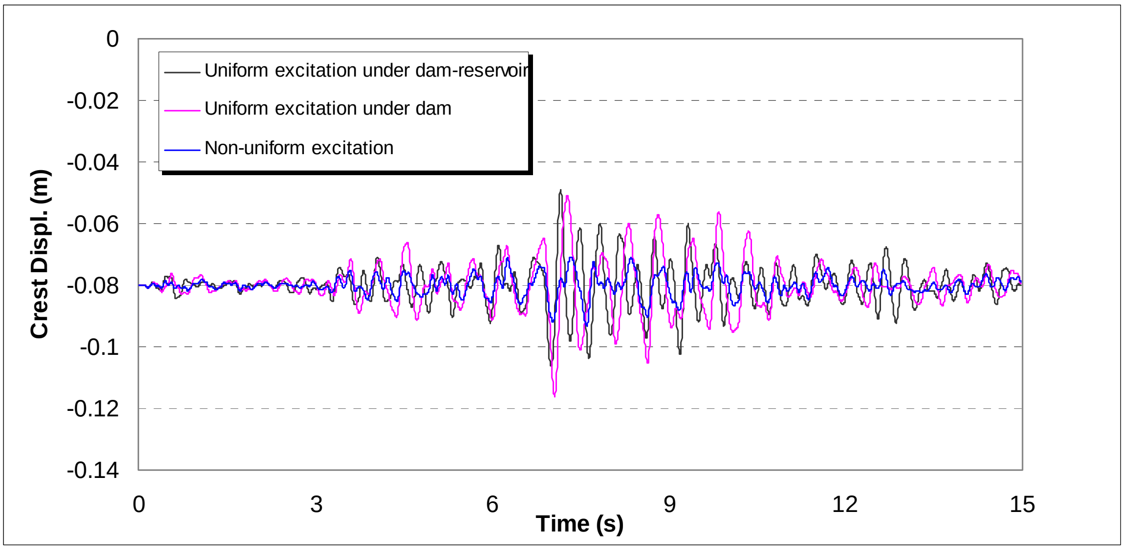
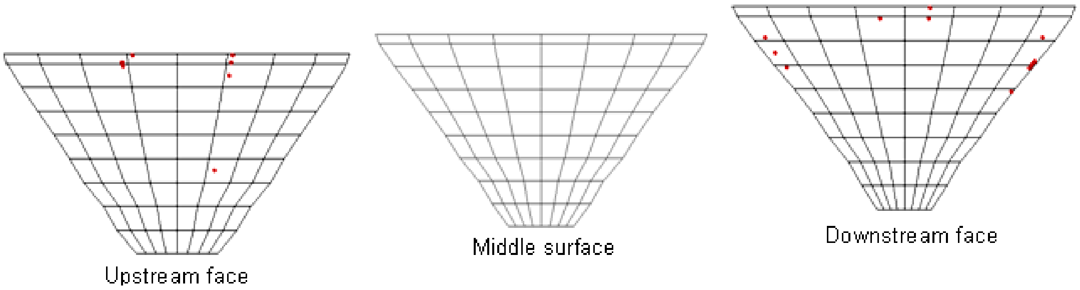


Figure 18: Crest displacement of the crown cantilever in vertical direction for various excitation conditions

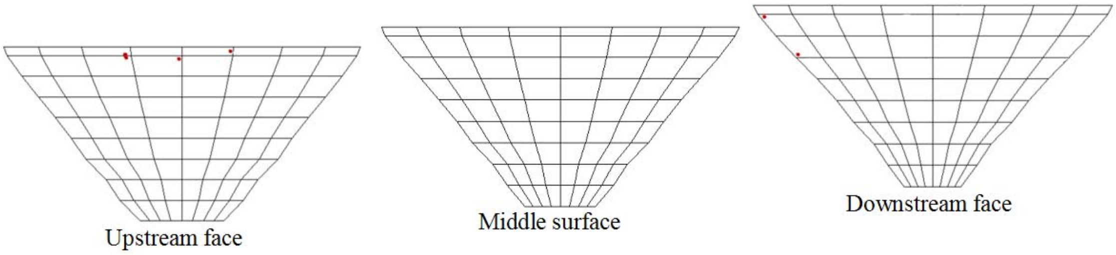


Upstream face

Middle surface

Downstream face

Figure 19: Cracked profile within the dam body; uniform excitation under dam-reservoir



Upstream face

Middle surface

Downstream face

Figure 20: Cracked profile within the dam body; no excitation under reservoir