The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

EARTHQUAKE RISK REDUCTION AND SEISMIC SAFETY EVALUATION OF ARCH DAMS USING INFINITE ELEMENTS

Ali Noorzad[1], H. Mirzabozorg[2], M. Ghaemian[3]

[1]Corresponding Author, Assistant Professor, Faculty of Water Engineering, Water and Power University of Technology, Tehran, Iran, email: noorzad@pwut.ac.ir
[2]Assistant Professor, Department of Civil Engineering, KN-Toosi University of Technology, Tehran, Iran, email: mirzabozorg@kntu.ac.ir
[3]Associate Professor, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran, email: ghaemian@sharif.edu

ABSTARCT:

Uncertainty in seismic behavior of arch dams due to the effect of foundation and reservoir interaction is an important issue in the seismic safety evaluation of existing dams. In the present paper, a direct time domain procedure is used for dynamic analysis of the coupled system of reservoir-dam-foundation in 3D space. In the present paper, it is attempted to simulate the foundation radiation effect on the system by infinite elements and the reservoir water is assumed to be compressible. Material nonlinearity of the mass concrete is modeled by smeared crack approach which is able to simulate the non-uniform cracking within the finite elements of the dam body. Amir-kabir arch dam in Iran is chosen as a case study to investigate the nonlinear seismic behavior of the coupled system. It is realized that the crack profiles within the dam body are less when the foundation is assumed massed. It is found that the proposed numerical algorithm is useful in seismic safety evaluation of arch dams in 3D space and the assumptions in the pertinent environments within the coupled problem are more realistic. Due to the reduction of the seismic response of the coupled system, it is expected to reduce the seismic risk of dams using more real assumptions in the numerical models.

KEYWORDS: Concrete arch dams, Dam-reservoir-foundation Interaction, Earthquake risk reduction, Infinite elements, Non-linear behavior, Safety evaluation

1. INTRODUCTION

Design and seismic safety evaluation of concrete dams is major task in the engineering field due to the vast socio-economic disasters which may be caused by collapse of these infrastructures. Several numerical models have been developed for seismic design and safety evaluation of concrete dams in the two and three-dimensional space. In the article presented by Mirzabozorg et al. (2007) some recent studies in the field of foundation interaction effects are given. Amung them, Tan and Chopra (1995a and b) used the boundary element method to compute the impedance matrix and they analyzed the dam-reservoir foundation in the frequency domain. Gaun et al. (1994) presented the efficient numerical procedure in the time domain in which the dam is modeled using the finite element method and the dynamic soil-structure interaction is included to compute the impedance function of the half-space. Recently, Ghaemian et al. (2006) studied the effects of the foundation shape and mass on the linear seismic response of arch dams using finite element method including structure-reservoir interaction. In the present paper, an appropriate 3D infinite element is utilized to simulate the radiation damping on the far-end boundary of the foundation medium. In addition, the smeared crack approach presented in Mirzabozorg et al. (2007) is utilized to model the nonlinear behavior of the mass concrete. The staggered displacement method is used to solve the coupled problem of the dam-reservoir-foundation system. The developed numerical algorithm is utilized to simulate the nonlinear behavior of arch dams including the massed foundation, semi infinite media at the far end boundary of the foundation and the compressible reservoir behind the dam body.

2. CONSTITUTIVE LAW FOR MASS CONCRETE

The numerical model used for the nonlinear seismic analysis of the mass concrete in the present study can be found in Mirzabozorg et al. (2007). The utilized numerical approach is able to simulate the behavior of the system during the following phases:

- Pre-softening behavior
- Fracture energy conservation
- Non-linear behavior during the softening phase
- Crack closing/reopening behavior.

It is worth noting that the proposed model falls into **C**o-axial **R**otating **C**rack **M**odel (CRCM) category.

3. FOUNDATION MEDIUM

One of the main aspects in the seismic loading and wave propagation within the semi-infinite media such as rock media underlying structures is to prevent the wave reflection from the artificial boundary of the infinite media in the finite element analysis. Using the infinite elements, the stiffness and the damping pertinent to the semi-infinite media via the artificial boundary of the structure are accounted for in the analyses. 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 any limitation as the coordinate of i-th node approaches infinity, and is applied to the geometry. The standard shape functions N_i are applied to the field variables. A classic example is the line element which is depicted in Figure 1.

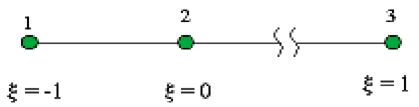


Figure 1 Line element 1-2-3 of infinite element

The geometric properties within the element are interpolated as

$$x = M_1 x_1 + M_2 x_2 \tag{3.1}$$

$$M_1 = -\frac{2\xi}{1-\xi}, M_2 = \frac{1+\xi}{1-\xi} \tag{3.2}$$

The formation of the property matrices (i.e. the stiffness matrix) proceeds in the standard method, except the mapping function M_1 and M_2 are used to form the Jacobian matrix, [J]. According to Bettes (1992), the growth shape functions, M_i, and their derivatives are presented in Table 1 for a 20-node solid element with a face in the infinity as shown in Figure 2.

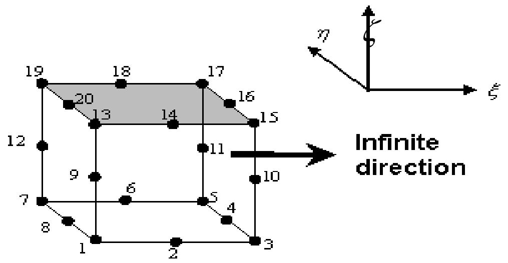


Figure 2 Solid element with one face in infinity

Table 1 Growth shape functions and their derivatives for one face in the infinity

Node, i	ξ_i	η_i	ζ_i
1	-1	-1	-1
2	0	-1	-1
6	0	1	-1
7	-1	1	-1
8	-1	0	-1
9	-1	-1	0
12	-1	1	0
13	-1	-1	1
14	0	-1	1
18	0	1	1
19	-1	1	1
20	-1	0	1

Node, i	M_i	$\partial M_i/\partial\xi$
1	$-(1-\eta)(1-\zeta)(2+\xi+\eta+\zeta)/2(1-\xi)$	$-(1-\eta)(1-\zeta)(3+\eta+\zeta)/2(1-\xi)^2$
2	$(1+\xi)(1-\eta)(1-\zeta)/4(1-\xi)$	$(1-\eta)(1-\zeta)/2(1-\xi)^2$
6	$(1+\xi)(1+\eta)(1-\zeta)/4(1-\xi)$	$(1+\eta)(1-\zeta)/2(1-\xi)^2$
7	$-(1+\eta)(1-\zeta)(2+\xi-\eta+\zeta)/2(1-\xi)$	$-(1+\eta)(1-\zeta)(3-\eta+\zeta)/2(1-\xi)^2$
8	$(1-\eta)(1+\eta)(1-\zeta)/(1-\xi)$	$(1-\eta)(1+\eta)(1-\zeta)/(1-\xi)^2$
9	$(1-\eta)(1-\zeta)(1+\zeta)/(1-\xi)$	$(1-\eta)(1-\zeta)(1+\zeta)/(1-\xi)^2$
12	$(1+\eta)(1-\zeta)(1+\zeta)/(1-\xi)$	$(1+\eta)(1-\zeta)(1+\zeta)/(1-\xi)^2$
13	$(1-\eta)(1+\zeta)(-2-\xi-\eta+\zeta)/2(1-\xi)$	$(1-\eta)(1+\zeta)(-3-\eta+\zeta)/2(1-\xi)^2$
14	$(1+\xi)(1-\eta)(1+\zeta)/4(1-\xi)$	$(1-\eta)(1+\zeta)/2(1-\xi)^2$
18	$(1+\xi)(1+\eta)(1+\zeta)/4(1-\xi)$	$(1+\eta)(1+\zeta)/2(1-\xi)^2$
19	$(1+\eta)(1+\zeta)(-2-\xi+\eta+\zeta)/2(1-\xi)$	$(1+\eta)(1+\zeta)(-3+\eta+\zeta)/2(1-\xi)^2$
20	$(1-\eta)(1+\eta)(1+\zeta)/(1-\xi)$	$(1-\eta)(1+\eta)(1+\zeta)/(1-\xi)^2$

Node, i	$M_i/\partial\eta$	$\partial M_i/\partial\zeta$
1	$(1-\zeta)(1+\xi+2\eta+\zeta)/2(1-\xi)$	$(1-\eta)(1+\xi+\eta+2\zeta)/2(1-\xi)$
2	$-(1-\zeta)(1+\xi)/4(1-\xi)$	$-(1+\xi)(1-\eta)/4(1-\xi)$
6	$(1+\xi)(1-\zeta)/4(1-\xi)$	$-(1+\xi)(1+\eta)/4(1-\xi)$
7	$-(\zeta-2\eta+\xi+1)(1-\zeta)/2(1-\xi)$	$(1+\eta)(1+\xi-\eta+2\zeta)/2(1-\xi)$
8	$-2\eta(1-\zeta)/(1-\xi)$	$-(1-\eta)(1+\eta)/(1-\xi)$
9	$-(1-\zeta)(1+\zeta)/(1-\xi)$	$-2\zeta(1-\eta)/(1-\xi)$
12	$(1-\zeta)(1+\zeta)/(1-\xi)$	$-2\zeta(1+\eta)/(1-\xi)$
13	$-(1+\zeta)(\zeta-2\eta-\xi-1)/2(1-\xi)$	$(1-\eta)(-1-\xi-\eta+2\zeta)/2(1-\xi)$
14	$-(1+\xi)(1+\zeta)/4(1-\xi)$	$(1+\xi)(1-\eta)/4(1-\xi)$
18	$(1+\xi)(1+\zeta)/4(1-\xi)$	$(1+\xi)(1+\eta)/4(1-\xi)$
19	$(1+\zeta)(\zeta+2\eta-\xi-1)/2(1-\xi)$	$(1+\eta)(-1-\xi+\eta+2\zeta)/2(1-\xi)$
20	$-2\eta(1+\zeta)/(1-\xi)$	$(1-\eta)(1+\eta)/(1-\xi)$

The effect of semi-infinite media at the far-end boundary of the foundation is taken into account when the obtained stiffness matrices and their related proportional damping matrices are assembled into the global stiffness matrix and the global damping matrix of the system.

4. FLUID- STRUCTURE INERACTION AND THE COUPLED PROBLEM

The governing equation in the reservoir media is Helmoltz equation from the Euler's equation.

$$\nabla^2 p = \frac{1}{C^2}\frac{\partial^2 p}{\partial t^2} \tag{4.3}$$

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 media to solve Eqn. 4.3 are explained in Mirzabozorg et al. (2003). In addition, a detailed definition of matrices and vectors used has been provided in Mirzabozorg et al. (2003). The coupled equation of dam-reservoir is solved using the staggered displacement method.

5. FINITE ELEMENT IMPLEMENTATION AND NUMERICAL SOLUTION

The 20-node iso-parametric "brick" finite elements are implemented to model the structure, mathematically. The requirement for integration and generation of the mass, stiffness and damping matrices for this type of element is 27 Gaussian points in 3*3*3 order within each element. It is worthy to note that in the smeared crack approach, cracking process is applied on each Gaussian point within the considered element.
Based on the implemented algorithm, strains are computed and the cracking initiation criterion is checked in each Gaussian points. Cracking in each Gaussian point is simply modeled by adjusting the modulus stiffness matrix contribution of the considered point in the element stiffness matrix which is co-axial with the principal strain directions.
The foundation in the near field is simulated utilizing 20-node solid elements and the infinite elements with one face at the infinity are used to simulate the semi-infinite media via the far-end boundary of the foundation media. Finally, the fluid domain is modeled using 8-node fluid elements in which the DOF at their nodes is the hydrodynamic pressure. The coupled problem of the dam-reservoir-foundation system is solved using the staggered displacement method where the nodal acceleration vector is estimated at the current time step to compute the other components.
Amir-Kabir dam, located in Iran, has been selected as a case study to investigate the effects of the foundation interaction on the seismic response of the structure. The dam is double curvature arch dam with the height of 168m and its crest length is 390m. The dam structure is modelled with 72 iso-parametric 20-node elements and its foundation media surrounding the dam body is simulated using 980 elements in which the number of the infinite elements at the far-end boundary of the foundation is 240. It should be noted that the depth of the foundation media is about twice of the dam height in the three global directions.
The fluid is modelled using 1024 iso-parametric 8-node fluid elements and is extended about twice of the height of the dam body in the upstream direction. Figure 3 illustrates the finite element model of the dam body and its foundation.

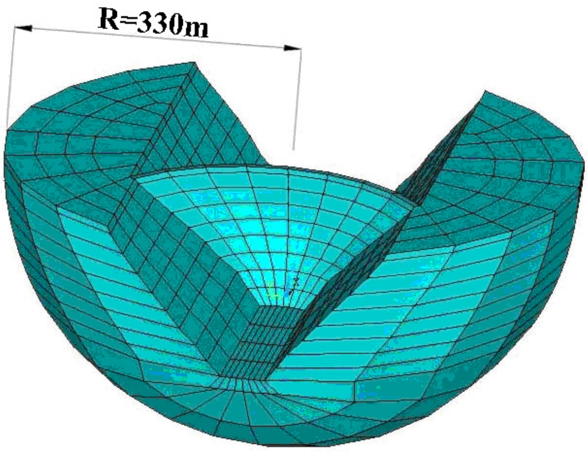
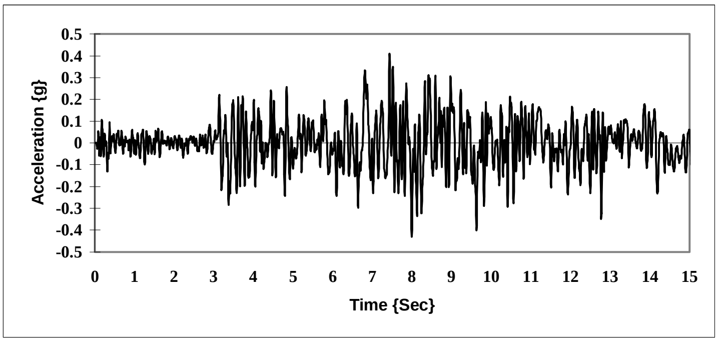


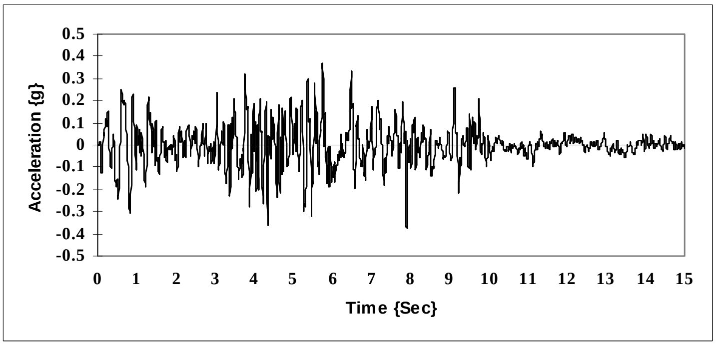
Figure 3 Finite element model of the structure, the dam body and its surrounding foundation

The modulus of elasticity, Poisson's ratio, the unit weight, the true tensile strength and the ratio of the apparent to the true tensile strength, the specific fracture energy and the dynamic magnification factor applied on both the tensile strength and the specific fracture energy are 26GPa, 0.17, 24.027kN/m^3, 3.662MPa, 1.35, 150N/m and 1.20, respectively. For the foundation medium, the modulus of elasticity, Poisson's ratio and the unit weight are taken as 16.3GPa, 0.15 and 29.400kN/m^3. The velocity of wave propagation and the unit weight of water in the reservoir are assumed to be 1436m/s and 9.807kN/m^3, respectively. The wave reflection coefficient of the reservoir bottom and sides is given as 0.8, conservatively.

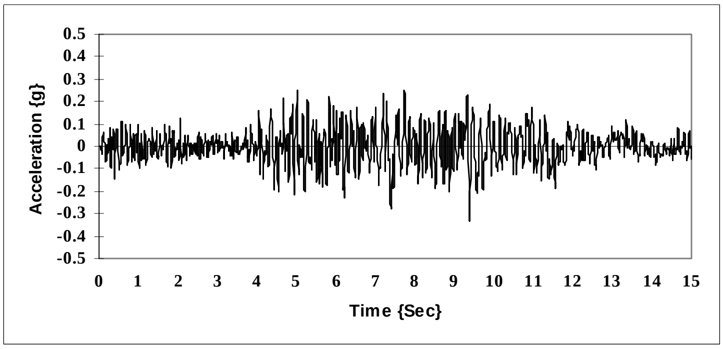
The stiffness proportional damping is used in the analyses in which the damping ratio for the fundamental mode is considered 10%. Applied loads on the system are the self weight, the hydrostatic pressure and the seismic load. The values of the integration parameters in the α-method are taken as α=-0.2, β=0.36 and γ=0.7. The quasi-linear damping mechanism is used for the structure in the dynamic analysis in which the stiffness proportional damping is updated during the element cracking within the dam body.
Figure 4 shows three components of the ground motion recorded at the Ab-bar station during Manjil-Iran earthquake on 20 June 1990 which is chosen for the analyses. This record is normalized and filtered for the 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. It is required to mention that all the components are multiplied by 1.5 to cause crack profiles within the dam body.



(a) Horizontal, upstream-downstream direction



(b) Horizontal, cross-stream direction



(c) Vertical direction
Figure 4 Components of the Manjil-Iran earthquake on June 20, 1990

At the first load step, there is not any cracked Gaussian point due to the self-weight and the hydrostatic load. At the second load step, the system is excited simultaneously in the three directions using the components shown in Figure 4. Figure 5 presents the crack profiles at the three layers of the Gaussian points through the thickness of the dam body when the foundation medium is assumed to be massless. The results of using the massed foundation and infinite elements to model the near field of the semi-infinite medium are given in Figure 6.

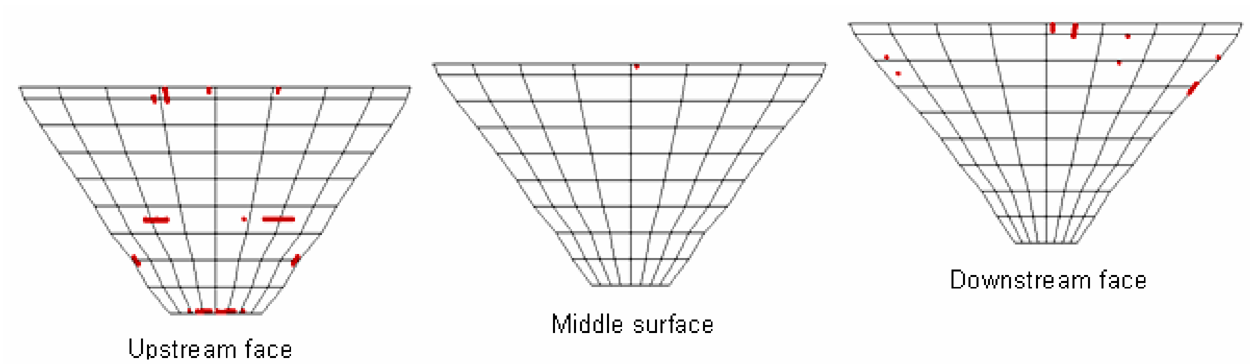


Figure 5 Cracked profile within the dam body; massless foundation

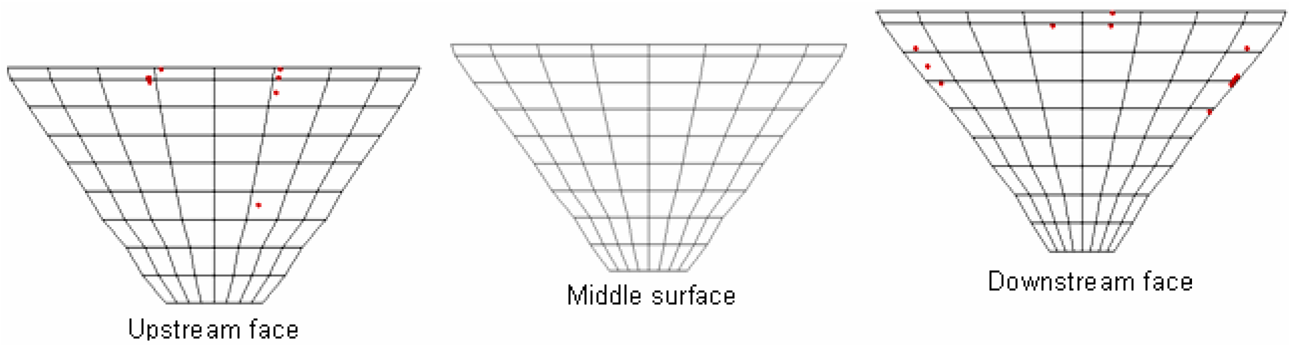
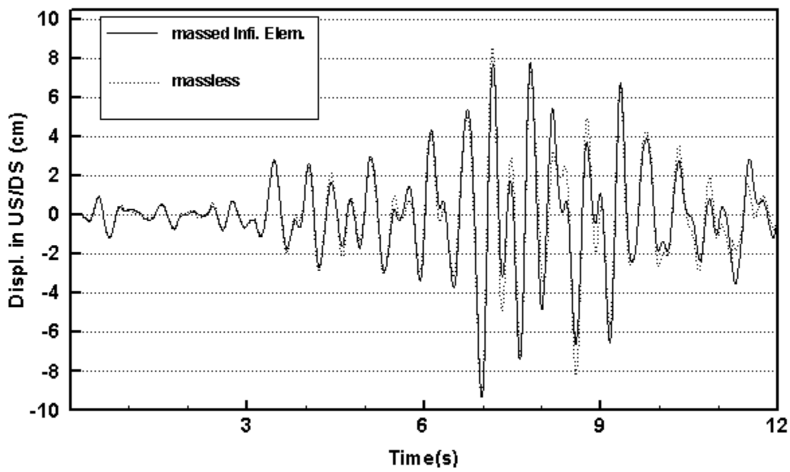


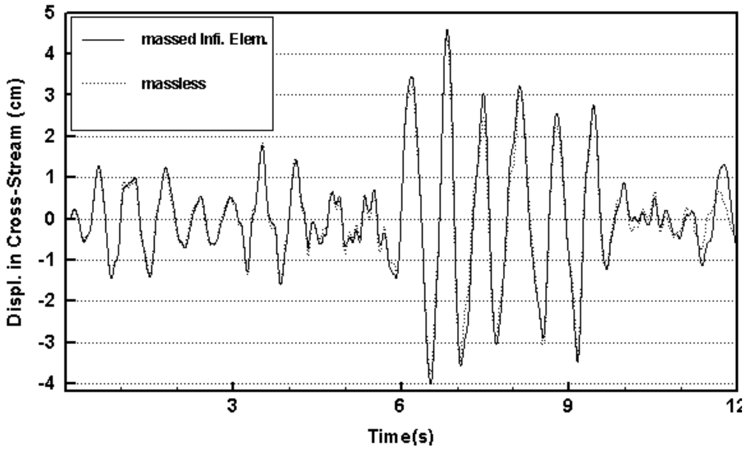
Figure 6 Cracked profile within the dam body; massed foundation using infinite elements

Comparing the crack profiles shown in Figures 5 and 6, using massed foundation and infinite elements leads to less cracked Gaussian points which seems to be real. It is worth noting that in the model with massless foundation, the fist crack occurred at 3.39s, while, the first crack in the second model (massed foundation including infinite elements) initiates at 6.855s. In fact, because of larger response of the structure with massless foundation, it is in good agreement with the actual behavior.

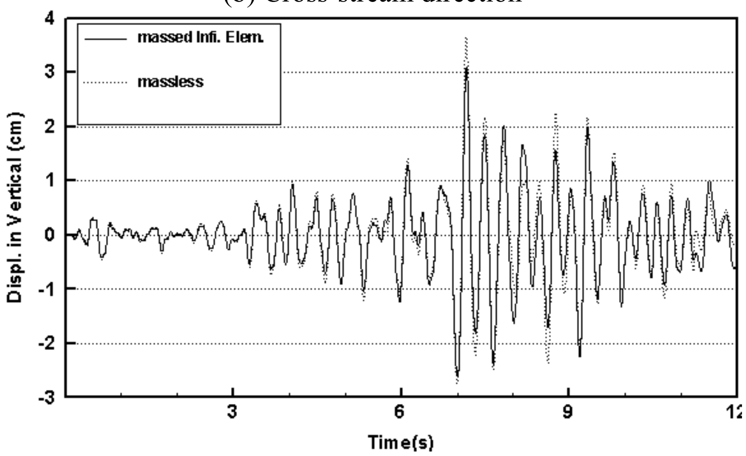
Figure 7 compares the time history of the crown crest displacement in the three directions. It can be observed that the model with massed foundation and infinite elements gives a lower response in comparison with the other model.



(a) Upstream/Downstream direction



(b) Cross-stream direction



(c) Vertical direction

Figure7 Crest displacement of the crown cantilever

6. CONCLUSIONS

The effect of the semi infinite medium at the far-end boundary of the foundation and the radiation damping has been simulated using infinite elements on the far-end boundary of the massed foundation medium. The smeared crack approach is utilized to simulate the nonlinear behavior of the dam body and the reservoir medium has been assumed to be compressible. The dam-reservoir-foundation system is analyzed using the staggered displacement method. Amir-kabir double curvature arch dam in Iran is analyzed as a case study and based on the obtained results the nonlinear response of the dam body is more severe when the foundation is assumed massless. In addition, using massed foundation including the infinite elements at the truncated boundary leads to crack initiation at the longer period of excitation and also to less crack profiles within the dam body. One of the main aspects of the proposed numerical algorithm is the stability of the linear and nonlinear dynamic analyses during the seismic excitation. Finally, based on the results of analyzing the case study, the proposed algorithm can be an innovative method to overcome some uncertainties for design and safety evaluation of concrete dams.

REFERENCES

Gaun, F., Moore, I.D. and Lin, G. (1994). Seismic Analysis of Reservoir-Dam-Soil Systems in the Time Domain. *Computer Methods and Advances in Geo-mechanics*, 917-922.

Ghaemian, M., Noorzad, A. and Moghaddam, R.M. (2006). Foundation Effect on Seismic Response of Concrete Arch Dams Including Dam-Reservoir Interaction. *European Earthquake Engineering (EEE)* **3**, 49-57.

Mirzabozorg H., Khaloo A.R. and Ghaemian M. (2003). Staggered Solution Scheme for Three-Dimensional Analysis of Dam-Reservoir Interaction. *Dam Engineering Journal* **XIV: 3**, 1-33.

Mirzabozorg, H., Khaloo, A.R., Ghaemian, M. and Jalalzadeh, B. (2008). Non-Uniform Cracking in Smeared Crack Approach for Seismic Analysis of Concrete Dams in 3D Space. *Paper will be published in European Earthquake Engineering (EEE).*

Tan, H. and Chopra, A.K. (1995). Earthquake Analysis of Arch Dams Including Dam-Reservoir-Foundation Rock Interaction. *Earthquake Engineering and Structural Dynamics* **24**, 1453-1474.

Tan, H. and Chopra, A.K. (1995). Dam-Foundation Rock Interaction Effects in Frequency-Response Functions of Arch Dams. *Earthquake Engineering and Structural Dynamics* **24**, 1475-1489.

Bettess, P. (1992). Infinite Elements. Penshaw Press, 1st edition.