SEISMIC RESPONSE OF CONCRETE ARCH DAMS INCLUDING DAM-RESERVOIR-FOUNDATION INTERACTION USING INFINITE ELEMENTS PART I: LINEAR ANALYSIS

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ABSTRACT

A direct time domain procedure is used for dynamic linear analysis of the coupled system of reservoir-dam-foundation in 3D space. The foundation's mass is considered in the analysis and infinite elements are used to model the semi infinite media via the far-end boundary of the massed foundation model. The water is assumed to be compressible and is modeled utilizing the finite element method with appropriate boundary conditions. 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 effect of massed foundation on the seismic response of the dam-reservoir-foundation system. It is found that the response of the system is the same as such that viscous absorbing boundary on the far-end boundary of the foundation model is installed. It is also realized that assuming the foundation to be mass-less, the resulted seismic stresses within the dam body can be conservative. The main aspects of the proposed model are; its simplicity in applying restrains on the far-end boundary of the foundation media and there is no need to obtain the parameters pertinent to the traveling wave within the bedrock. In addition, the model can be used easily in nonlinear analysis of the dam-reservoir-foundation system.

Key words: Concrete arch dam, Dam-reservoir-foundation interaction, Infinite element, Linear seismic behavior, Massed foundation

INTRODUCTION

Considering an arch dam to be adequately massive and stiff, while the foundation is relatively soft, the motion at the base of the structure may be significantly different from the free-field surface motion. However, it is apparent that the most of interaction effects occurs near the structure and at some finite distance from the base of the structure. Therefore, the field behavior converges back to the free field state.

During the past decades, various methods have been developed to analyze concrete gravity and arch dams with different assumptions and complexities concerning on the interaction effects of reservoir and foundation of the system. The computer program, EAGD-84 is one of the most well-known software that is based on the finite element method and has the capability to analyze the coupled system of concrete gravity dams in 2D space including the foundation interaction effect [1 and 2]. The effect of foundation interaction in this program is accounted using the impedance matrix of the foundation media and the coupled problem is solved using the substructure method in frequency domain.

EACD-3D [3] is another well-known code for analyzing concrete dams in 3D space. In this program, Fok et al. (1986) used the impedance matrix to account the effect of foundation on the seismic response of the system. However, only the flexibility of the foundation was considered and the inertia and damping effects were ignored. Later, Tan

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and Chopra used the boundary element method for developing impedance matrix [4], [5]. In their work, they solved a series of mixed boundary value problems governing the steady state response of the canyon cut in 3D semi-unbounded foundation rock region to develop the required foundation impedance matrix [4 and 5].
The above procedures are applicable in frequency domain analyses, which are used for linear problems. Therefore, an appropriate procedure in time domain must be represented to account for the interaction effect of the foundation on the seismic response of dam-reservoir-foundation system. For the dam problem, the influence of the reservoir on the dam response is also very important. Some outstanding work on reservoir-dam-foundation problem interaction in the frequency domain or the indirect time domain has been carried out by Chopra and his co-workers which some of them were pointed out. The reservoir-dam-foundation interaction problem has been studied in the time domain by Antes and Estorff [6] using the full space transient Green's functions for wave propagation in both the foundation and the reservoir. In the work presented by Gaun et al. [7], an efficient numerical procedure has been described to investigate the dynamic response of a reservoir-dam-foundation system directly in the time domain. The dam has been modeled by the finite element method and the dynamic soil-structure interaction has been included by computing the impedance of the half-space. The reservoir influence on the dam was applied using the added mass approach. Mirzabozorg et al. [8] presented a paper in which the linear behavior of the dam-reservoir system is modeled using finite element method in 3D space. A simplified viscous boundary was introduced on the far-end boundary of the massed foundation to model the energy absorption on the boundary [9]. Recently, Ghaemian et al. [10] investigated the effects of foundation shape and mass on the linear seismic response of arch dams using finite element method including structure-reservoir interaction.
In the present paper, appropriate 3D infinite elements are used to model the radiation damping on the far-end boundary of the foundation media. To solve the coupled problem of dam-reservoir-foundation system, a robust time domain solution called the staggered displacement method is used, which is in the category of direct integration schemes as referred in [11 and 12].

FOUNDATION INTERACTION AND WAVE PROPAGATION

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 finite element analysis. Normal finite element foundation boundaries are inappropriate since seismic waves may be reflected back into the structure thus amplifying the structural response. Alternatively, interaction effects can be analyzed using either rigorous or approximate modeling techniques. Rigorous techniques are applied to a substructure consisting of the structure or foundation and dam-foundation interface. Substructure methods consist of boundary element method; consistent boundary procedure; forecasting method; consistent infinitesimal finite element cell method and damping-solvent extraction method approaches modeling the energy absorption and refracting outgoing waves in semi-infinite media.
Approximate techniques can be used in the direct method of analysis, which consists of the dam and foundation enclosed by an artificial boundary some distance away from the dam-foundation interface. At this artificial boundary, the radiation condition is approximately enforced using a transmitting boundary, which essentially makes sure that incoming waves are not reflected back into the structure. Examples of transmitting boundaries are given as:

- Viscous boundary which consists of dashpots absorbing plane waves propagating perpendicularly to the artificial boundary.
- Superposition boundary that averages symmetric and anti-symmetric boundary solutions and thus eliminates reflected waves.
- Extrapolation boundary method in which artificial boundary displacements are extrapolated from prior interior foundation data.
- Double-asymptotic boundary that consists of viscous dashpots and coupled static springs.

Considering an imaginary convex boundary enclosing all sources of energy and irregular geometrical features, propagation of energy occurs from interior region toward the exterior media, such that all the energy arriving to the boundary will pass through it. Therefore, the effect of exterior region on the interior one is energy absorption or nonreflecting boundary. The interior region is represented by finite elements subjected to a boundary condition as exterior region ensuring that all energy arriving at the boundary is absorbed. In addition to the approximate techniques, one of the most promising procedures in 3D problems is infinite elements. 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 [13]. A classic example is the line element which is depicted in Figure (1).

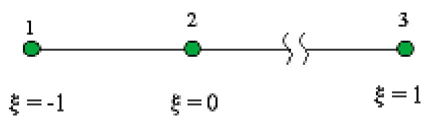


Figure 1: Line element 1-2-3 of infinite element

The geometric properties within the element are interpolated as

$$x = M_1 x_1 + M_2 x_2 \tag{1}$$

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

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*, [13].

Infinite Element Implementation

To simulate From modeling the effect of semi-infinite media via the near field medium of the foundation, 20-node solid elements with one face in infinity is utilized. This element is illustrated in Figure (2).

ζ

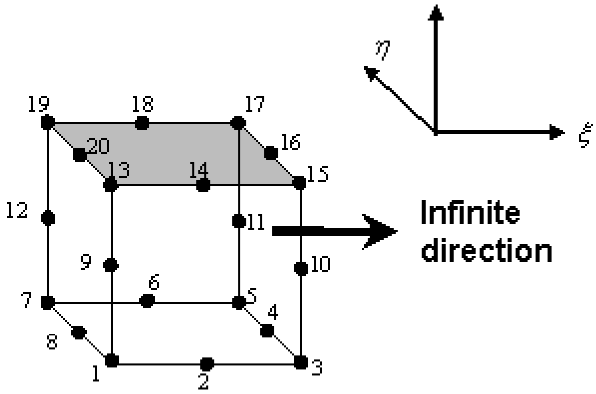


Figure 2: Solid element with one face in infinity

According to Bettes (1992), the growth shape functions, M_i, and their derivatives are presented in table (1) [14].

Table 1: Growth shape functions and their derivatives for one face in the infinity, as in Figure 2

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 procedure for the formation of a stiffness matrix is given as

(a) Form the Jacobian matrix with relative growth shape functions and their derivatives as illustrated in Equation (3)

$$[J]=\begin{bmatrix}\frac{\partial M}{\partial \xi}\\ \frac{\partial M}{\partial \eta}\\ \frac{\partial M}{\partial \zeta}\end{bmatrix}\begin{bmatrix}X & Y & Z\end{bmatrix} \tag{3}$$

where, *X*, *Y* and *Z* are nodal coordinate vectors of the element.

(b) Invert $[J]$ to give $[J]^{-1}$.

(c) Use the parent finite element shape functions, N_i, to obtain the matrix $[B]$

$$[B]=[J]^{-1}\begin{bmatrix}\frac{\partial N}{\partial \xi}\\ \frac{\partial N}{\partial \eta}\\ \frac{\partial N}{\partial \zeta}\end{bmatrix} \tag{4}$$

where, $[B]$ is the matrix transforming the nodal displacement of the considered element to the Gaussian point strains within the element.

(d) Form the stiffness matrix of the element, $[K]$

Finally, the effect of semi-infinite media via the far-end boundary of the foundation is taken into consideration 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.

FLUID- STRUCTURE INERACTION

Reservoir Governing Equation of Motion

The governing equation in the reservoir media is Helmoltz equation given in equation (5) extracted from the Euler's equation [12].

$$\nabla^2 p=\frac{1}{C^2}\frac{\partial^2 p}{\partial t^2} \tag{5}$$

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 equation (5) are explained in the following sections. These boundaries are demonstrated in Figure (3), schematically.

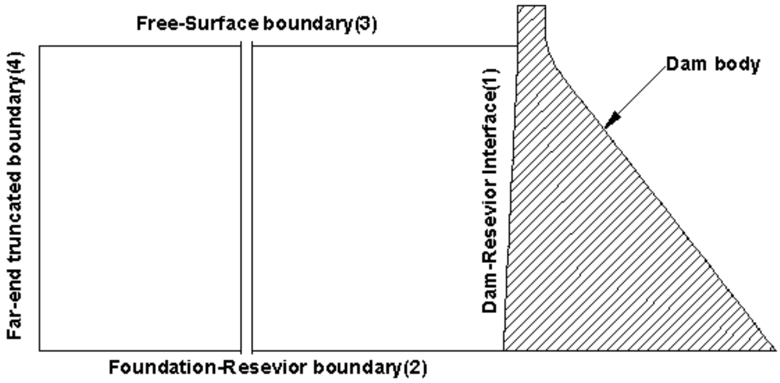


Figure 3: Reservoir boundary condition

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

$$\frac{\partial p}{\partial n} = -\rho a_n^s \quad (6)$$

where n is the normal vector to the surface and a_n^s is normal acceleration of the dam at the interface.

Foundation-reservoir boundary- B.C. (2)

In the case of reservoir with sediment at the bottom and sides, it is assumed that the hydrodynamic pressure waves incident on the reservoir bottom only excite vertically and propagate dilatational waves in the reservoir bottom materials. After some mathematical operations, the following condition is given [12]:

$$\begin{aligned} &\frac{\partial p}{\partial n} - q\frac{\partial p}{\partial t} = -\rho a_n^s \\ &q = \frac{\rho}{\rho_r C_r} = \frac{1-\kappa}{(1+\kappa)} \end{aligned} \quad (7)$$

where ρ_r, C_r and κ are the reservoir bottom/sides density, velocity of pressure wave within the reservoir bottom/sides material and wave reflection coefficient, respectively. q is the admittance coefficient.

Free surface boundary- B.C. (3)

In the case of surface wave with negligible surface tension (gravity waves), the following boundary condition is applied on the free surface of the reservoir:

$$\frac{1}{g}\frac{\partial^2 p}{\partial t^2} + \frac{\partial p}{\partial z} = 0 \quad (8)$$

where g is the gravitational acceleration. Generally, the free surface waves in the reservoir media of dams are neglected, as has been done in the present study.

Far-end truncated boundary- B.C. (4)

The boundary condition used for modeling the complete absorption of propagating waves in the upstream direction applied on B.C. (4) as shown in Figure (3) is:

$$\frac{\partial p}{\partial n} = -\frac{\pi}{2h} p - \frac{1}{C} . \frac{\partial p}{\partial t} \tag{9}$$

where h is the height of reservoir and n is the vector normal to the surface of the boundary. The above boundary condition is found to be effective and efficient for a wide range of the excitation frequencies [15].

THE COUPLED STRUCTURE-RESERVOIR PROBLEM

In the present research, the staggered displacement method, which is an unconditionally stable approach [11], is utilized to solve the coupled problem [12]. The equations of the dam-foundation structure and the reservoir take the form:

$$\begin{aligned} &[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{f_1\} - [M]\{\ddot{U}_g\} + [Q]\{P\} = \{F_1\} + [Q]\{P\} \\ &[G]\{\ddot{P}\} + [C']\{\dot{P}\} + [K']\{P\} = \{F\} - \rho [Q]^T (\{\ddot{U}\} + \{\ddot{U}_g\}) = \{F_2\} - \rho [Q]^T \{\ddot{U}\} \end{aligned} \tag{10}$$

where, $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices of the structure including dam and its foundation media 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. A detailed definition of matrices and vectors mentioned in Equation (10) has been provided in elsewhere. The coupled Equation (10) is solved using the staggered displacement method [12].

NUMERICAL EXAMPLE

Amir-Kabir dam , which is located in Iran, is selected to consider the effect of the foundation on the seismic response of the system. 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 (4) shows the finite element model of the dam body and its near field foundation.

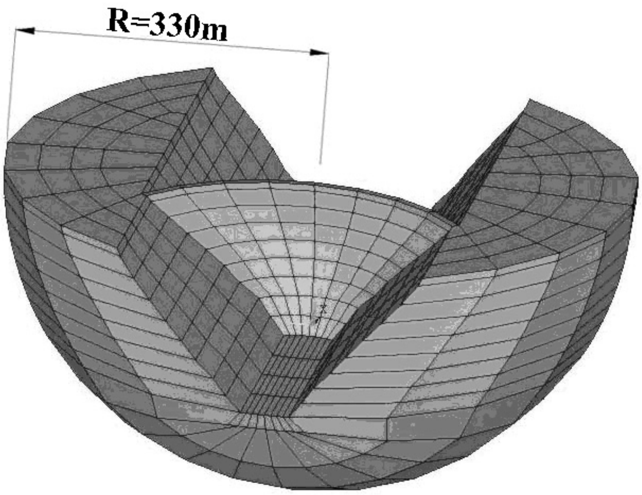


Figure 4. Dam-foundation system with constant cross-section valley

The foundation is modeled using 980 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 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 (5).

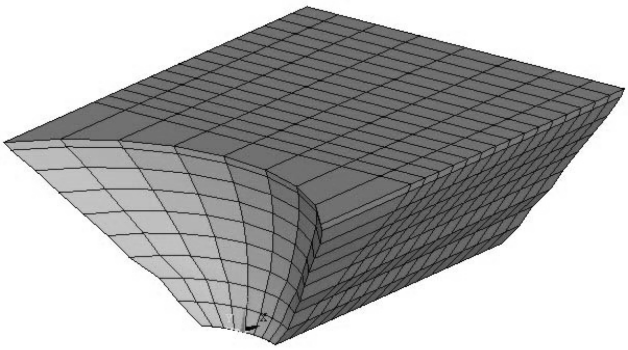
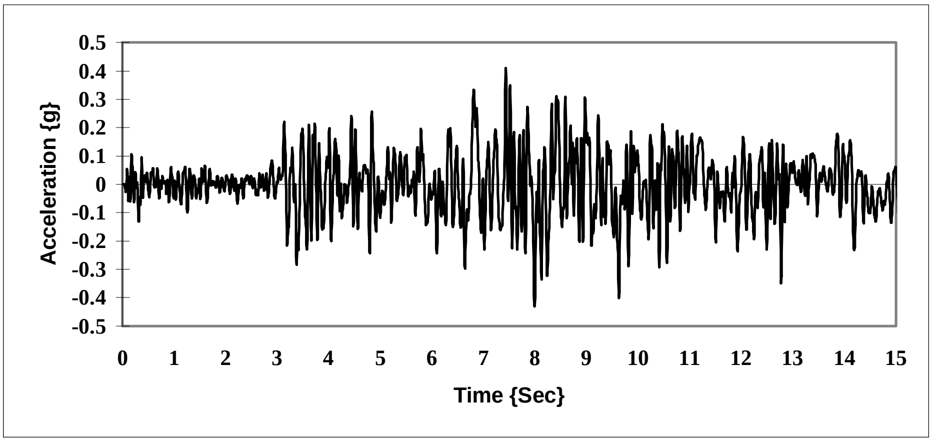


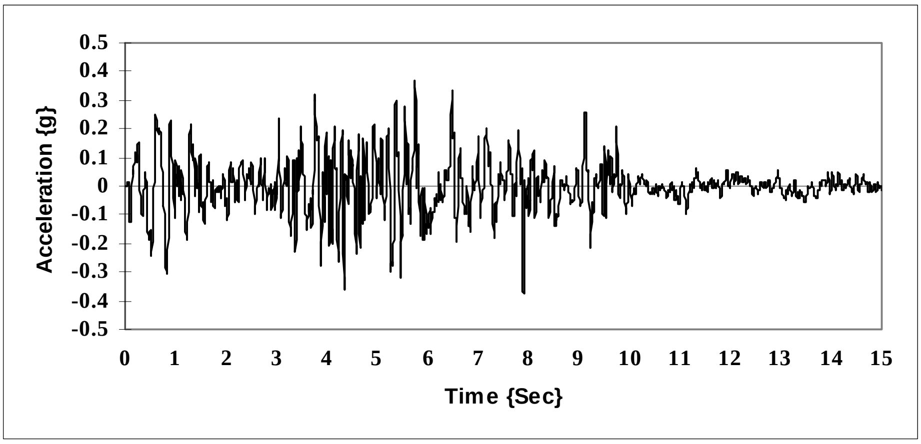
Figure 5: Reservoir finite element model

The dynamic modulus of elasticity, the unit weight and Poisson's ratio are taken as 32.50GPa, 24027N/m^3 and 0.17, respectively [16]. The static deformation modulus of the foundation is used for both the static and the dynamic analysis [17]. The deformation modulus, the unit weight and Poisson's ratio for the rock foundation are considered as 16.30GPa, 29400N/m^3 and 0.15, respectively [16]. The velocity of pressure wave propagation and the unit weight of water in the reservoir are assumed 1436m/sec. and 9807 N/m^3, respectively. And finally, the wave reflection coefficient of the reservoir boundary is chosen to be 0.8 [17].
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 values of the integration parameters in the α-method are taken as $\alpha=-0.2$, $\beta=0.36$ and $\gamma=0.7$ [12].
Figure (6) 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 the Amir-kabir dam site. The

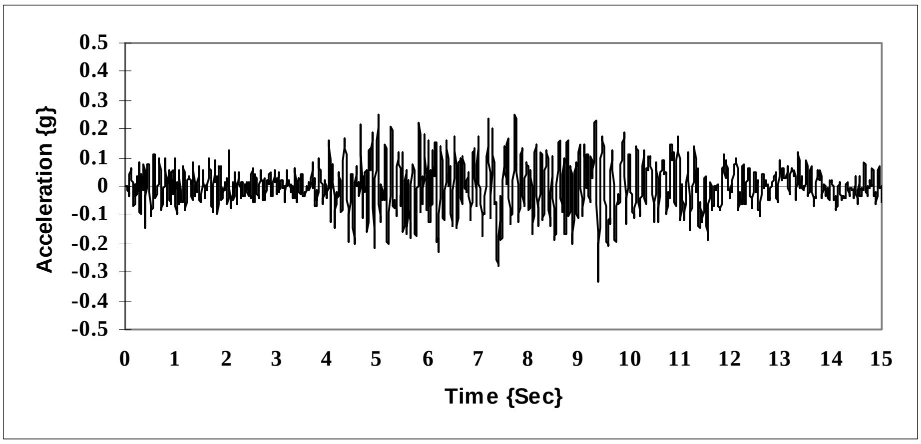
horizontal and vertical PGA at MCE level of excitation are 0.43g and 0.33g at the dam site, respectively [16].



(a) Horizontal, upstream-downstream direction



(b) Horizontal, cross-stream direction



(c) Vertical direction

Figure 6: Components of the Manjil-Iran earthquake of June 20, 1990

In Figure (7), the crest displacement of the crown cantilever in upstream-downstream direction in various conditions of the foundation is depicted. It can be observed that considering infinite elements and viscous boundary [10] on the far-end boundary on the foundation region decrease the crest response of the system in comparison with the system with mass-less foundation.

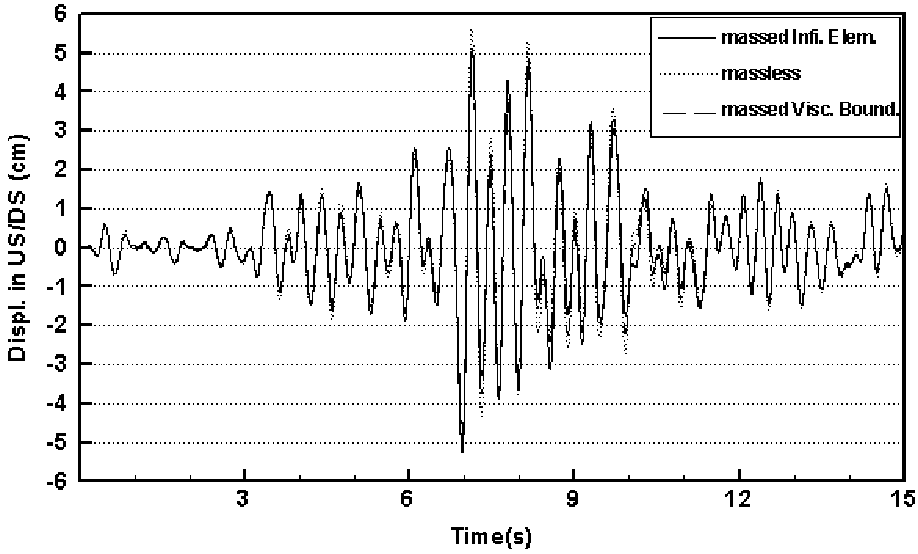


Figure 7. Crest displacement of the crown cantilever in upstream-downstream direction for various conditions of the foundation media

The crest displacement of the crown cantilever in cross-stream direction is presented in Figure (8). As shown, there is not any noticeable difference between the results from various conditions of the foundation.

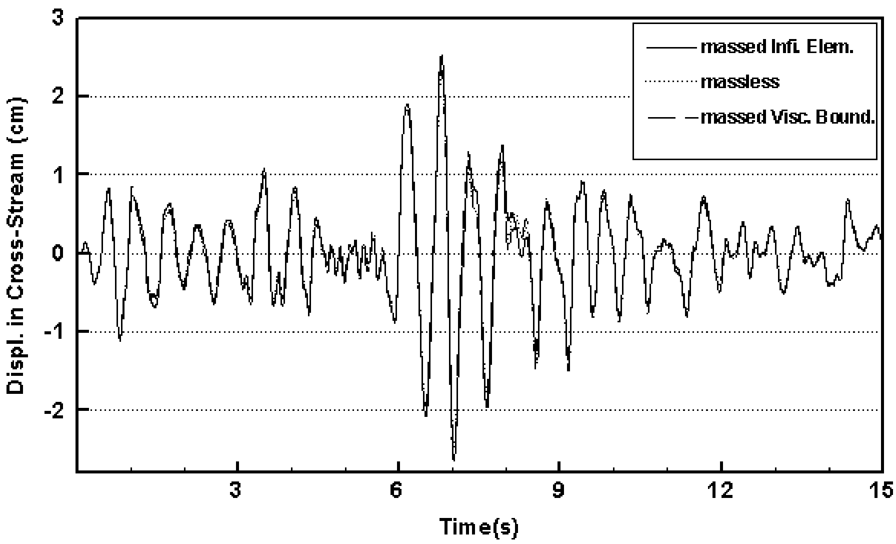


Figure 8. Crest displacement of the crown cantilever in cross-stream direction for various conditions of the foundation media

Finally, Figure (9) shows the crest displacement of the crown cantilever in vertical direction. Obviously, implementing infinite elements and viscous boundary on the far-end boundary decrease the crest displacement in vertical direction in comparison with the system simulated using mass-less foundation.

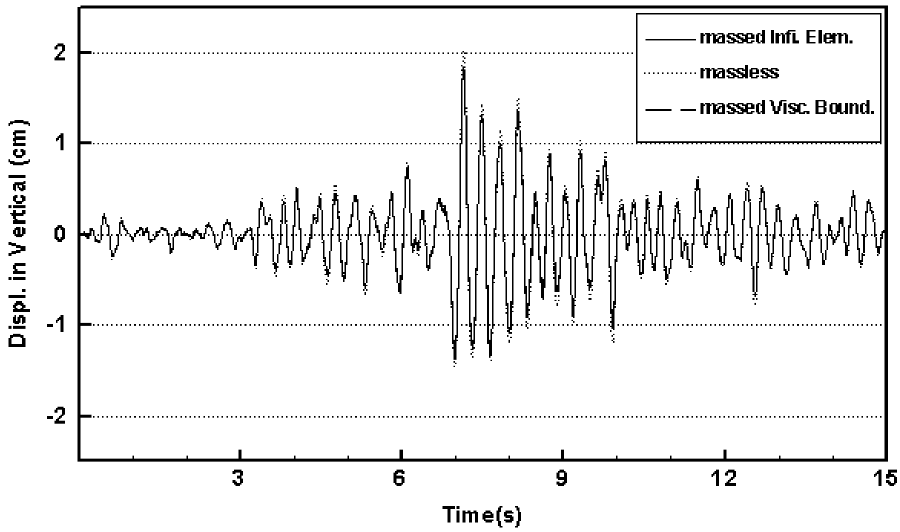
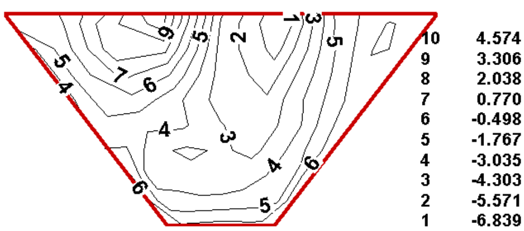
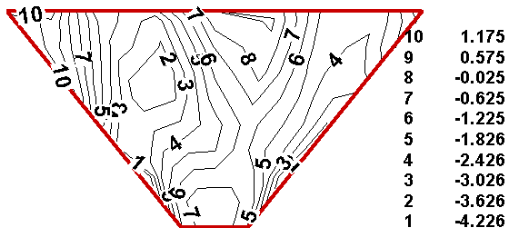


Figure 9. Crest displacement of the crown cantilever in vertical direction for various conditions of the foundation media

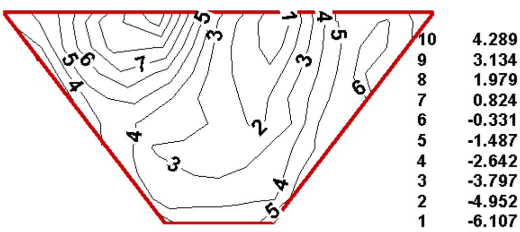
Figures (10) and (11) illustrate contours of the cantilever and arch stresses resulted from the seismic loads in upstream and downstream faces of the dam body. As shown, the stresses obtained from the model with the massed foundation are less than the arch and cantilever stresses when the foundation is assumed mass-less. However, when the far-end boundary of the massed foundation is modeled using viscous boundary [10] or infinite elements, the obtained stress distribution within the dam body are the same.



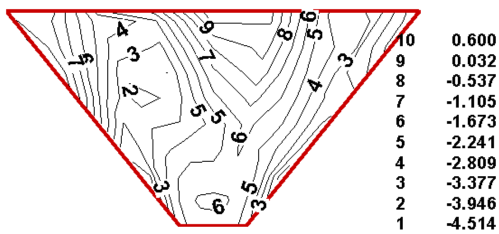
(a) Upstream; mass-less foundation



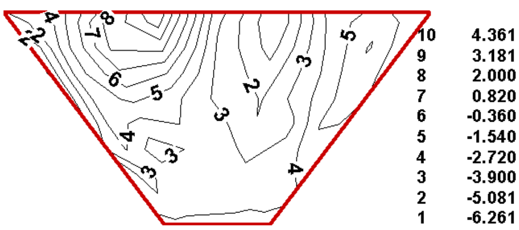
(b) Downstream; mass-less foundation

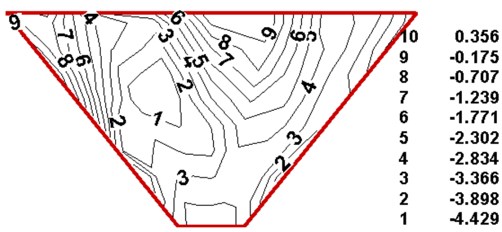


(c) Upstream; massed viscous



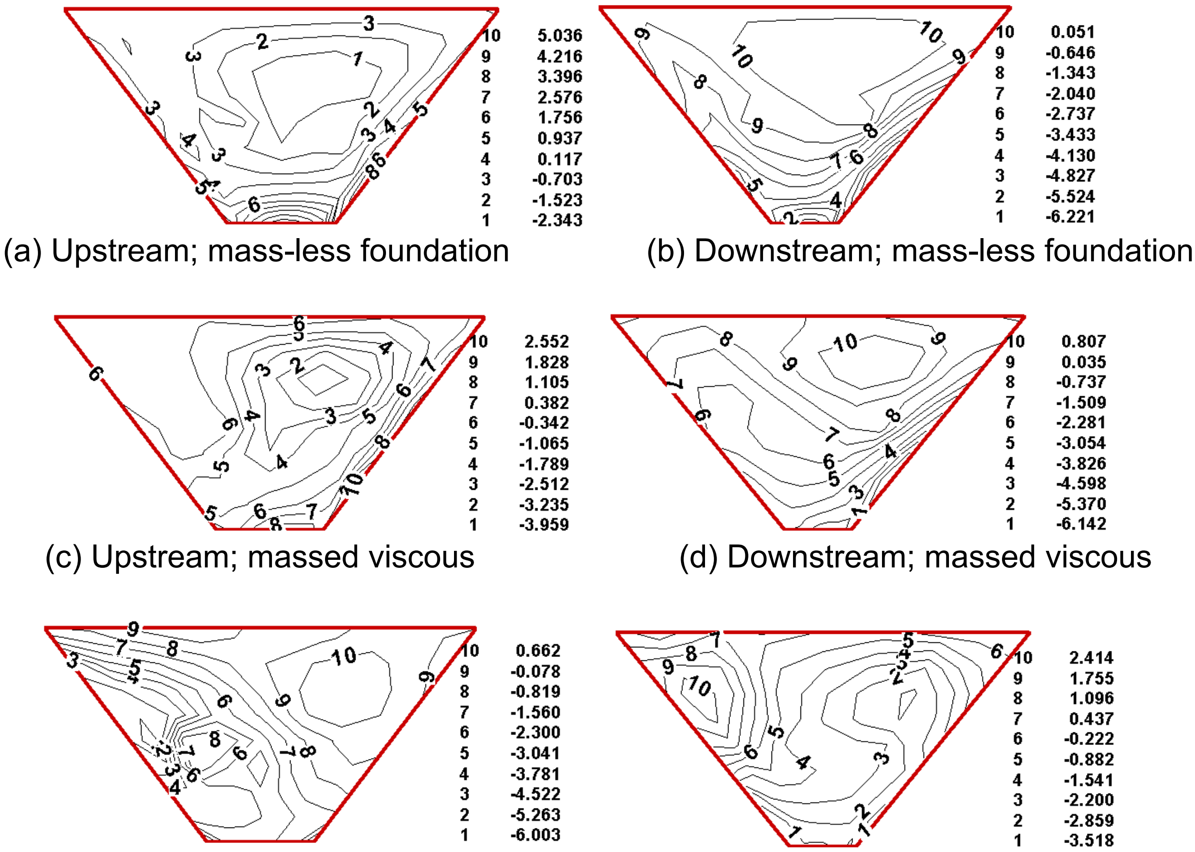
(d) Downstream; massed viscous





(e) Upstream; massed infinite element (f) Downstream; massed infinite element

Figure 10. Foundation mass effects on seismic arch stress contours in MPa



(a) Upstream; mass-less foundation (b) Downstream; mass-less foundation

(c) Upstream; massed viscous (d) Downstream; massed viscous

(e) Upstream; massed infinite element (f) Downstream; massed infinite element

Figure 11. The effect of foundation mass on seismic cantilever stress contours in MPa

Table (2) presents the summary of the maximum tensile stresses resulted from the seismic analyses. The effect of massed foundation on cantilever stresses is much more than those on the arch stresses. The results obtained from the two models of massed foundation are approximately the same. When the semi infinite media via the far-end boundary of the foundation is modeled using infinite elements, the maximum arch and cantilever stresses are reduced 5.2% and 47.5%, respectively. These reductions reach to 7.4% and 44.1%, respectively, when the far-end boundary of the foundation is constrained for the case of the viscous boundary.

Table 2. Maximum tensile dynamic stresses

Stress	Foundation state	Value (MPa)
Arch	mass-less foundation	5.842
Arch	massed foundation-viscous boundary	5.440
Arch	massed foundation-infinite element	5.541
Cantilever	mass-less foundation	5.856
Cantilever	massed foundation-viscous boundary	3.275
Cantilever	massed foundation-infinite element	3.073

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 using the staggered displacement method. The foundation media is assumed to be massed and the effect of semi-infinite media via the far-end boundary of the foundation is modeled using the infinite elements. Amir-kabir double curvature arch dam in Iran is used to consider the effect of foundation media on the linear seismic response of the dam body. It is found that the seismic crest displacement is approximately the same in various foundation assumptions. However, the cantilever and arch stress distributions are changed when the foundation is assumed massed. Also, it is deduced that the results obtained from the model with mass-less foundation is too conservative and modeling massed foundation including radiation damping leads to a reduction in stress levels within the dam body specially in cantilever stresses which have significant effect in seismic design of arch dams.

Based on the obtained results, using infinite elements or applying the viscous boundary on the far-end boundary of the foundation media gives very close seismic behavior. In fact, in spite of using the viscous boundary, the model which utilizes the infinite elements doesn't require any information about the wave traveling within the media. Also, there is not any problem in nonlinear seismic analysis when the infinite elements are used to model the semi-infinite media via the far-end boundary of the foundation. These advantages show that using infinite elements in the foundation media gives powerful tool to conduct nonlinear seismic analyses of concrete dams to evaluate the seismic behavior and safety of these infra-structures.

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