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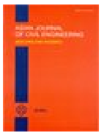

AN INVESTIGATION OF DAM-WATER-FOUNDATION ROCK INTERACTION EFFECTS ON LINEAR AND NONLINEAR EARTHQUAKE RESPONSE OF CONCRETE ARCH DAMS

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ABSTRACT

Dam-water-foundation rock interaction effects on linear and nonlinear earthquake response of arch dams are investigated. For this purpose, the dam-water-foundation rock system subjected to earthquake ground motion is idealized using the finite element method involving the materially and geometrically nonlinear effects. A real world arch dam is considered and the dam is analyzed for various conditions of interaction problem for both linear and nonlinear behaviors. Numerical results indicate that the dam-water-foundation rock interaction with a materially nonlinear behavior affects the arch dam response significantly and they should be included to achieve a safe design for arch dams.

Keywords: arch dams; dam-water-foundation rock interaction; nonlinearity effects; earthquake response; finite element method

1. INTRODUCTION

Arch dams are very important structures. The collapse of an arch dam due to earthquake ground motion may cause an extensive damage to property and life losses. Therefore, the proper design of arch dams is an important issue in dam engineering. An integral part of this procedure is to accurately estimate the dam earthquake response. The prediction of the actual response of an arch dam subjected to earthquake is a very complicated problem. It depends on several factors such as arch dam-foundation rock interaction, arch dam-water interaction, material model used and the analytical model employed. During the last years,

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some studies concerning the interaction effects on the earthquake response of arch dams have been made by researchers. The effects of dam-water-foundation rock interaction on linear response of arch dams subjected to earthquake have been studied by Tan and Chopra [1] where a combination of finite and boundary element methods has been utilized to simulate the dam-water-foundation rock system. Reservoir water level effects on nonlinear dynamic response of arch dams have been investigated by Akkose *et al.* [2] using the Lagrangian approach to represent the reservoir. Use of a potential-based fluid finite element formulation for seismic analysis of dam-reservoir system has also been assessed by Bouaanani and Lu [3] and the effects of fluid–structure interaction and reservoir bottom absorption on dynamic response of the system have been discussed.

The main aim of this study is to investigate the effects of interaction problem on linear and nonlinear earthquake response of arch dams. For this purpose, arch dam-water-foundation rock system is simulated using the finite element method. Dam body is treated as a materially and geometrically nonlinear structure. A compressible and inviscid fluid using an acoustical model is employed to represent the reservoir. Foundation rock is also considered as a linearly elastic structure. The performance of the finite element model is validated through a well-known model available in the literature [1]. In order to study the effects of dam-water-foundation interaction on earthquake response of arch dams, an existing arch dam is selected. Four cases are considered to represent the various conditions of dam-water-foundation interaction. For each case, some useful responses of the dam are extracted for both linear and nonlinear behaviors. Numerical results show that the dam-water-foundation rock interaction and materially nonlinear effects can have a significant role to precisely estimate the arch dam response.

2. FINITE ELEMENT MODEL OF ARCH DAM-WATER-FOUNDATION ROCK SYSTEM

In order to formulate the fluid-nonlinear structure interaction problem using the finite element method the discretized dynamic equations of fluid and structure need to be considered simultaneously to obtain the coupled fluid-structure equation as discussed in detail by Seyedpoor *et al.* [4]:

$$\begin{bmatrix} \boldsymbol{M}_{\mathrm{s}} & 0 \\ \boldsymbol{M}_{\mathrm{fs}} & \boldsymbol{M}_{\mathrm{f}} \end{bmatrix} \begin{Bmatrix} \ddot{\boldsymbol{u}}_{\mathrm{e}} \\ \ddot{\boldsymbol{p}}_{\mathrm{e}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{C}_{\mathrm{s}} & 0 \\ 0 & \boldsymbol{C}_{\mathrm{f}} \end{bmatrix} \begin{Bmatrix} \dot{\boldsymbol{u}}_{\mathrm{e}} \\ \dot{\boldsymbol{p}}_{\mathrm{e}} \end{Bmatrix} + \begin{Bmatrix} \boldsymbol{f}_{\mathrm{s}} + \boldsymbol{K}_{\mathrm{fs}} \boldsymbol{p}_{\mathrm{e}} \\ \boldsymbol{K}_{\mathrm{f}} \boldsymbol{p}_{\mathrm{e}} \end{Bmatrix} = \begin{Bmatrix} -\boldsymbol{M}_{\mathrm{s}} \ddot{\boldsymbol{u}}_{\mathrm{g}}(t) \\ -\boldsymbol{M}_{\mathrm{fs}} \ddot{\boldsymbol{u}}_{\mathrm{g}}(t) \end{Bmatrix} \tag{1}$$

where $\boldsymbol{M}_{\mathrm{s}}$ and $\boldsymbol{C}_{\mathrm{s}}$ are structural mass and damping matrices, respectively; $\boldsymbol{M}_{\mathrm{f}}$, $\boldsymbol{C}_{\mathrm{f}}$ and $\boldsymbol{K}_{\mathrm{f}}$ are fluid mass, damping and stiffness matrices, respectively; $\boldsymbol{M}_{\mathrm{fs}}$ and $\boldsymbol{K}_{\mathrm{fs}}$ are referred to as coupling mass and stiffness matrices, respectively; $\dot{\boldsymbol{u}}_{\mathrm{e}}$ and $\ddot{\boldsymbol{u}}_e$ are nodal velocity and acceleration vectors, respectively; $\boldsymbol{p}_e$, $\dot{\boldsymbol{p}}_e$ and $\ddot{\boldsymbol{p}}_e$ are nodal pressure vector, the first and second order derivatives of nodal pressure vector with respect to time, respectively. In addition, $\boldsymbol{f}_{\mathrm{s}}$ denotes the vector of internal forces of structure and $\ddot{\boldsymbol{u}}_g(t)$ represents the nodal ground acceleration vector varying with time. The coupled fluid-structure equation can be written in a more compact form as

$$\boldsymbol{M}_c\ddot{\boldsymbol{u}}_c + \boldsymbol{C}_c\dot{\boldsymbol{u}}_c + \boldsymbol{f}_{in} = \boldsymbol{f}_{ex}(t) \tag{2}$$

where $\boldsymbol{M}_c$ and $\boldsymbol{C}_c$ are constant mass and damping matrices of coupled system, respectively; $\boldsymbol{f}_{in}$ and $\boldsymbol{f}_{\mathrm{ex}}(t)$ represent the vectors of internal forces and time-varying external loads, respectively.

The incremental form of the coupled fluid-structure system of Eq. (2) that is suitable for nonlinear analysis can be written as

$$\boldsymbol{M}_c\Delta\ddot{\boldsymbol{u}}_c^i + \boldsymbol{C}_c\Delta\dot{\boldsymbol{u}}_c^i + \boldsymbol{K}_c^i\Delta\boldsymbol{u}_c^i = \Delta\boldsymbol{f}_e^{\,i} \tag{3}$$

where $\boldsymbol{K}^i$ is the stiffness matrix in the *i*th time step. Also, $\Delta\ddot{\boldsymbol{u}}_c^i$, $\Delta\dot{\boldsymbol{u}}_c^i$, $\Delta\boldsymbol{u}_c^i$ and $\Delta\boldsymbol{f}_e^{\,i}$ are equivalent to the vectors of incremental acceleration, velocity, displacement and external load in the *i*th time step, respectively. The incremental equation of the coupled fluid–structure system in Eq. (3) may be solved by means of a direct integration type method.

In the present study, the arch dam is treated as a 3D-nonlinear structure concidering both geometrically and materially nonlinear effects. The geometrically nonlinear behavior is considered to account for the effects of large deflection and large strain in dam body. The materially nonlinear behavior of dam concrete is idealized as an elasto-plastic material via an associative Drucker–Prager model [5-6]. The dam body is discretized using an eight-noded solid element having three degrees of freedom per node, i.e., translations in the nodal x, y and z directions. The reservoir is assumed to be uniform shape as considered by *Aftabi* Sani and Lotfi [7]. An eight-noded fluid element is utilized to discretize the fluid medium and the interface of the fluid-structure interaction problem. The element has four degrees of freedom per node: translations in the nodal x, y and z directions and pressure. The translations, however, are applicable only at nodes that are on the interface. In order to consider the damping effect arising from the propagation of pressure waves in the upstream direction, the reservoir length is selected as three times the dam height and zero pressure are imposed on all nodes of far end boundary. In this study, foundation rock treating as a linearly elastic structure is represented via an eight-noded solid element as well. The foundation rock is assumed to be massless in which only the effects of foundation flexibility are considered and the inertia and damping effects of the foundation rock are neglected [8-9]. The foundation rock is extended to three times dam height in upstream, downstream and downward directions [8]. Interaction between the fluid and foundation rock is considered through a damping boundary condition applied along the bottom and sides of the reservoir [10]. The damping matrix of dam body is also accomplished using Rayleigh damping. Since no wave propagation takes place in the massless foundation model, the seismic input is obtained from the earthquake motions recorded on the ground surface. In this study, dynamic analysis of arch dam is also performed according to the assumption that the dam is subjected to uniform ground motion along the dam–foundation interface. In analysis phase, static analysis of arch dam–water-foundation rock system is initially implemented under gravity load and the hydrostatic pressure and then, the dynamic analysis of the system is performed using the Newmark time integration method [11].

3. NUMERICAL RESULTS AND DISCUSSION

In order to examine the effects of interaction problem on linear and nonlinear earthquake response of arch dams, Morrow Point arch dam located 263 km southwest of Denver, Colorado, is considered as a real world structure. The material properties of the dam, water and foundation rock are given in Table 1.

Table 1: The material properties of the dam, water and foundation

Dam body	Elasticity modulus of concrete	27580 MPa
	Poison's ratio of concrete	0.20
	Mass density of concrete	2483 kg m^{-3}
	Uniaxial compressive strength of concrete	30 MPa
	Uniaxial tensile strength of concrete	3.0 MPa
	Biaxial compressive strength of concrete	36 MPa
	Cohesion factor of concrete	3.0 MPa
	Angle of internal friction of concrete	45°
Water	Mass density of water	1000 kg m^{-3}
	Speed of pressure wave	1440 m s^{-1}
	Wave reflection coefficient	0.90
Foundation rock	Elasticity modulus of foundation rock	27580 MPa
	Poison's ratio of foundation rock	0.20
	Mass density of foundation rock	0.00

The selected arch dam including dam-water-foundation rock interaction is simulated using the finite element method as shown in Figure 1 and then, three types of analysis are separately implemented as

(a) Harmonic response analysis
(b) Linear transient dynamic analysis
(c) Nonlinear transient dynamic analysis

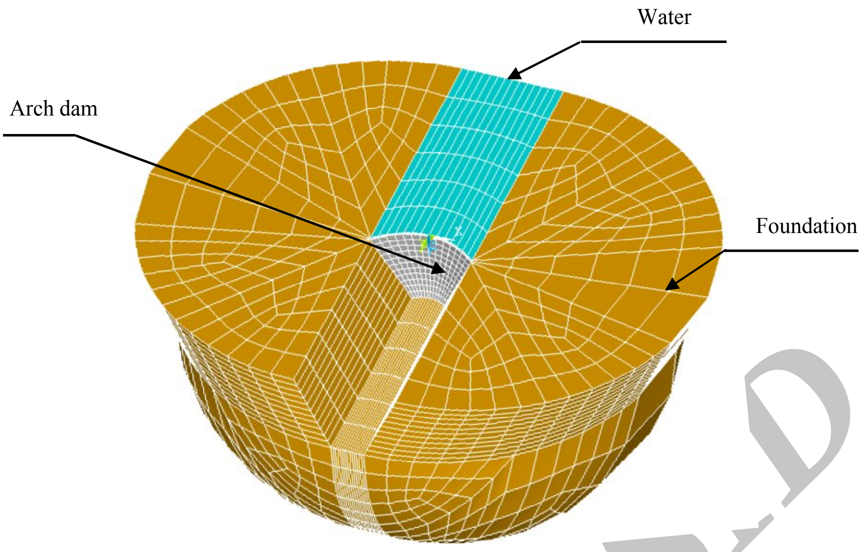

Figure 1. Finite element model of Morrow Point arch dam-water-foundation rock system

In each analysis type, four cases regarding the various conditions of interaction problem are considered as follows:

Case 1: Dam with empty reservoir and rigid foundation.
Case 2: Dam with empty reservoir and flexible foundation.
Case 3: Dam with full reservoir and rigid foundation.
Case 4: Dam with full reservoir and flexible foundation.

The specifications of all cases are listed in Table 2.

Table 2: The specifications of four design cases for the Morrow Point dam

Case	Foundation rock	Reservoir	Wave reflection coefficient	Loading
1	Rigid	Empty	-	Gravity earthquake
2	Flexible	Empty	-	Gravity earthquake
3	Rigid	Full	$\alpha = 0.90$	Gravity hydrostatic hydrodynamic earthquake
4	Flexible	Full	$\alpha = 0.90$	Gravity hydrostatic hydrodynamic earthquake

3.1 Harmonic response analysis of Morrow Point arch dam

Harmonic response analysis is a technique used to determine the steady-state response of a linear structure to harmonic loads. This technique can be simply employed to determine the natural frequencies of a structure. The idea is to calculate the structure's response at several frequencies and obtain a graph of some response quantities such as displacement versus frequency. The corresponding frequencies of peak responses can be then identified as the natural frequencies of the structure. In current study, the first natural frequency of symmetric mode of the dam for cases 1 to 4 is determined from the frequency-response function of the crest displacement of the dam subjected to harmonic ground acceleration. The frequency-dependent crest displacements of all cases are shown in Figure 2. It should be mentioned that the response quantity is the amplitude of the complex valued crest displacement in upstream-downstream direction. In this Figure, peaks in the frequency response functions correspond to the natural frequencies of the arch dam.

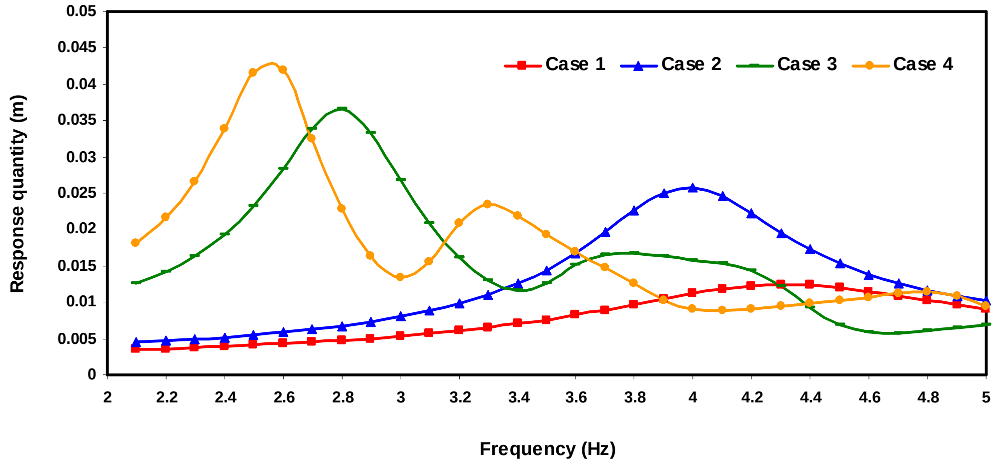

Figure 2. The frequency-dependent crest displacements for cases 1 to 4

The natural frequencies from the finite element model and those reported in the literature are given in Table 3. It can be observed that a good conformity has been achieved between the results of the present work with those of the literature.

Table 3: A comparison of the natural frequencies from the literature with the FE model

Case	**Foundation rock condition**	**Water**	**Wave reflection coefficient α**	**Natural frequency (Hz)**		
				Tan and Chopra [1]	**Present study**	**Error (%)**
1	Rigid	Empty	-	4.2735	4.29	0.39
2	Flexible	Empty	-	3.9216	3.99	1.74
3	Rigid	Full	0.9	2.8169	2.80	0.60
4	Flexible	Full	0.9	2.5974	2.55	1.82

It can be observed that when the reservoir is empty and the foundation is rigid (case 1) the main frequency of the dam is maximal. Furthermore, a minimum value for the main frequency is obtained when the dam-water-foundation rock interaction (case 4) is considered.

3.2 Linear transient dynamic analysis of Morrow Point arch dam

In order to investigate the effects of dam-water and dam-foundation rock on the time history response of arch dams, the linear earthquake response of Morrow Point dam is determined for the specified cases. For all cases a static analysis is initially implemented and then, the dam is subjected to the El-Centro N–S record of Imperial Valley earthquake (1940) shown in Figure 3 in upstream-downstream direction.

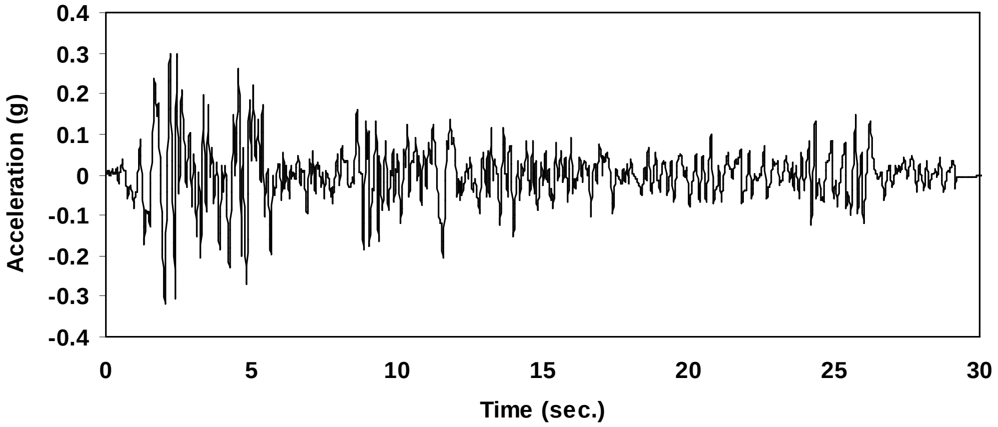

Figure 3. The El-Centro N–S record of Imperial Valley earthquake (1940)

The time history of crest displacement as a useful response for cases 1-2 and cases 2-3 are compared in Figures 4 and 5, respectively.

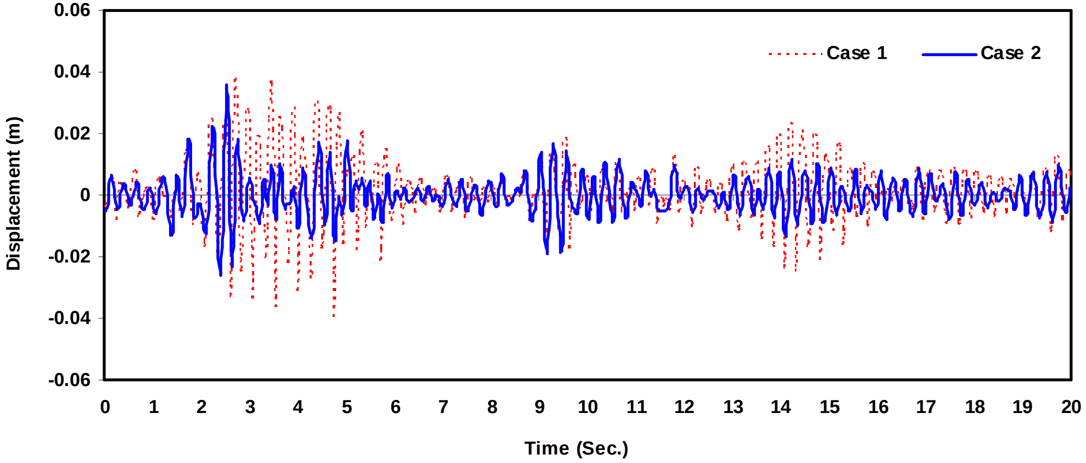

Figure 4. The time history linear response of crest displacement for cases 1 and 2

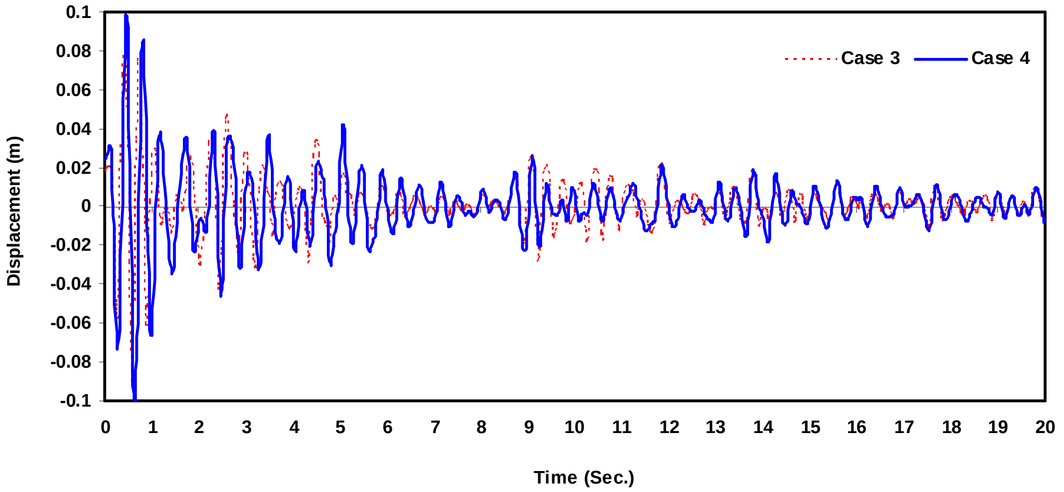

Figure 5. The time history linear response of crest displacement for cases 3 and 4

Peak displacement distribution on the central vertical section of the dam is also depicted in Figure 6 for all cases.

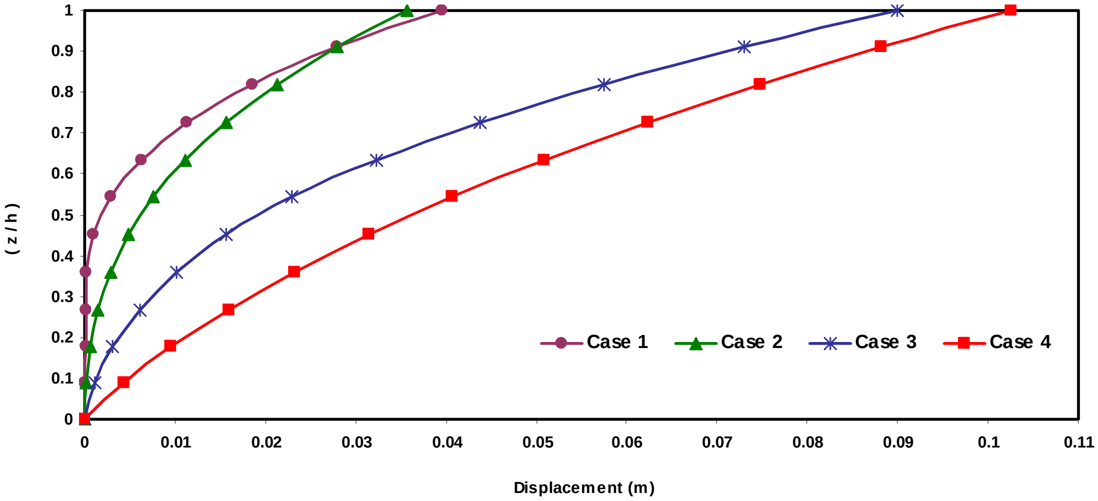

Figure 6. Peak displacement distribution on the central vertical section of the arch dam

All of the Figures demonstrate that the maximum responses are related to the dam with full reservoir and flexible foundation (case 4). Therefore in the next section, the linear and nonlinear responses of the arch dam are compared only for the case 4.

3.3 Nonlinear transient dynamic analysis of Morrow Point arch dam

In order to examine the nonlinearity effects on the time history response of arch dams, the earthquake response of Morrow Point dam is determined when materially nonlinear analysis (MNA), geometrically nonlinear analysis (GNA), and materially and geometrically nonlinear analysis (MGNA) are performed separately and the results are compared with those obtained using a linear analysis (LA) of the arch dam-water-foundation rock system. The time history response of crest displacement for LA, GNA, MNA and MGNA are compared in Figure 7.

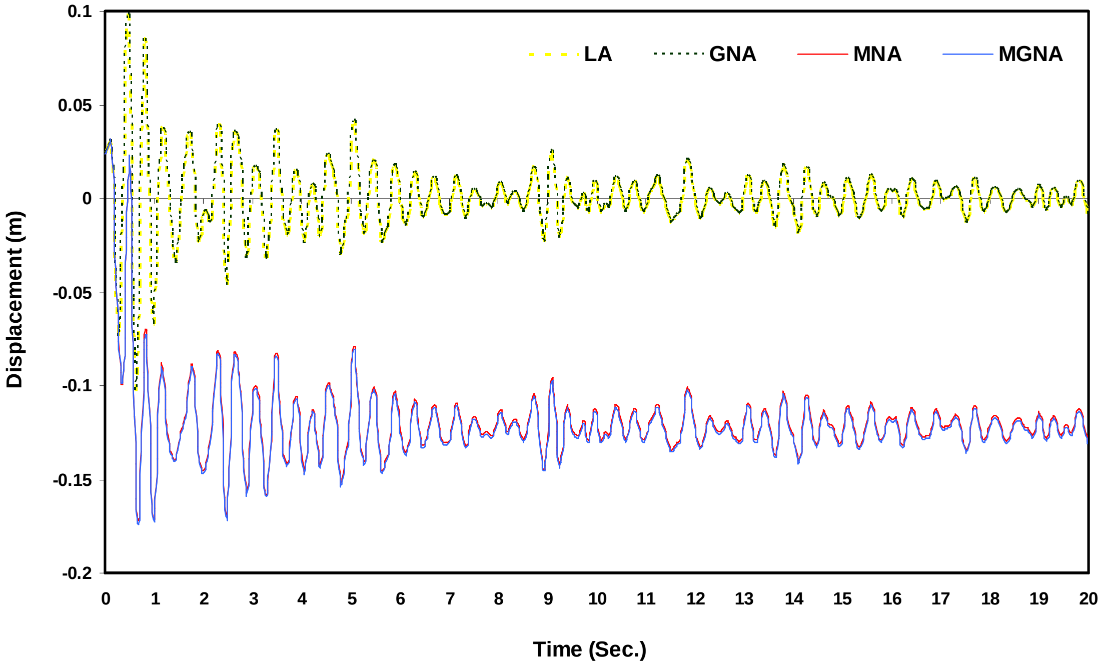

Figure 7. The time history of crest displacement for LA, GNA, MNA and MGNA

Peak displacement distribution on the central vertical section of the dam is also depicted in Figure 8 for both linear and different nonlinear analyses.

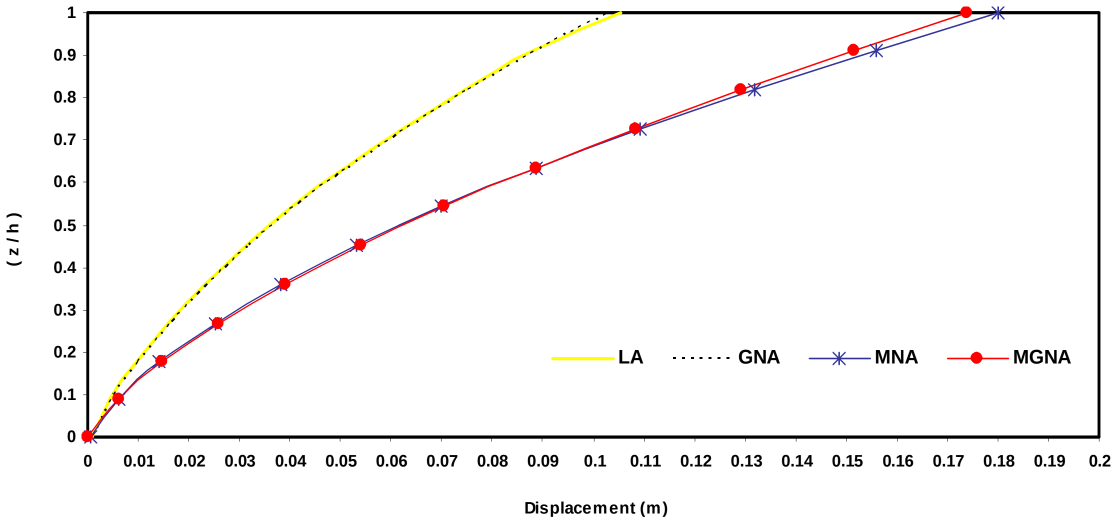

Figure 8. Peak displacement distribution on the central vertical section of the arch dam

By comparing the various responses of the dam an interesting point is concluded. It is important to note that considering the geometrically nonlinear behavior in arch dam analysis can not significantly affect the time history response of the dam. Moreover, materially nonlinear effect of arch dams can considerably influence the earthquake response of the dam and it must be considered to accurately estimate the arch dam response.

For a further comparison between the linear and nonlinear responses of the arch dam the time history of principal stresses at dam heel for LA and MNA are also shown in Figures 9-a to 9-c. It can be found the materially nonlinear behavior can increase the principal stresses of the dam heel.

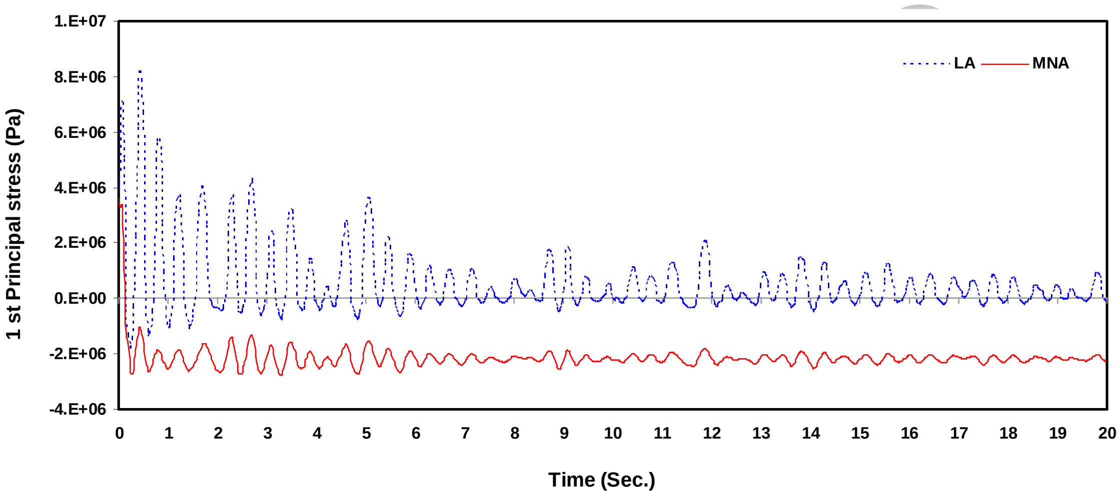

Figure 9(a). Time history of the first principal stress at dam heel for LA and MNA

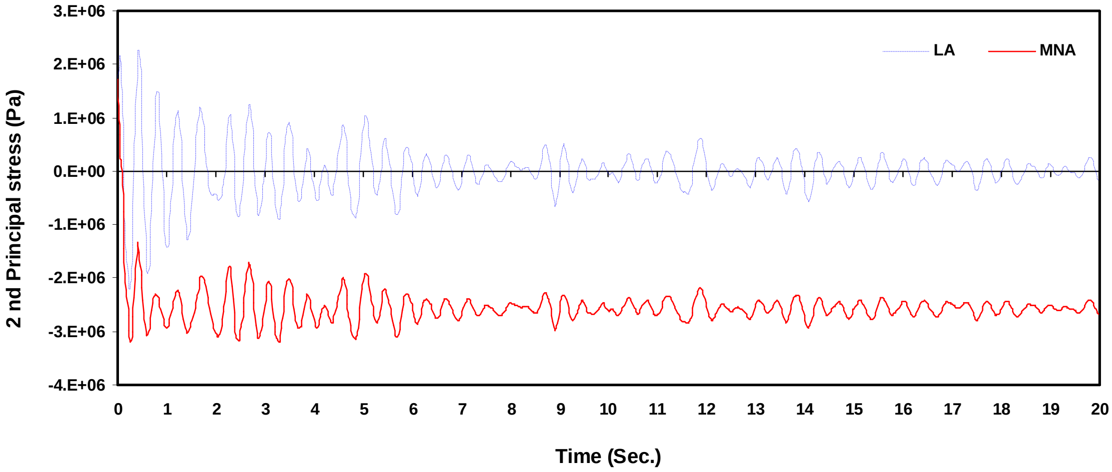

Figure 9(b). Time history of the second principal stress at dam heel for LA and MNA

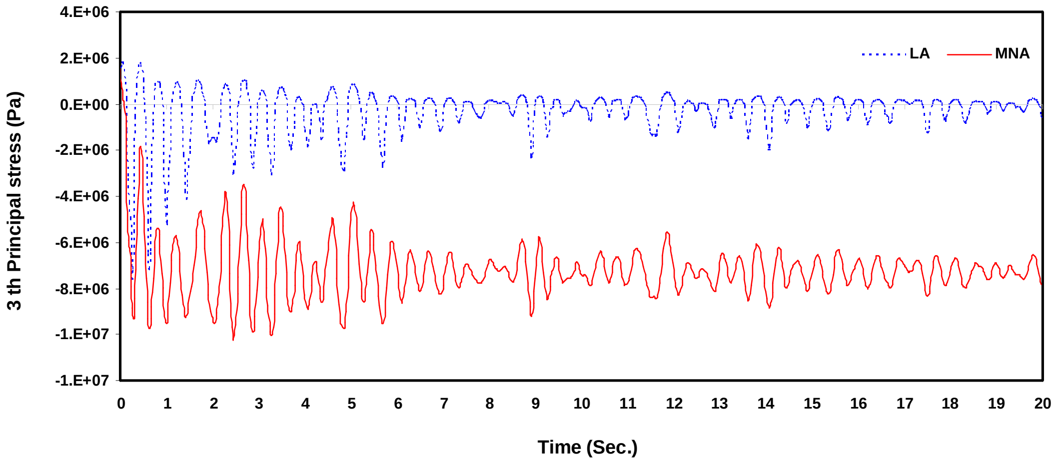

Figure 9(c). Time history of the third principal stress at dam heel for LA and MNA

4. CONCLUSIONS

The effects of dam-water-foundation rock interaction on linear and nonlinear earthquake response of concrete arch dams are investigated in this paper. For this purpose, a finite element model is conducted to simulate the linear and nonlinear behaviors of arch dams. In nonlinear analysis both materially and geometrically nonlinearities are considered. Various responses of an existing arch dam are extracted using the conducted finite element model. Numerical results show that the dam-water-foundation rock interaction and materially nonlinear effect of arch dams play an important role in accurately estimating the arch dam response.

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