Behavior of Concrete Dam under Seismic Load

A. Hebbouche
Ecole Nationale Supérieure d'Hydraulique, Blida-Algérie
Departement of civil engineering, Saad dahlab university, Blida, Algeria

M. Bensaibi
Departement of civil engineering, Saad dahlab university, Blida, Algeria

H. Mroueh
Université Lille 1 Sciences et Technologies, France

SUMMARY
Dams are often subjected to earthquakes due to their localization in seismic zones. So, their behavior must be studied carefully. In this study, a concrete dam is studied taking into account the soil-fluid-structure interaction. The study is conducted using a non-linear analysis for finite element model. The dam of Oued el Fodda (Algeria) is taken as an example to apply the developed model. Two earthquakes were considered Kocaeli Izmit (1999) and Northridge (1994) and the obtained displacements and stress are compared.

Keywords: dam-reservoir-foundation interaction, nonlinear analysis, gravity dam, seismic excitation.

1. INTRODUCTION

Dynamic analysis of dam-reservoir systems is an important subject in civil engineering practice. Extensive work has been done during the last decades, and many numerical procedures including the interaction between several domains, (concrete dam, foundation rock, water, and bottom sediments) have been developed by using finite element method, boundary element method and also combinations of both Nasserzare (2000). Many of them were built in highly seismic areas and have been operating for a long period of time. Earthquakes may impair their proper functioning and trigger catastrophic failure causing property damage and loss of life. The real behavior of these important structures has not been evaluated completely yet (Jeeho (1998), Maeso (2004), Küçükarslan (2004) and Huang (2008)). This paper addresses these issues by developing a numerical procedure for studying the effects of near-and-far fault ground motion on the response of concrete gravity dams using the finite element method. The proposed methodology is presented with the Oued el Fodda dam in Algeria. A finite element code is employed to carry out the analysis. A dynamic analysis is then performed by applying two earthquake motions Kocaeli Izmit (1999) and Northridge (1994) as excitations to the model. Both near-and-far fault ground motions are utilized so that the effects of the type of the earthquake motions on the dam response are explored.

2. STRUCTURAL MODELING OF DAM BEHAVIOR

The study is based on a concrete gravity dam with a vertical upstream face, which maintains a reservoir of water that extends to infinity in the upstream direction and is based on a semi-infinite foundation. The geometry of the dam-reservoir-foundation system is shown in Fig.2.1.

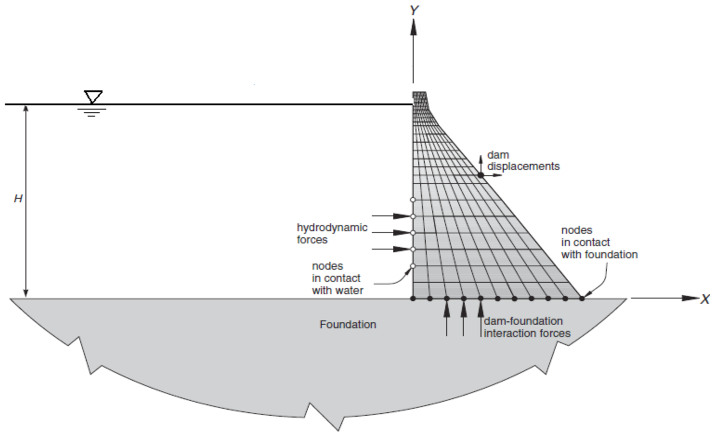


Figure 1. Geometry of dam-reservoir-foundation system

2.1 Description of model

The model of the dam, used 4-node, bilinear finite elements. The concrete-rock interface is assumed to be horizontal and to obey the Coulomb friction law. The foundation material was assumed to be a Mohr-Coulomb material, with its non-linear behavior assumed to be perfectly plastic. The concrete in the dam was modeled as an impervious material. The bottom horizontal boundary of the FE model is the application point of the de-convolved seismic ground motion. Different boundary conditions must be imposed on the nodes on the vertical boundaries of the FE model. Those nodes, representing the outlying nodes where the effect of dam–foundation interaction is presumed to have attenuated, are constrained to move together in the horizontal direction. While the spatial variation of the earthquake ground motion across the base of the model is neglected, those nodes in the vicinity of the base of the dam clearly are affected by the dam–foundation interaction. The above provisions provide an adequate model for the dam–foundation interaction.

2.2 Dam–water–foundation interaction

The modeling of a concrete gravity dam for seismic effects must consider the dynamic interactions among the reservoir, the dam and the foundation. The equation of motion of the dam–reservoir-foundation system can be written as

$$M\ddot{x} + C\dot{x} + Kx = -M1a(t) + F(t) \tag{2.1}$$

in which M, C, K are the mass, damping and stiffness matrices for the finite elements system, x is the vector of nodal point displacements relative to the free-field ground displacement at the base of the dam, a(t) is the free-field ground acceleration and 1 is a unit column vector. The force vector F(t) includes the hydrodynamic forces due to the dam–reservoir interaction. These forces are expressed in terms of accelerations of the upstream face of the dam and the reservoir bottom Eqn.2.1. These interactions have been studied and reported extensively, beginning with the work on the dam–water (hydrodynamic) interaction by Westergaard (1933). Later approaches to modeling these interactions have solved the governing equations in the frequency domain Chopra (1981, 1992), or have used a hybrid frequency-time domain (HFTD) procedure Fenves (1996). In this study, a simplified two-parameter model presented by Darbre (1998) is used. The model consists of incompressible water mass attached in series to dampers. The dampers are fixed to the upstream face of the dam. As the model is discrete, it can be implemented directly in a non-linear, time-domain analysis. It was shown by work investigated by Darbre (1998) that the two parameter models is a valid approximation when both the frequency content of the excitation and the significant natural frequencies of the dam extend over several resonant frequencies of the reservoir.

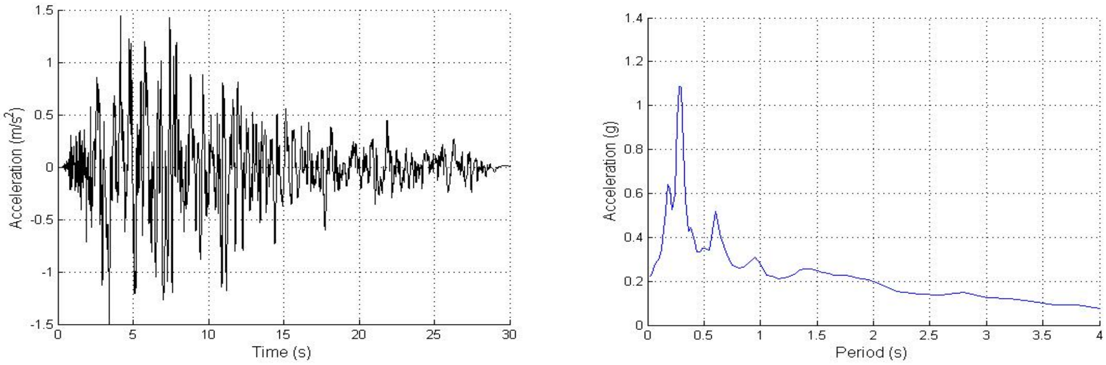
2.3 Earthquake response of dams subjected to near and far-fault ground motions

In this paper, a near-fault ground motion record is selected as an input ground motion from 1999 Kocaeli Izmit earthquake (Mw = 7.4). This record is taken from Izmit station. On the contrary, another set of earthquake record, recorded at another site condition with epicenter far away from the site (Mw = 6.7), is selected to illustrate far-fault ground motion characteristics. The ground motion records are obtained from the PEER Strong Motion Database PEER (2007). The databases have information on the site conditions and the soil type for the instrument locations. The acceleration and the acceleration response spectra of the horizontal component of the near-fault ground motion recorded in Izmit station are shown in Fig.2.2 (a) and Fig.2.2 (b). The far-fault ground motion acceleration and spectra recorded at station 127 Lake Hughes are shown in Fig.2.3 (a) and Fig.2.3 (b) for comparison. The long period response of the near-fault ground motion is more excessive than the one of the far-fault ground motion. In order to investigate the near- and far-fault effects on the response of dam–reservoir–foundation systems, the earthquake analyses of the dams are performed.

The Kocaeli Izmit (1999) and Northridge (1994) earthquake are recorded with the magnitude of 7.4 and 6.7 respectively, and they are both considered in this study. The distance of the recording site from the source is ranged from 5.31 to 44.3 km. A scatter plot of the magnitude–distance pair for the records of strong ground motions is shown in Fig.2.4. The record characterizing near-fault ground motion is obtained from the distance less than 10 km to epicenter and the other record characterizing far-fault ground motion is obtained from the distance more than 10 km to epicenter. The characteristics of applied ground motion are described in table 2.1.

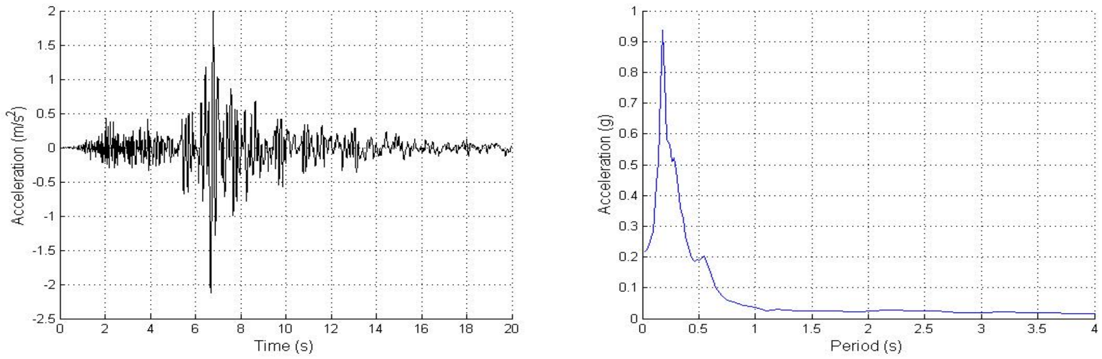
Table 2.1. Ground motion records selected for analyses PEER (2007)

Type	Earthquake record	Station	Magnitude	Distance (km)	Peak acceleration
Near fault	1999 Kocaeli	Izmit	7.4	5.31	0.152 g
Far fault	1994 Northridge	127 Lake Hughes #9	6.7	44.3	0.217 g



(a) (b)

Figure 2. The near-fault ground motion: (a) acceleration and (b) response spectra for 1999 Kocaeli Izmit earthquake



(a) (b)

Figure 3. The far-fault ground motion: (a) acceleration and (b) response spectra for 1994 Northridge earthquake

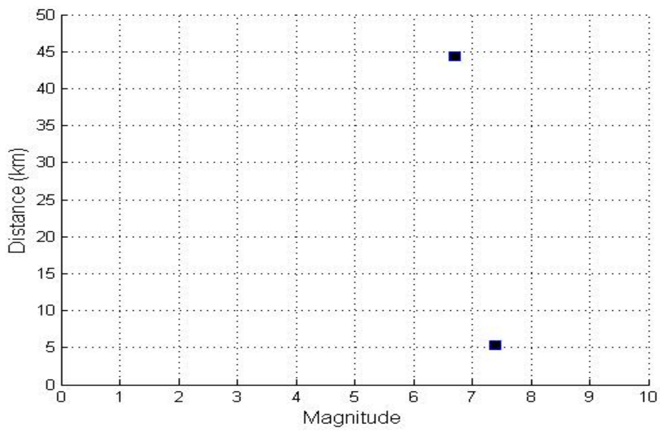


Figure 4. The sight of magnitude–distance distribution

3. NUMERICAL EXAMPLE

3.1 Material properties

In this study, the values of material properties used for dam model are: Unit weight of the concrete is 2500 kg/m3, 0.2 Poisson's ratio, and the modulus of elasticity is taken as 31000 MPa. Compressive strength of the concrete has been assumed as 30 MPa. The concrete tensile strength is assumed to be 15% of compressive strength (4.5 MPa). The water has the unit weight, 1000 kg/m3, pressure wave velocity 1440 m/s. In the analysis, the damping ratio is assumed to be 5% of the fundamental frequency of system.

3.2 Free-vibration analysis

The concrete gravity dam of Oued el Fodda is analyzed with full reservoir. A static analysis of the dam-foundation system is first carried out with the load applied to assess its pre-seismic state. The results of static analysis are then utilized as the initial conditions for the subsequent seismic analyses. This represents the state of the dam before an earthquake occurs. Then, a time-domain dynamic analysis is performed with the deconvolved seismic ground motion applied at the base of the finite elements model of the foundation. To determine the dynamic properties of the system, the natural frequencies were extracted prior to conducting this dynamic analysis. The largest four periods of the dam on a rigid foundation are 0.244 sec, 0.103 sec, 0.08 sec and 0.059 sec. The largest four vibration periods of the dam-foundation system are 0.343 sec, 0.198 sec, 0.169 sec and 0.164 sec. The results for the rigid foundation case are in good agreement with those obtained by Chopra and Chakrabarti (1973). The results also indicate that the vibration periods lengthen with increasing foundation flexibility, which coincides with the investigation of Leger and Boughoufalah (1989).

3.3 Seismic analysis

The behavior of the dam subjected to earthquake ground motion is illustrated by its response to Kocaeli Izmit (1999) and Northridge (1994) earthquake. To assess the effects of dam-foundation and type of earthquakes on the response of the coupled system, we considered two cases of ground motion loading: cases 1 and 2 take into consideration an near-and far- fault ground motion respectively. For each case we opted for two types of calculation, the first type consider a dam on a rigid foundation subjected to seismic excitation applied at the rigid base and the second type considers a dam with foundation by considering the interaction dam-foundation and the seismic excitation was applied at the bottom of the foundation. To be consistent with Darbre's two-parameter model described earlier, only the horizontal component of Kocaeli Izmit (1999) and Northridge (1994) earthquake are considered.

4. RESULTS AND DISCUSSION

4.1 Displacements

The horizontal displacements at the crest of dam obtained from nonlinear behavior for both input motion Kocaeli and Northridge are presented in Fig.4.5 Fig.4.6. For case 1, the result obtained seen that the displacements at the top of dam is greater for near fault motion then the displacement obtained for far fault motion. However, in the case 2 the displacement at the top of the dam is lower for far fault motion then the displacement resulted from near-fault ground motion.

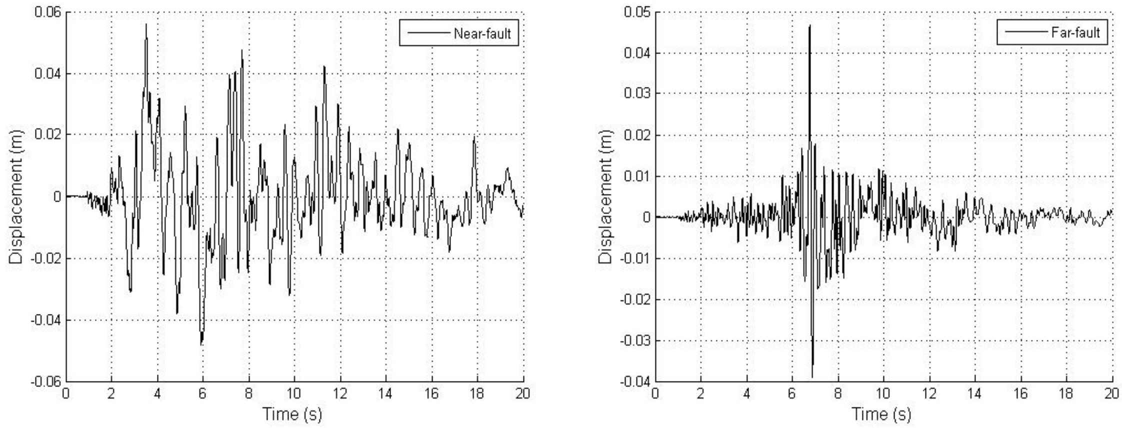


Figure 5. The time-histories of horizontal displacements at the crest of dam without dam-foundation interaction

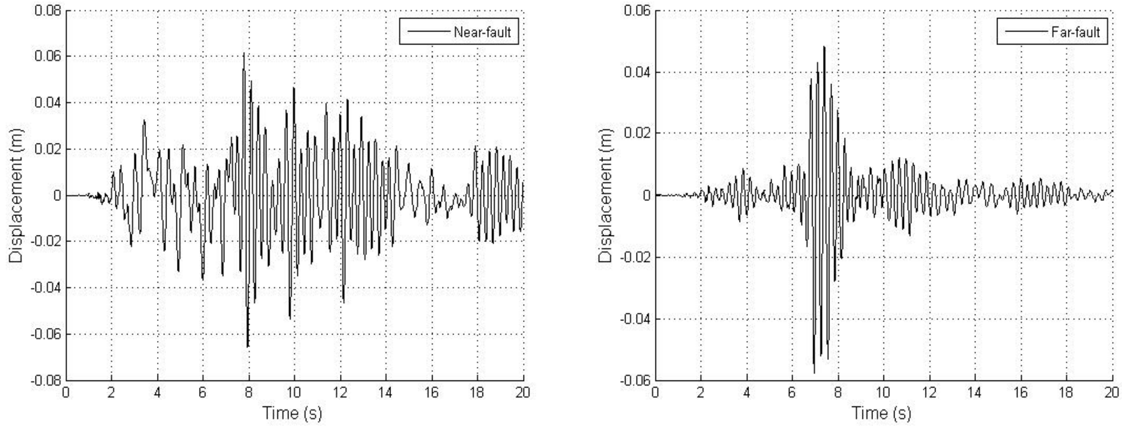


Figure 6. The time-histories of horizontal displacements at the crest of dam with dam-foundation interaction

4.1.2 Normal stresses

The analysis of maximum normal stress at the heel and the toe of the dam for the both cases are depicted in Fig.4.7 to Fig.4.10. For case 1, the results obtained in term of maximum normal stress σ_{11} and σ_{22} for dam without foundation under near- and far-fault earthquake shown in Fig.4.7 and Fig.4.8, it can be seen that the maximum normal stress σ_{11} and σ_{22} are generally higher for near fault motion.

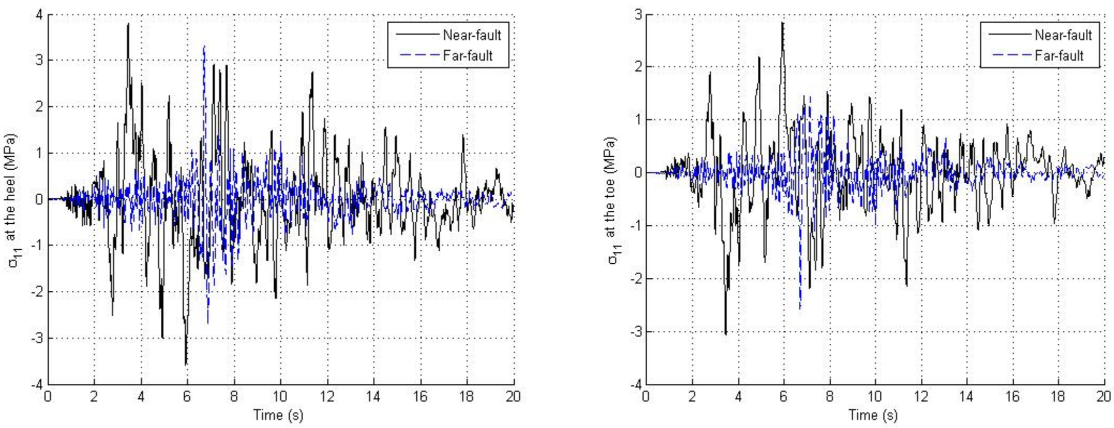


Figure 7. Normal stress σ_{11} at the heel and the toe of the dam

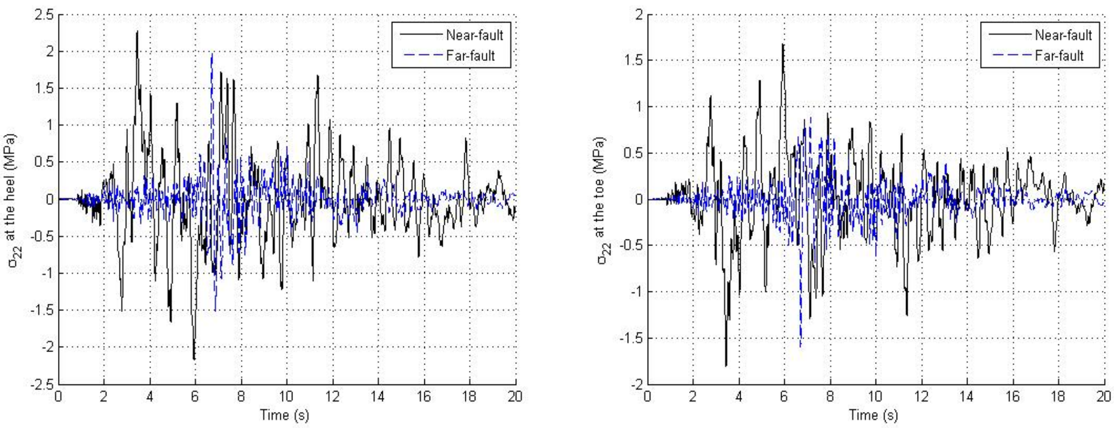


Figure 8. Normal stress σ_{22} at the heel and the toe of the dam

For case 2, the results are presented in Figs 9-10, in which the maximum normal stress σ_{11} and σ_{22} for dam with dam-foundation interaction system are lower for far-fault earthquake.

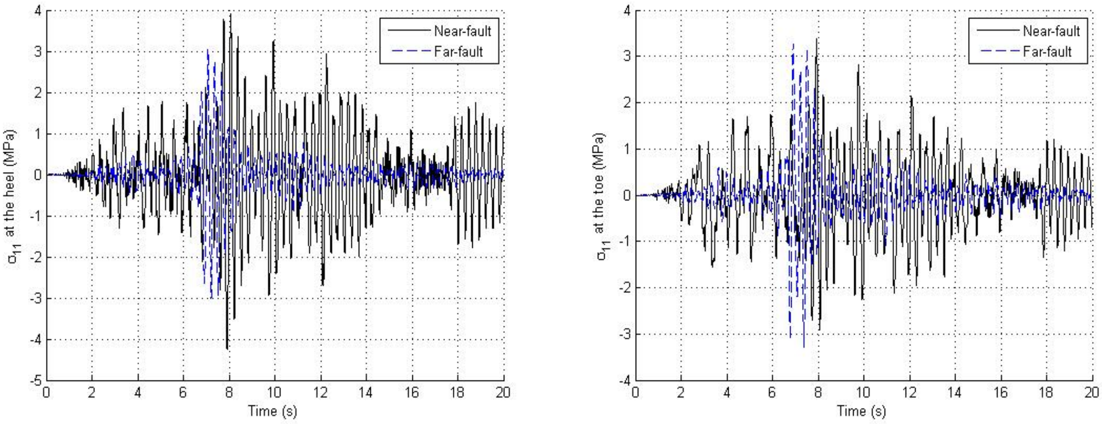


Figure 9. Normal stress σ_{11} at the heel and the toe of the dam

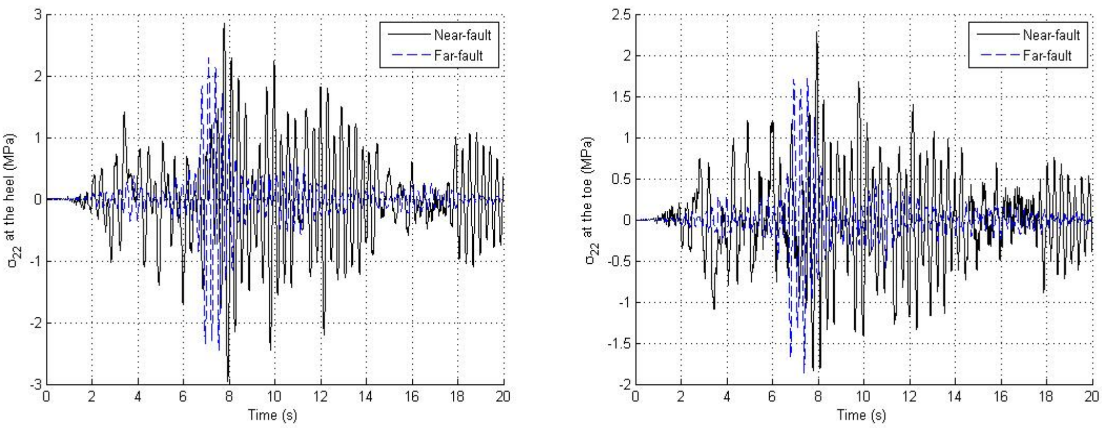


Figure 10. Normal stress σ_{22} at the heel and the toe of the dam

4. CONCLUSIONS

In this work, the effect of the non linear dynamic behavior of the Oued el Fodda concrete dam is taken into account in both cases near- and far-fault ground motion. It is concluded from the study that the displacements at the top of dam is generally higher for near-fault then far-fault motion. In terms of the normal stresses σ_{11} and σ_{22}, at the heel and the toe of dam without and with dam-reservoir-foundation interaction system, the results obtained demonstrate that the normal stresses resulting for far-fault motion are lower than those obtained for near-fault earthquake.

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