The study of the foundation role in the seismic nonlinear behavior of concrete gravity dams

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ABSTRACT:

During the recent years, the seismic nonlinear behavior of concrete gravity dams was in the center of consideration of dam engineers. Numerous researches have been conducted in order to determine how the dams behave against the seismic loads. Many achievements were obtained in the process of analysis and design of concrete dams. In this paper, we study the dam-reservoir-foundation interaction during an earthquake. For this purpose, a two-dimensional finite element model of a concrete gravity dam including the dam body, a part of its foundation and a part of the reservoir was made. In addition, the proper boundary conditions were used in both reservoir and foundation in order to absorb the energy of waves at the far end boundaries. Using the finite element method and smeared crack approach, some different seismic nonlinear analyses were done to study the impact of the foundation mass and flexibility on the seismic behavior of the dam. The results show that both the foundation mass and flexibility have an outstanding impact on the nonlinear behavior of dams and therefore it is necessary to consider the foundation effect while analyzing concrete dams.

KEYWORDS:
Absorbing boundary condition, Concrete gravity dams, Dam-reservoir-foundation interaction, Nonlinear dynamic analysis, Seismic energy response, Staggered displacement method

1. INTROUDUCTION:

In the past years, numerous researches have been conducted in order to determine how dams behave nonlinearly against the seismic loads. Although many achievements were obtained in the process of analysis and design of concrete dams, there are still many important questions unsolved. One of these crucial questions is the dam-reservoir-foundation interaction during an earthquake. When subjected to earthquake, the analysis of dam-reservoir interaction effects is a complex problem. Westergaard [1] introduced an approach to determine approximately the linear response of the dam-reservoir system by a number of masses that are added to the dam body. Ghaemian and Ghobarah [2] showed that the added mass approximation may not be a suitable approach for nonlinear analysis of dam-reservoir systems.

The dam-reservoir system can be categorized as a coupled field system in a way that these two physical domains interact only at their interface. The staggered solution is a partitioned solution procedure that can be organized in terms of sequential execution of a single field analyzer. Ghaemian and Ghobarah [3] proposed two unconditionally stable methods of staggered solution procedure for the dam-reservoir interaction problem.

To simplify and economize the finite element modeling of an infinite reservoir, the far-end boundary of the reservoir has to be truncated. As a rule for the truncated boundary, there is no reflection for the outgoing wave. Sommerfeld boundary condition [4] is an appropriate boundary condition for the truncated part of the reservoir. In the mentioned condition, the fluid is assumed to be incompressible. Sharan [5] proposed a damper radiation boundary condition for the time domain analysis of a compressible fluid with small amplitude. This Boundary condition is found to be very effective and efficient for a wide range of excitation frequencies.

The consideration of dam-foundation interaction and modeling the foundation is an important part in modeling dam-reservoir-foundation interaction. In the past two decades, some solutions have been introduced for this question. Fenves and Chopra [6] studied the dam-reservoir-foundation rock interaction in a frequency domain linear analysis. Leger and Bhattacharjee [7] presented a methodology which is based on frequency-independent models to approximate the representation of dam-reservoir-foundation interaction problem.

Bhattacharjee and Leger [8] studied the energy response of concrete gravity dams using the proposed smeared crack model. In the work presented by Gaun, Moore and Lin [9], an efficient numerical procedure has been described to study the dynamic response of a reservoir-dam-foundation system directly in the time domain. Later, Ghaemian, Noorzad and Moghaddam [10] showed that the effects of foundation's shape and mass on the linear response of arch dams are considerable.

Just like the reservoir, it is wise and economical to truncate the far-end boundaries of the foundation. Probably the most widely used model for soil radiation damping is the one of Lysmer and Kuhlemeyer [11]. In this model the foundation is wrapped by dashpots tuned to absorb the S and P waves.

In the present article, a two dimensional dam-reservoir-foundation system is analyzed using finite element method and smeared crack approach. The dam-reservoir interaction is solved by staggered solution procedure while the Sharan Boundary condition is applied at the reservoir's far-end truncated boundary. The foundation is defined as a part of the structure and viscous boundary conditions are applied at its truncated boundaries. Moreover, in order to estimate the free field motion at the site of dam, we use the SSI method [12].

2. DAM-RESERVOIR INTERACTION:

The equation of motion in structure–reservoir interaction is governed with the following two second order differential Eqns [2]:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{f_1\}-[M]\{\ddot{u}_g\}+[Q]\{p\}=\{F_1\}+[Q]\{p\} \tag{2.1}$$

$$[G]\{\ddot{p}\}+[C']\{\dot{p}\}+[K']\{p\}=\{F_2\}-\rho[Q]^T\{\ddot{u}\} \tag{2.2}$$

where $[M]$,$[C]$ and $[K]$ are mass, damping and stiffness matrices of the structure, and $[G]$,$[C^{'}]$ and $[K^{'}]$ are matrices representing mass, damping and stiffness of the reservoir, respectively. $[Q]$ is the coupling matrix and $\{f_1\}$ is the vector of body force and hydrostatic force. $\{F_2\}$ is the component of the force due to acceleration at the boundaries of the dam–reservoir and reservoir–foundation. $\{p\}$ and $\{u\}$ are the vectors of pressures and displacements. $\{\ddot{u}_g\}$ is the ground acceleration and ρ is the density of the fluid. The dot represents the time derivative. Direct integration scheme is used to determine the displacement and hydrodynamic pressure at time increment $i+1$. The α -method [13, 14] is used for discretization of both equations (implicit-implicit method).

3. DAM-FOUNDATION INTERACTION:

The most common soil–structure interaction (SSI) approach is based on the "added motion" formulation. This formulation is valid for free–field motions caused by earthquake waves generated from all sources. The method requires that the free–field motions at the base of the structure be calculated prior to the soil–structure interaction analysis [12].

Therefore, nonlinear dynamic analysis of concrete gravity dams including dam-reservoir-foundation interaction, Eqn. 2.1 must be replaced with Eqn. 3.1 as following:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+K\{u\}=-[m]_s\{\ddot{u}_g\}+\{f_1\}+[Q]\{p\} \tag{3.1}$$

where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices, respectively, of the dam-foundation structure and $[m_s]$ is only the mass matrix of the dam structure.

3.1. Seismic Energy Balance and Modified Energy Balance Error:

In the design of structures subjected to earthquake loading, the energy equation can be used to study nonlinear behavior of structures under various earthquake ground motions [2, 15].

For dam-reservoir interaction the energy balance error of the dam structure is governed by Eqn. 2.1 [2], but when the dam–foundation interaction effects are considered by using massed foundation, the energy balance error must be modified and according to Eqn. 3.1.
In the present study, the results of the fracture response are presented for the time before the 5% energy balance error is reached. The error in the energy balance represents an excessive amount of damage when numerical damping is introduced.

3.2. Viscous boundary condition:

This boundary condition is defined using Lysmer's theory about radiation damping [11]. According to this theory, an appropriate viscous boundary, which is a non-consistent boundary (sometimes called local boundary), is applied at the far-end boundary of the foundation in 2-D space given as [11]:

$$\sigma = a\rho V_P \dot{w} \tag{3.2}$$

$$\tau = b\rho V_S \dot{u} \tag{3.3}$$

where, σ and τ are the normal and shear stresses, V_P and V_S are primary and secondary wave propagation velocity within the foundation, and $\dot{w}$ and $\dot{u}$ are the normal and tangential velocities, respectively. The two parameters of a and b are dimensionless numbers and it was found that applying the two boundary condition with a and b equal to unity on the far-end boundary of the foundation media leads to the highest efficiency in absorbing the outgoing seismic waves [11].
Radiation damping derived from Eqns. 3.2 and 3.3 and applied on the far-end boundary of the foundation is made up of dashpots that are added to the global damping matrix of the structure. In the present study, these lumped dashpots are determined as follows:

$$C_{11}^{i} = V_P \rho \int_{l_e} N_i dl \tag{3.4}$$

$$C_{22}^{i} = V_S \rho \int_{l_e} N_i dl \tag{3.5}$$

where, C_{11}^{i} and C_{22}^{i} are the components of lumped damping in normal and tangential directions, respectively. Fig. 1 shows the defined boundary condition based on Lysmer's theory.

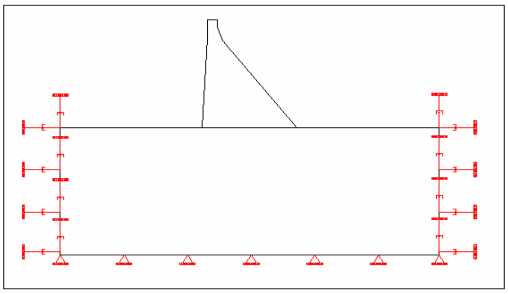


Figure 1. Lysmer model with viscous boundary condition for foundation

4. NUMERICAL RESULTS:

The tallest monolith of the Pine Flat dam is selected for nonlinear dynamic analysis including dam–reservoir–foundation interaction and considering the effect of massed foundation model and radiation damping on the seismic response of the system. This particular dam was used because it was the subject of numerous experimental and theoretical studies. It has a typical configuration of concert gravity dam. The crest of the dam is 560m long and the height of the tallest monolith is 122m.

The material properties of the dam are modulus of elasticity, mass density and Poisson's ratio which are 27580MPa, 2400 kg/m^3 and 0.2, respectively.

. The tensile strength of the concrete is taken to be 2.7 MPa which is 10% of the compressive strength. Fracture energy of concrete is 250 N/m. A dynamic magnification factor of 1.2 is considered for the tensile strength and for the fracture energy. An elasto-brittle damping model in which cracked elements do not contribute to the damping matrix is considered for the analysis. The stiffness proportional Rayleigh damping of 5%, tuned fundamental frequency of the dam–foundation system, is applied on the equation of the dam–foundation system.

The finite model is used for the analysis of dam–foundation interaction. The overall model with near and far fields and the discretization of the near field is shown in Fig. 2 and 3, respectively.

The dam is modeled with 1984 four-node, iso-parametric elements and the foundation by additional 1320 elements. The dam as well as the foundation is in a state of plane stress. The foundation consists of a flexible layer, which extends to infinity in the horizontal direction resting on a rigid half space. The height of this layer is 1.5 time of the base of the dam body.

The modulus of elasticity, mass density and poisson's ratio of the foundation layer are taken as 13790 MPa, 2639 kg/m^3 and 0.2, respectively.

For proper modeling of the foundation layer, the foundation is truncated at about 1.5 time of the base width from each side in upstream and downstream direction of the dam, Fig. 4.

The α-method of time integration is used to solve the coupled problem [2] and the highest value of numerical damping ($\alpha = -0.2, \beta = 0.46, \gamma = 0.7, \Delta t = 0.002$) is applied for dissipating high frequency shock waves. This method is useful in structural dynamics simulations incorporating many degrees of freedoms [14].

In order to determine the hydrodynamic pressure on the dam due to horizontal ground motion under the assumption of infinite reservoir, the length of the finite element model of the reservoir is taken about 10 time of the reservoir height and Sharan boundary condition is applied on the far–end truncation boundary of the reservoir as shown in Fig.5. The depth of the reservoir is 116.88 m.

The velocity of pressure wave in water is taken 1438.66 m/sec and no absorption is considered at the reservoir bottom (the wave refection coefficient according to the reservoir bottom is assumed unity).

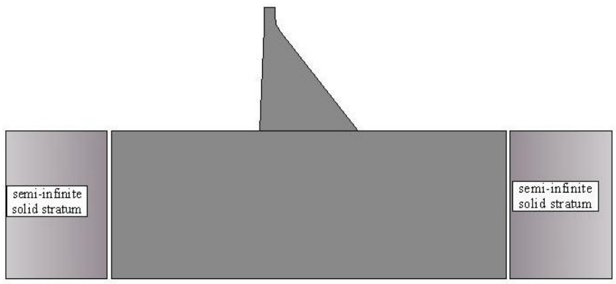


Figure 2. Dam-foundation interaction model with two semi infinite solid strata

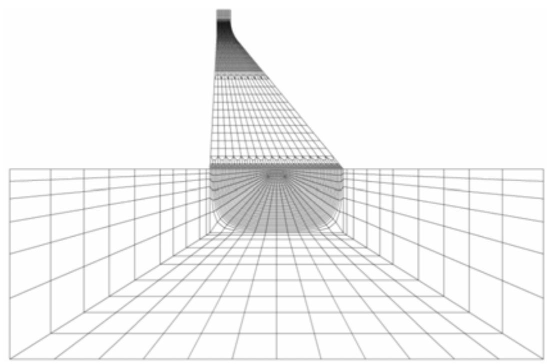


Figure 3. Finite element model of the dam-foundation system

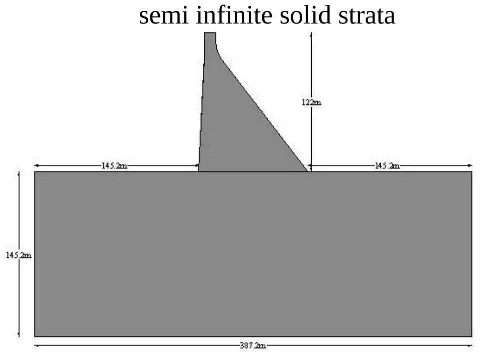


Figure 4. Dimensions of the foundation

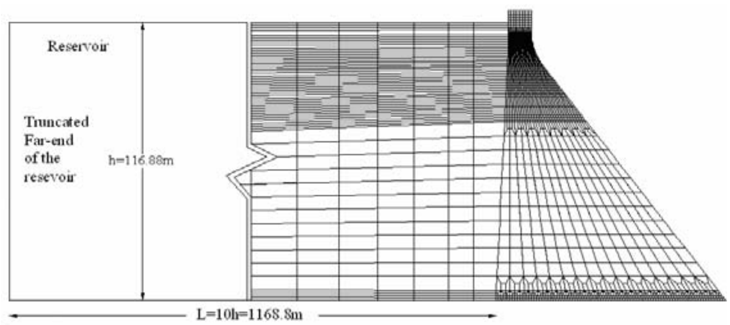


Figure 5. Finite element model of the dam-reservoir system

The horizontal earthquake component recorded in Kern County site (PGA=0.179g) shown in Fig. 6 is used to excite the dam–reservoir–foundation system. In order to develop cracking in the dynamic analysis, according to the type of the model, the earthquake time history is scaled by factors of 1.5 and 2.8 (PGA=0.27, 0.50).

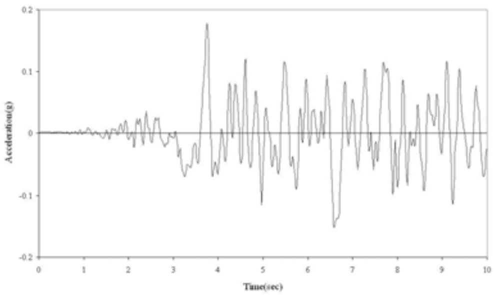


Figure 6. First 10 sec of the horizontal earthquake component recorded in Kern County site due to Taft Lincoln earthquake on 21 July 1959.

4.1. Mass-less Foundation Model:

The dam–foundation interaction effects are typically presented by a “standard” mass-less foundation model [14]. In this case, it is assumed that the displacement at the bottom of the foundation vanishes and roller supports is placed at the vertical sides of the foundation.

The analysis was performed with the earthquake record scaled by a factor of 1.5. If the dam–foundation interaction effects are considered by a “standard” mass-less foundation, only flexibility and structural dumping of the foundation are applied but its inertia and radiation damping are ignored [16,17].

Fig. 7 shows the time history of the dam crest displacement. The energy balance error of dam is shown in Fig. 8. The cracked configuration of the dam–foundation system for the earthquake record scaled by a factor of 1.5 is shown in Fig. 9 at different times.

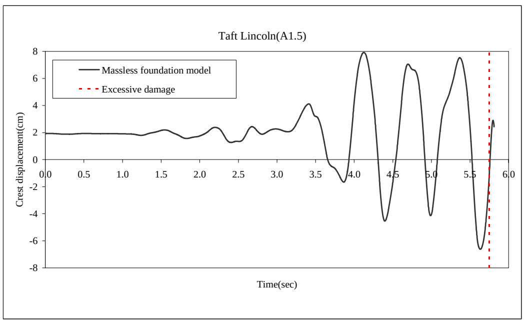


Figure 7. The time history of the horizontal dam crest displacement for mass-less foundation model

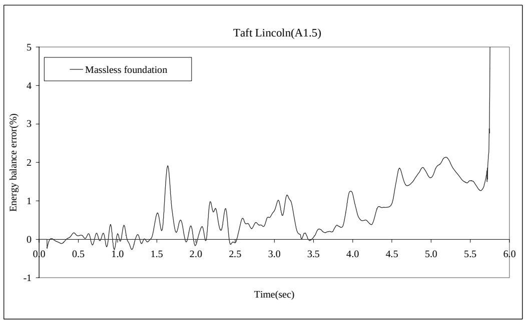
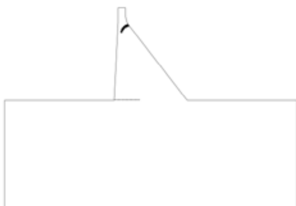


Figure 8. Energy balance error due to Taft earthquake record scaled by a factor of 1.5 for mass-less foundation model

a) Initiation of crack profile at the heel of the dam at t=3.332 sec

b) Propagation of crack profile at the heel of the dam at t=4.138 sec

c) Initiation of crack profile at the top of the dam at t=4.978 sec



d) Occurrence of excessive damage at the dam body at t=5.70 sec

Figure 9. The cracked configuration of dam-foundation system at different times due to Taft earthquake record scaled by factor of 1.5 for mass-less foundation model

4.2. Lysmer Model:

In this case for modeling the radiation damping on the far–end boundary of the massed foundation, 2- node elements as boundary elements are used to apply the lumped dashpot on the far–end nodes of the massed foundation model. The viscous boundary condition is applied on the far–end boundary of the foundation to prevent the wave reflection form the artificial boundary of the infinite media in finite element analysis.

As shown in Fig. 10, in comparison with mass-less foundation model, the time history of the dam crest displacement in horizontal direction reduces. The dam response to the Taft earthquake record scaled by a factor of 1.5 indicated no damage at the part of the dam and the solution remained stable. The energy balance error of the dam is shown in Fig. 11. It can bee seen that for the earthquake record scaled by a factor of 1.5, the maximum error remains less than 5% and the excessive damage does not occur. The cracked configuration of the dam–foundation system for the earthquake record scaled by a factor of 1.5 is shown in Fig. 12.

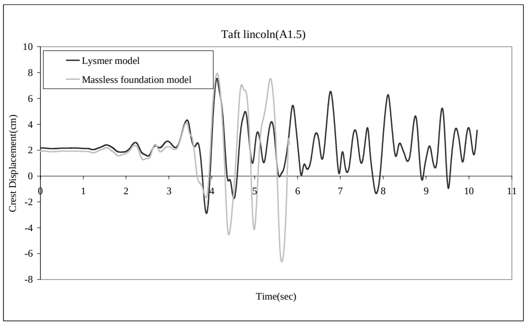


Figure 10. The time history of the horizontal dam crest displacement for mass-less foundation and Lysmer models

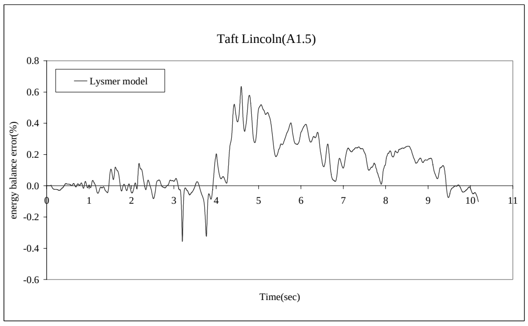


Figure 11. Energy balance error due to Taft earthquake record scaled by a factor of 1.5 for Lysmer model

a) Initiation of crack profile at the heel of the dam at t=3.328 sec

b) Propagation of crack profile at the heel of the dam at t=4.228 sec

Figure 12. The cracked configuration of dam-foundation system at different times due to Taft earthquake record scaled by factor of 1.5 for Lysmer model

The analysis was then conducted with the earthquake scaled by a factor of 2.8. The time history of the dam crest displacement in horizontal direction is shown in Fig. 13. The energy balance error of dam is shown in Fig. 14. As shown before excessive damage occurs at time of approximately 4.65 sec. the maximum error remains less than 5%. The cracked configuration of the dam–foundation system is shown in Fig. 15 at different times.

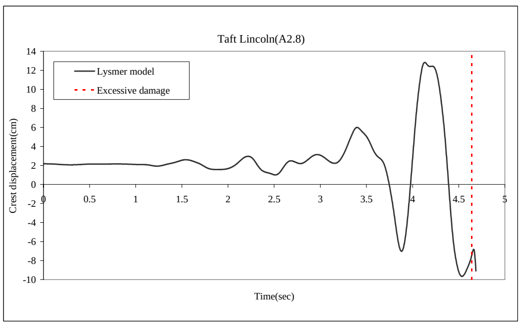


Figure 13. The time history of the horizontal dam crest displacement for Lysmer model

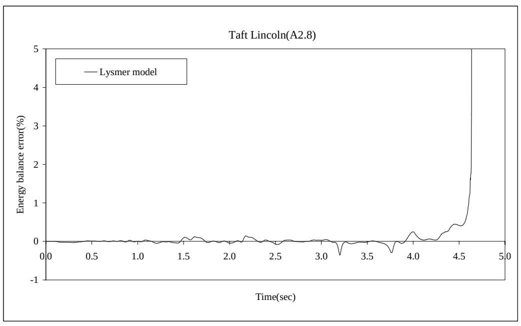


Figure 14. Energy balance error due to Taft earthquake record scaled by a factor of 2.8 for Lysmer model

a) Initiation of crack profile at the heel of the dam at t=3.264 sec

b) Initiation of crack profile at the toe of the dam at t=3.808 sec

c) Initiation of crack profile at the top of the dam at t=3.878 sec

d) Entrance of crack profile in to the foundation of the dam at t=4.088 sec

e) Propagation of crack profile at the heel of the dam at t=4.20 sec

f) Occurrence of excessive damage at the dam body at t=4.65 sec

Figure 15. The cracked configuration and deformation of dam-foundation system at different times due to Taft earthquake record scaled by factor of 2.8 for Lysmer model

4.3. Foundation Modulus of Elasticity Effect:

In order to investigate the effect of the foundation modulus of elasticity, E_f, on dynamic response of the dam-reservoir-foundation system, three different values of E_f (as of E_c, $0.5E_c$ and $0.25E_c$) are used. The dam-foundation interaction effects are considered by Lysmer model and the analysis was performed with the earthquake record scaled by a factor of 1.5. As shown in Fig.16, increasing the modulus of elasticity of foundation leads to decrease in crest response of the dam.

Fig. 17 shows the crack profile within the dam-foundation system when analyses are performed for the three values of the foundation modulus of elasticity, E_f.

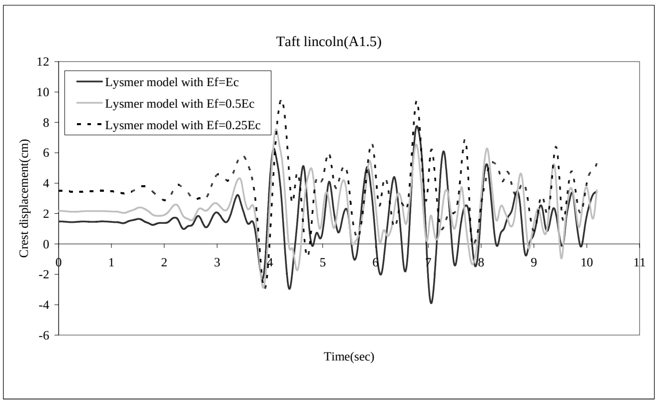


Figure 16. The time history of the horizontal dam crest displacement for Lysmer model with various foundation stiffness

a) $E_f = 0.25E_c$

b) $E_f = 0.5E_c$

c) $E_f = E_c$

Figure 17. the crack pattern predicted for Lysmer models with various foundation stiffness due to Taft earthquake record scaled by a factor of 1.5.

As shown, increasing E_f leads to increase cracked elements at the base of the dam. This conclusion is logic. When the foundation becomes more flexible, the greatest inertia load, $m\ddot{u}$, shifts from the upper portion of the dam to the lower portion. In other words, although the total inertia loads, or base shear do not vary noticeably, a considerable variation occurred in the load pattern [18].

6. CONCLUSIONS:

A nonlinear seismic fracture analysis of concrete gravity dams which includes the dam–reservoir–foundation interaction is conducted. The reservoir–structure interaction is accounted for using finite element method and coupled equations of the system are solved using the staggered displacement method. The nonlinear fracture mechanics is modeled using the smeared crack and energy radiation damping is accounted using viscous boundary conditions applied on the far–end boundary of the massed foundation.

In the case of the studied dam, it was found that the results obtained from the model with mass-less foundation is too conservative. If the foundation material and radiation damping were ignored, it could lead to an erroneous conclusion that an existing dam may be unsafe. Therefore, modeling massed foundation including radiation damping leads to a reduction in response and decreases crack profiles significantly. Finally dynamic finite element analysis results incorporating dam-foundation rock interaction are dependent on the dam and foundation modulus used in the analysis.

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