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Seismic response of concrete gravity dam-ice covered reservoir-foundation interaction systems

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Abstract. This paper examines the ice cover effects on the seismic response of concrete gravity dam-reservoir-foundation interaction systems subjected to a horizontal earthquake ground motion. ANSYS program is used for finite element modeling and analyzing the ice-dam-reservoir-foundation interaction system. The ice-dam-reservoir interaction system is considered by using the Lagrangian (displacement-based) fluid and solid-quadrilateral-isoparametric finite elements. The Sarıyar concrete gravity dam in Turkey is selected as a numerical application. The east-west component of Erzincan earthquake, which occurred on 13 March 1992 in Erzincan, Turkey, is selected for the earthquake analysis of the dam. Dynamic analyses of the dam-reservoir-foundation interaction system are performed with and without ice cover separately. Parametric studies are done to show the effects of the variation of the length, thickness, elasticity modulus and density of the ice-cover on the seismic response of the dam. It is observed that the variations of the length, thickness, and elasticity modulus of the ice-cover influence the displacements and stresses of the coupled system considerably. Also, the variation of the density of the ice-cover cannot produce important effects on the seismic response of the dam.

Keywords: concrete gravity dam; ice cover; fluid-structure interaction; earthquakes response; finite element method; Lagrangian approach.

1. Introduction

Seismic behavior of concrete gravity dams during earthquakes have been investigated by considering fluid-structure-soil interaction because of the fact that the reservoir and foundation soil significantly affect the dynamic response of the gravity dams. The dynamic analyses of concrete dams considering the dam-reservoir-foundation interactions were represented in prior studies (Chopra and Chakrabarti 1981, Wilson and Khalvati 1983, Calayır *et al.* 1996, Bayraktar *et al.* 1996, Bayraktar *et al.* 2005a, b, Bayraktar *et al.* 2008, Zhu *et al.* 2010).

Ice sheets can damage the dam-reservoir interaction system located in cold areas. In the winter cold season, the thickness of the ice cover on reservoir of the dams ranges from 1 m to 2 m. To illustrate the effect of ice cover on the dynamic behavior of dam-reservoir system, only a few

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studies relating to the ice-cover-dam interaction problem were presented. Paultre *et al.* (2002) carried out an extensive forced vibration testing on a concrete gravity dam. Acceleration and hydrodynamic frequency responses were obtained in different locations on the dam and in the reservoir. A comparison of the results in summer and winter showed the effects of the ice-cover on the dynamic response of the dam-reservoir-foundation systems. Bouaanani *et al.* (2002) developed a two-dimensional numerical model to determine the effects of the presence of an ice-cover on the dynamic behavior of large gravity dams. Numerically predicted frequency curves for acceleration and hydrodynamic pressure in the reservoir were compared with those obtained experimentally. The computations showed that the agreement between the predicted and measured results is satisfactory. Bouaanani *et al.* (2004a, b) presented mathematical modeling as well as parametric and numerical studies concerning the dynamic response of a concrete dam with an ice covered reservoir. In these studies, a frequency domain substructure method was used and a new boundary condition along the ice-cover-reservoir interface was proposed. In addition to these investigations, Bouaanani and Paultre (2005) proposed a new boundary condition accounting for energy radiation at the far end of the covered reservoir. The boundary condition was investigated through analysis of the hydrodynamic pressure using boundary element modeling (BEM). Finally, Fuamba *et al.* (2007) developed a numerical formulation to model the wave propagation and hydrodynamic pressure in partially covered channels. Hacıefendioğlu *et al.* (2009) predicted the stochastic response of concrete gravity dams to multi-support seismic excitation including ice-dam-reservoir-foundation interaction. The study showed that the ice cover influenced the stochastic response of concrete gravity dam. Hacıefendioğlu (2009) also investigated the effects of ice cover on the stochastic response of concrete faced rockfill (CFR) when subjected to spatially varying ground motions.

The researches on the dynamic behavior of concrete dam-foundation impounding the ice covered reservoir systems are very limited. The presented paper aims to investigate the effects of ice-cover on the dynamic response of dam-reservoir-foundation interaction system subjected to an earthquake ground motion by using the finite element method. The dynamic analyses of the Sarıyar dam to Erzincan earthquake are done by considering different cases of ice-cover. Also, the effects of variations in the length, thickness, elasticity modulus and density of the ice-cover on the displacements and stresses of the coupled system are investigated.

2. Formulation

In this section, the finite element formulation of fluid systems based on Lagrangian approach, the formulation of dynamic analysis of fluid-structure interaction systems including ice cover and solution of this equation are given.

2.1 Formulation of dynamic response of fluid-structure systems

The formulation of the fluid system is presented according to the Lagrangian approach (Wilson and Khalvati 1983). In this approach, fluid is assumed to be linearly elastic, compressible, inviscid and irrotational. Two dimensional stress strain relationships of this fluid are given by

$$\begin{Bmatrix} P \\ P_z \end{Bmatrix} = \begin{bmatrix} \beta & 0 \\ 0 & \alpha_z \end{bmatrix} \begin{Bmatrix} \varepsilon_V \\ w_z \end{Bmatrix} \qquad (1)$$

where P is pressure, β is the bulk modulus of the fluid, and ε_v is the volumetric strain. w_z is rotation around axis z and P_z and α_z are the stress and constraint parameter related with w_z, respectively.

In this study, the equations of motion of the fluid system are obtained using energy principles. Using the finite element approximation, the potential energy of the fluid system may be written as

$$\pi_e = \frac{1}{2} u_f^T K_f u_f \tag{2}$$

where K_f and u_f are the stiffness matrix and the nodal displacement vector of fluid system, respectively.

An important behavior of fluid systems is the ability to displace without a change in volume. For reservoir and storage tanks, this movement is known as sloshing waves in which the displacement is in the vertical direction. Using the finite element method, the free surface potential energy is expressed in terms of the vertical node displacements at the free surface as

$$\pi_s = \frac{1}{2} u_{fs}^T S_f u_{fs} \tag{3}$$

where S_f and u_{fs} are the free surface stiffness matrix and the free surface vertical displacement vector of the fluid system, respectively.

Total potential energy can be obtained by summing Eqs. (2) and (3)

$$\pi_t = \pi_e + \pi_s \tag{4}$$

Finally, the kinetic energy of the fluid system must be considered to complete the energy contributions. This energy is given by

$$T = \frac{1}{2} \dot{u}_f^T M_f \dot{u}_f \tag{5}$$

where M_f and $\dot{u}_f$ are the mass matrix and the nodal velocity vector of the fluid system, respectively. Equation of motion can be obtained substituting the expressions for the potential and kinetic energies into Lagrange's equation (Clough and Penzien 1993) which are given as

$$\frac{\partial}{\partial t}\left(\frac{\partial T}{\partial q_i}\right) - \left(\frac{\partial T}{\partial q_i}\right) + \frac{\partial \pi_t}{\partial q_i} = Q_i \qquad (i = 1, \ldots, n) \tag{6}$$

where q_i and Q_i represent the generalized coordinate and force, respectively. The direct application of Lagrange's equation yields the following set of equations

$$M_f \ddot{u}_f + K_f^* u_f = F_f \tag{7}$$

where K_f^* and F_f are the system stiffness matrix including the free surface stiffness and time-varying nodal forces vector for the fluid system, respectively.

The equations of motion of the fluid system, Eq. (7), have a similar form with those of the structure system. To obtain the coupled equations of the fluid-structure system (ice-reservoir-dam-foundation system), the determination of the interface condition is required. Because the fluid is assumed to be inviscid, only the displacements in the normal direction to interfaces are continuous at the ice, dam and foundation interfaces.

Using the interface conditions, the equations of motion governing the linear dynamic response of the ice-reservoir-dam-foundation system subjected to ground motion including damping effects are given by

$$(M_s + M_f + M_{ice})\ddot{u}_c(t) + C_c\dot{u}_c(t) + (K_s + K_f^* + K_{ice})u_c(t) = -(M_s + M_f + M_{ice})\delta\ddot{u}_g(t)$$

or

$$M_c\ddot{u}_c(t) + C_c\dot{u}_c(t) + K_c u_c(t) = -M_c\delta\ddot{u}_g(t) \quad (8)$$

where M_s, M_{ice} are the mass matrices of the dam-foundation and ice-cover finite element systems and K_s, K_{ice} represent the stiffness matrices of the dam-foundation and ice-cover finite element systems. Also, M_c, C_c, and K_c are the mass, damping and stiffness matrices for the coupled system, respectively. $u_c(t), \dot{u}_c(t)$, and $\ddot{u}_c(t)$ are the vectors of the displacement, velocity, acceleration of the coupled system, respectively. δ is the earthquake influence vector.

2.2 Solution of coupled system equation

The matrix equation of motion with linear stiffness under earthquake excitation for coupled system given in Eq. (8) can be solved by using the Newmark Method.

The damping matrix is proportional the mass and stiffness matrices as seen in below

$$C_c = \hat{\alpha}M_c + \hat{\beta}K_c \qquad \hat{\alpha} = \frac{2\omega_i\omega_j(\xi_i\omega_j - \xi_j\omega_i)}{\omega_j^2 - \omega_i^2} \qquad \hat{\beta} = \frac{2(\xi_j\omega_j - \xi_i\omega_i)}{\omega_j^2 - \omega_i^2} \quad (9)$$

where ω_i, ω_j angular frequencies of i and j, and ξ_i, ξ_j are two values of damping for the i and j normal modes of vibration, respectively.

The final expression of equation of motion with linear behavior obtained by substituting the required parameters when the structure is subjected to an earthquake ground motion and equations into Eq. (8) leads the following relationships

$$\tilde{q}_{k+1} = \tilde{F}_N\tilde{q}_k + \tilde{H}_N^{(EQ)}a_{k+1} \quad (10)$$

where $\tilde{q}_k = \{u_k \ \dot{u}_k \ \ddot{u}_k\}^T$. The $\tilde{F}_N$ and $\tilde{H}_N^{(EQ)}$ matrices are functions of the time, and these matrices are computed at each time step. a_{k+1} is the acceleration record of earthquake ground motion at time step $k+1$.

$\tilde{F}_N$ and $\tilde{H}_N^{(EQ)}$ matrices are given as

$$\tilde{F}_N = \begin{bmatrix} I - \hat{\alpha}B^{-1}K_c(\Delta t)^2 & I(\Delta t) - \hat{\alpha}B^{-1}C_c(\Delta t)^2 - \hat{\alpha}B^{-1}K_c(\Delta t)^3 & \left(\frac{1}{2} - \hat{\alpha}\right)I(\Delta t)^2 - \hat{\alpha}B^{-1}G(\Delta t)^2 \\ -\hat{\alpha}B^{-1}K_c(\Delta t) & I - \delta B^{-1}C_c(\Delta t) - \delta B^{-1}K_c(\Delta t)^2 & (1-\delta)I(\Delta t) - \delta B^{-1}G(\Delta t) \\ -B^{-1}K_c & -B^{-1}C_c - B^{-1}K_c(\Delta t) & -B^{-1}G \end{bmatrix} \quad (11)$$

$$\tilde{H}_N^{(EQ)} = -\begin{bmatrix} \hat{\alpha}(\Delta t)^2 B^{-1} M_c \\ \delta(\Delta t) B^{-1} M_c \\ B^{-1} M_c \end{bmatrix} \tag{12}$$

where I is a unit matrix, and $\hat{\alpha}, \delta$ presents numerical solution method constants, respectively. Matrices in Eq. (9) and Eq. (10) require the inversion of the B matrix at each time step and it is given as below (Hart and Wong 1999).

$$B = M_c + \delta(\Delta t) C_c + \hat{\alpha}(\Delta t)^2 K_c \tag{13}$$

Also, G matrix can be expressed as

$$G = (1-\delta) C_c(\Delta t) + \left(\frac{1}{2} - \hat{\alpha}\right)(\Delta t)^2 K_c \tag{14}$$

In summary, the procedure for computing the response at time step $k+1$ considering all of the information at time step k and a_{k+1} is obtained using Eq. (10).

3. Numerical example

The Sarıyar concrete gravity dam constructed on Sakarya River, which is located 120 km in the northwest of Ankara, Turkey, is selected as an application. The dimensions of the dam including ice-cover are given in Fig. 1. There are two unknown displacements at each nodal point in the ice-cover, dam, reservoir and foundation finite element model. The fluid is assumed to be inviscid and compressible in this study. There is a need to include damper elements at the far ends of the foundation and the upstream reservoir to avoid reflection of seismic waves from the rigid boundaries. In this study, instead of using damper elements at the far boundaries, a large reservoir is taken into account to obstruct the wave reflections from the boundaries. Therefore, the-reservoir length in the upstream direction is taken as three times of the dam height, and the height of the

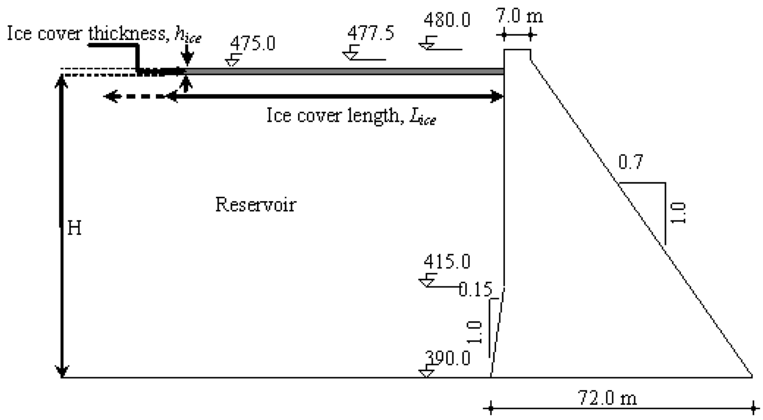


Fig. 1 The dimensions of the Sarıyar concrete gravity dam including ice-cover

foundation is taken as dam height (Calayır and Dumanoglu 1993, Bayraktar *et al.* 2005). Reservoir height is 85 m and the reservoir depth is assumed to be constant. For the dam, the elasticity modulus, the unit weight and Poisson's ratio are taken as 3.5×10^{10} N/m^2, 2.4×10^4 N/m^3, 0.20, respectively. Elasticity modulus and Poisson's ratio of the foundation are 2.10×10^{10} N/m^2 and 0.30, respectively. For the reservoir, the bulk modulus and the mass density of water are taken as 2.07×10^{9}N/m^2, 1000 kg/m^3, respectively. A damping ratio of 5% is adopted for dam-reservoir interaction system.

In the absence of adequate experimental data, the material properties of the ice were taken directly from the literature. In order to compare the effect of variability of the ice mechanical properties on the seismic behavior of the dam-reservoir interaction system, its average elasticity modulus, mass density, and Poisson's ratio are taken as $E_{iceo} = 9.5 \times 10^9$ N/m^2, $\rho_{iceo} = 910$ kg/m^3 and $\upsilon_{iceo} = 0.30$, respectively (Gold and Krausz 1971, McCullough *et al.* 1996, Michel 1978, Michel and Ramseier 1969).

4. Model for ice-dam-reservoir-foundation system

A finite element program is used to model the ice-dam-reservoir-foundation system as shown in Fig. 2. The dam concrete, ice, water in reservoir and foundation are assumed to have a linear, isotropic, homogeneous behavior. Therefore, non-linear phenomena such as material cracking and water cavitation are not considered in this study. The common objection to taking the effect of the ice cover in dam safety analyses for seismic events is that the ice cover is expected to be cracked and disbonded when, or very soon after, the event starts. However, for the present research, the ice cover stays coupled to the dam throughout the interaction during the seismic excitation. In order to model the ice-dam-reservoir-foundation interaction system and compute the seismic behavior of this coupled system under seismic excitation, the finite element structural analysis program ANSYS (2003) is used in this study. The ice-cover, dam and foundations are represented by plane-strain elements, and the reservoirs are represented by fluid elements in all dam models. Plane42 element is

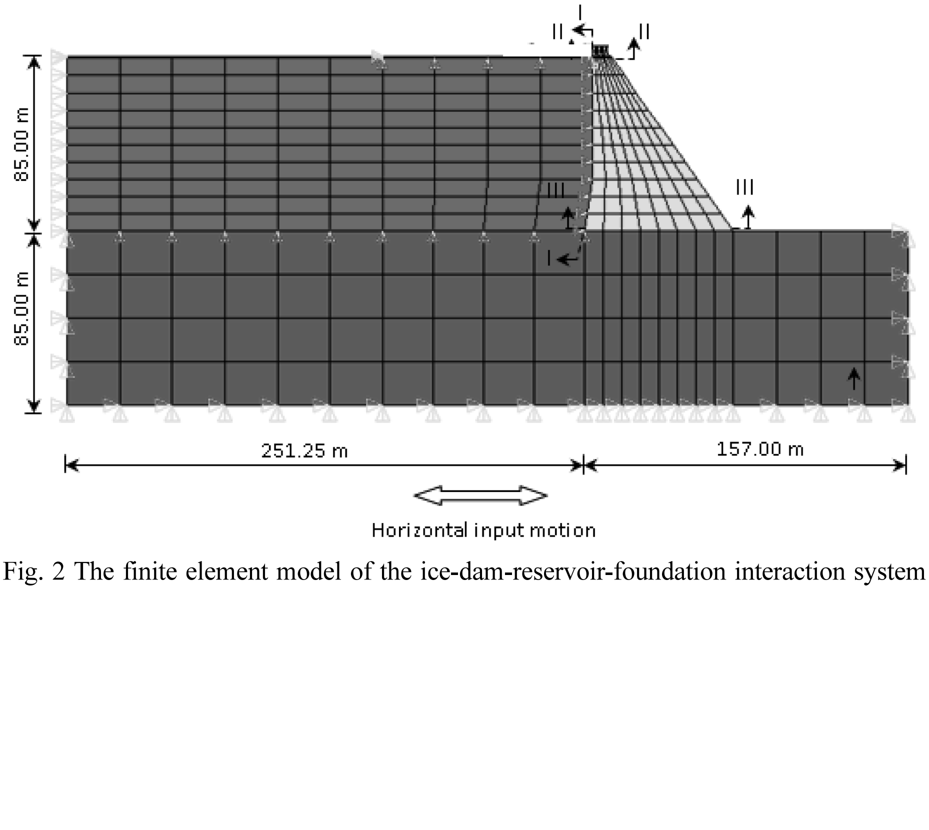


Fig. 2 The finite element model of the ice-dam-reservoir-foundation interaction system

used in the modeling of the ice cover, dam and foundation, and Fluid79 element is used in the modeling of the reservoir of the dam.

In the seismic analyses of the ice-dam-reservoir-foundation system, to avoid reflection of the outgoing earthquake waves, foundation finite elements are assumed to be massless. The dynamic interaction between the ice cover and reservoir can be rigorously modeled by applying the appropriate boundary conditions along the ice-reservoir interface. The derivation of this boundary condition, described in detail Bouaanani *et al.* (2004a), includes the effect of possible damping at the ice-reservoir interface represented by the viscous damping term. The damping coefficient is neglected in this study because of the lack of experimental information about it. At the reservoir-dam, reservoir-foundation and ice-cover-reservoir interfaces, length of coupling element is chosen as 0.001m. Main objective of the couplings are to hold equal the displacements between two reciprocal nodes. The spring element is also used to couple the ice block to the dam body.

5. Discussions

In order to evaluate the effect of the ice cover on dynamic behavior of the dam-reservoir-foundation system to earthquake seismic excitation, a parametric study is performed for various values of the length of the ice cover, L_{ice}, the thickness of the ice-cover, h_{ice}, the modulus of elasticity of the ice-cover, E_{ice} and finally its density, ρ_{ice}. The finite element model of the coupled system given in Fig. 2 is used here, and E-W component of the Erzincan earthquake (Fig. 3) is applied to the coupled system in the horizontal direction.

5.1 Effect of the length of the ice cover

To illustrate the effect of the ice-cover length on the displacements and stresses of the dam-reservoir-foundation interaction system, the ice-cover length was chosen as $0.50L_{iceo}$, $0.75L_{iceo}$ and $1.50L_{iceo}$ (L_{iceo} = 100 m). For these three cases, the thickness, elasticity modulus and mass density of the ice cover are taken as constant, which are h_{ice} = 1.00 m, E_{ice} = 9.5 × 10^9N/m^2, ρ_{ice} = 910 kg/m^3, respectively.

The absolute maximum horizontal displacement values obtained in Section I-I of the dam to the seismic excitation, for without ice-cover and different ice-cover lengths are plotted in Fig. 4. As seen from this figure, the displacements calculated without ice-cover have the largest values. It is also observed that an increase of L_{ice} from $0.50L_{iceo}$ to $1.50L_{iceo}$ cause decreasing in the displacement values obtained in Section I-I. Unexpected displacement behaviors have emerged at the end of each analysis for the ice length. When investigating the reason for this, it may be interpreted that the ice

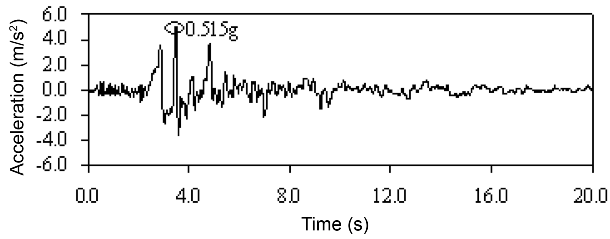


Fig. 3 Acceleration record of the east-west component of 13 March 1992 Erzincan Earthquake, Turkey

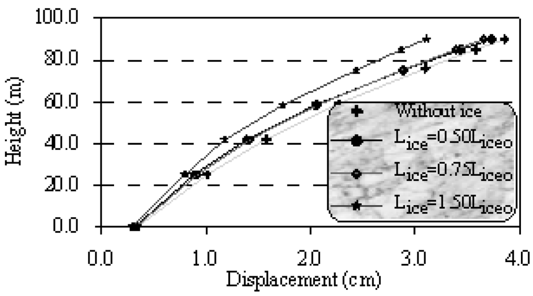
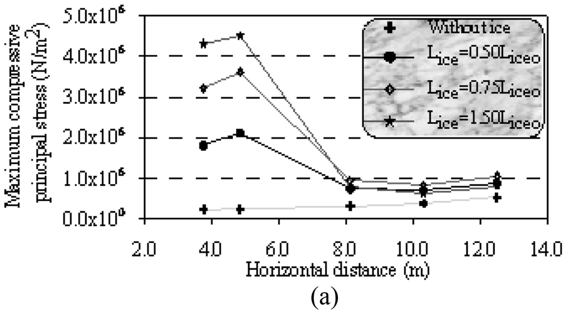


Fig. 4 Effect of the length of the ice-cover on the horizontal displacements in Section I-I



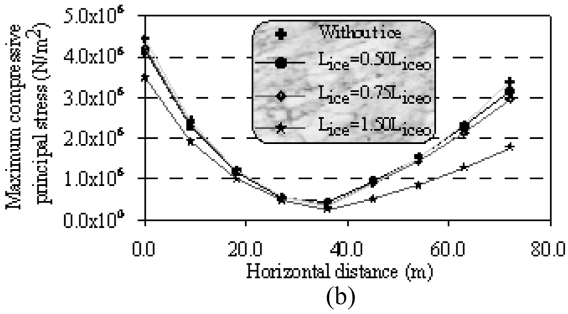


Fig. 5 Effect of the length of the ice-cover on the maximum compressive principal stresses in (a) Section II-II and (b) Section III-III, respectively

length increases the impact speed of the ice cover on the dam surface decreases. This will cause that the lower displacements occur on the upstream face of the dam. Using the three different ice-cover lengths and without ice-cover mentioned above, the absolute maximum compressive principal stress values in Section II-II and Section III-III of the dam-reservoir-foundation system are illustrated in Figs. 5(a-b). Fig. 5(a) reveals that the stress values in Section II-II increase considerably with increasing the length of the ice cover. It can also be seen that the stresses in Section II-II for without ice-cover have the smallest values. The displacements are slightly reduced by the ice-cover (Fig. 4). However, the principle stress on the upstream face of the dam has a dramatic increase (Fig. 5). This response is caused by the stress concentration. Figs. 6(a-d) show that compressive principal stress contours at the moment that maximum stress occurs at Point A, which representing the junction between the ice-cover and upstream face of the dam for without ice-cover and with ice-cover for $0.50L_{iceo}$, $0.75L_{iceo}$ and $1.50L_{iceo}$ (L_{iceo} = 100 m). It can be observed from these figures that the ice-cover considerably creates a stress concentration at Point A. The crest displacement obtained for without ice-cover case is %19.00, %5.00 and %3.37 larger than those obtained for $1.50L_{iceo}$, $0.75L_{iceo}$, and $0.50L_{iceo}$, respectively. The similar interpretations can be made for the stress values at the node representing the junction between the ice-cover and upstream face of the dam. The stress values obtained for $1.50L_{iceo}$ is %26.00, %58.00 and %95.00 larger than those obtained for $0.75L_{iceo}$, $0.50L_{iceo}$ and without ice cover case, respectively. The stress values in Section III-III (Fig. 5(b)) (bottom face of the dam) slightly decrease with increasing the length of the ice-cover. In this section, it can also be seen that the stresses for without ice-cover case have the largest values.

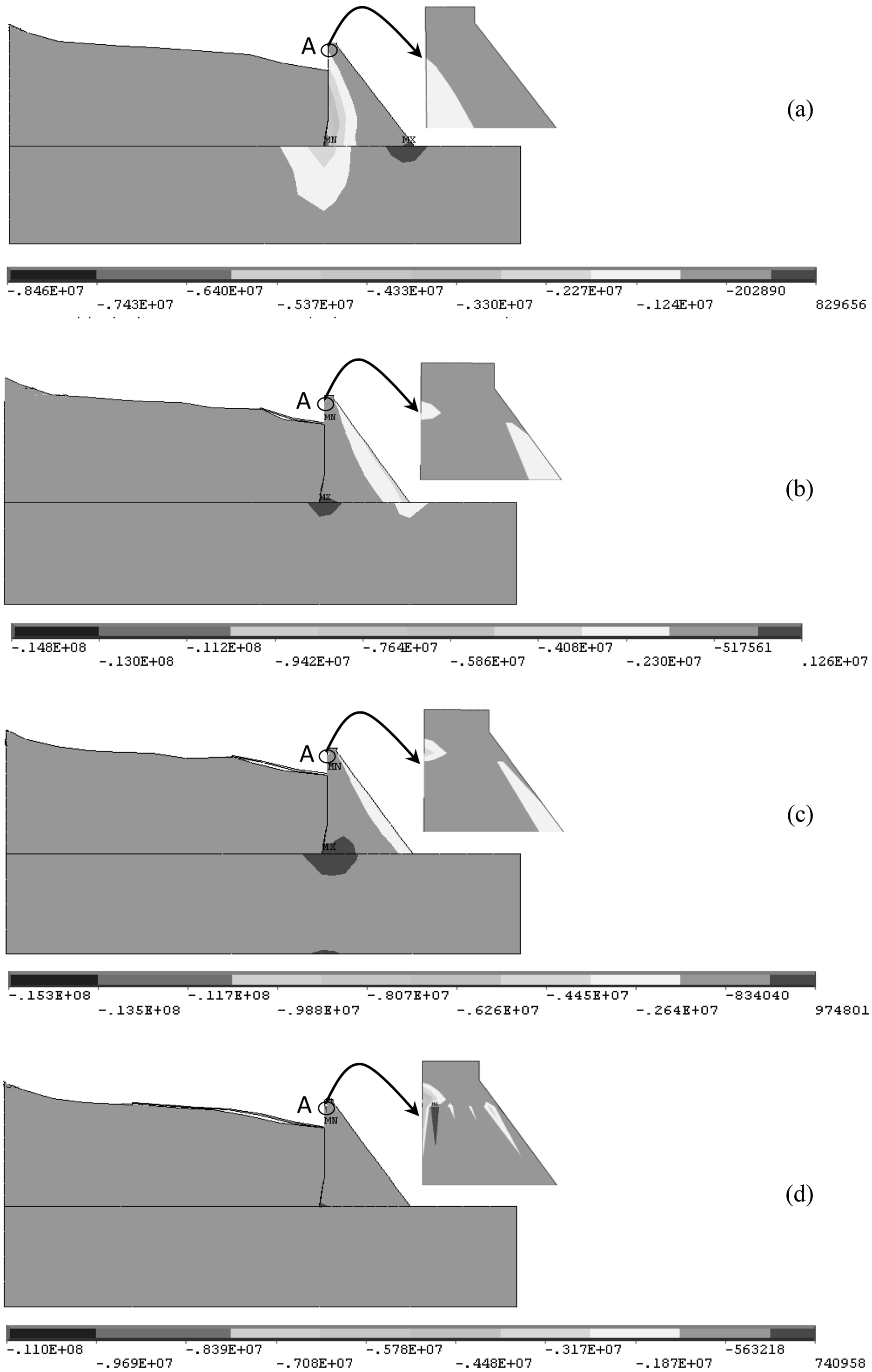


Fig. 6 The stress contours of compressive stress at the moment that maximum stress occurs at Point A, for without ice-cover and with ice-cover for $0.50L_{iceo}$, $0.75L_{iceo}$ and $1.50L_{iceo}$

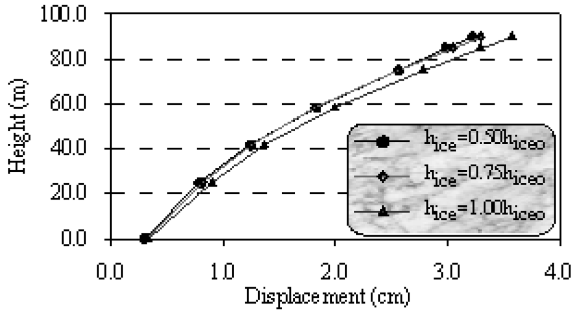


Fig. 7 Effect of the thickness of the ice-cover on the horizontal displacements in Section I-I

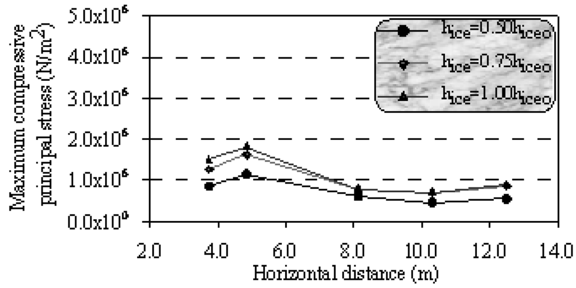


Fig. 8 Effect of the thickness of the ice-cover on the maximum compressive principal stresses in Section II-II

5.2 Effect of the thickness of the ice cover

Three different cases are considered in the finite element model of the coupled system (Fig. 2) in order to appraise the effect of the thickness of the ice-cover on the displacements and stresses. The displacements and stresses are calculated for the variation in h_{ice} from $0.50h_{iceo}$ to $1.00h_{iceo}$ (h_{iceo} = 1.00 m). For the ice-cover, the length (L_{ice}) is 100 m, elasticity modulus is 9.5×10^9 N/m^2 and mass density (ρ_{ice}) is 910 kg/m^3.

The effects of the variation in h_{ice} on distributions of the displacement values on Section I-I and stress values on Section II-II are illustrated in Figs. 7-8. These distributions indicate that an increase in h_{ice} causes increase in the displacement and stress values. The crest displacement for $1.00h_{iceo}$ is %10.00 and %8.00 larger than those for $0.50h_{iceo}$ and $0.75h_{iceo}$, respectively. The similar interpretations can be made for the stress values at the node representing the junction between the ice cover and upstream face of the dam. The stress values for $1.50h_{iceo}$ are %43.00 and %15.00 larger than those of $0.50h_{iceo}$ and $0.75h_{iceo}$, respectively.

5.3 Effect elasticity modulus of the ice-cover

The effect of variations of the elasticity modulus of the ice-cover on the displacements in Section

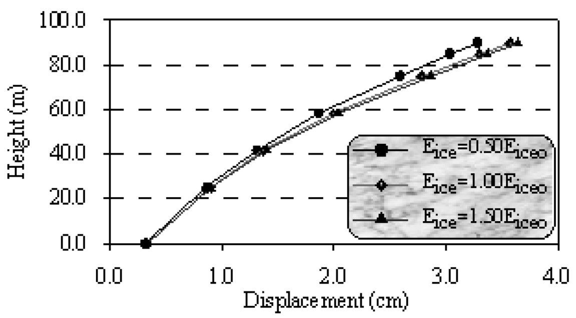


Fig. 9 Effect of the modulus of elasticity of the ice-cover on the horizontal displacements in Section I-I

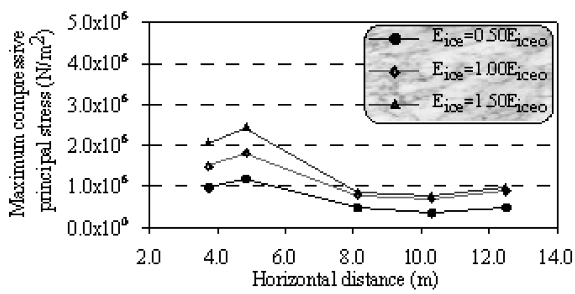


Fig. 10 Effect of the modulus of elasticity of the ice-cover on the maximum compressive principal stresses in Section II-II

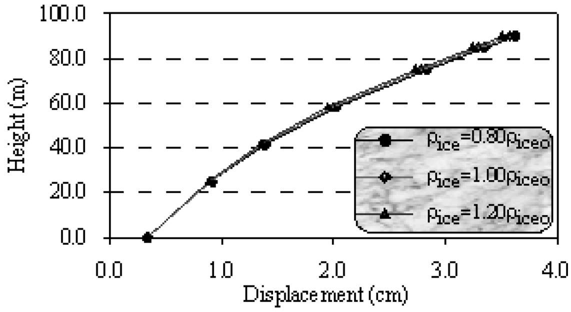


Fig. 11 Effect of the mass density of the ice-cover on the horizontal displacements in Section I-I

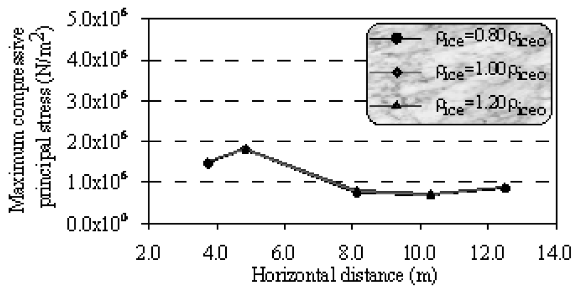


Fig. 12 Effect of the mass density of the ice-cover on the maximum compressive principal stresses in Section II-II

I-I and stresses in Section II-II is examined in this section. The elasticity modulus of the ice-cover was chosen as $0.50E_{iceo}$, $1.00E_{iceo}$ and $1.50E_{iceo}$ ($E_{iceo} = 9.5 \times 10^9$ N/m^2). For the ice-cover, the length (L_{ice}) is 100 m, the thickness (h_{ice}) is 1.00m and mass density (ρ_{ice}) is 910 kg/m^3.

The variations of the displacements in Section I-I and stresses in Section II-II according to the elasticity modulus of the ice-cover are illustrated in Figs. 9-10. It is shown from these figures that the displacements and stresses increase with increasing the elasticity modulus of the ice-cover. The crest displacement obtained for $1.50E_{iceo}$ is %10.00 and %2.00 larger than those obtained for $0.50E_{iceo}$ and $1.00E_{iceo}$, respectively. At the node representing the junction between the ice cover and upstream face of the dam, the stress values obtained for $1.50E_{iceo}$ is %53.00 and %28.00 larger than those obtained for $0.50E_{iceo}$ and $1.00E_{iceo}$, respectively.

5.4 Effect of the mass density of the ice cover

In this section, it is focused on the effect of the mass density of the ice cover on the dynamic response of the coupled system. The mass densities of ice are selected as $0.80\rho_{iceo}$, $1.00\rho_{iceo}$ and $1.20\rho_{iceo}$ (ρ_{iceo} = 910 kg/m^3). For the three cases, the thickness, length, elasticity modulus of the ice-cover are taken as constant, which are h_{ice} = 1.00 m, L_{ice} = 100 m, $E_{ice} = 9.5 \times 10^9$ N/m^2, respectively.

Fig. 11 and Fig. 12 illustrate the displacements obtained in Section I-I and stresses obtained in Section II-II. These figures plotted according to the mass density of the ice cover indicate that variations in ρ_{ice} do not have significant effect on the dynamic response of the coupled system. As seen from these figures, both the displacement and stress values are close to each other for each analysis case, separately. However, when these figures are evaluated in detail, it can be find that while the displacement values decrease slightly with increasing the mass density of the ice-cover, the stress values increase with increasing the mass density of the ice-cover. The crest displacement obtained for $0.80\rho_{iceo}$ is %1.65 and %3.31 larger than those for $1.00\rho_{iceo}$ and $1.20\rho_{iceo}$, respectively. At the node representing the junction between the ice-cover and upstream face of the dam, the stress values obtained for $1.20\rho_{iceo}$ is %3.63 and %1.39 larger than those for $1.00\rho_{iceo}$ and $0.80\rho_{iceo}$, respectively.

6. Conclusions

The main objective of this study is to investigate the effect of the ice cover on the seismic response of concrete gravity dams when subjected to horizontal earthquake ground motion. For this purpose, the ice-dam-reservoir-foundation interaction system is modeled by the finite element method. A parametric study is conducted to investigate the influence of various values of the length, thickness, elasticity modulus and density of the ice-cover on the displacements and stresses in the dam separately. It can be clearly concluded that the ice-cover affects the seismic response of the dam-reservoir-foundation interaction system. The displacement values decrease with increasing length of the ice cover, whereas the displacements increase with increasing the thickness and elasticity modulus of the ice-cover. In addition to these, the stress values increase with increasing the length, thickness, elasticity of the ice-cover. Moreover, the variation of the density of the ice cover does not significantly influence the displacements and the stress values of the coupled system.

The seismic response of concrete gravity dams to earthquake ground motion is affected by several factors including the intensity and characteristics of the earthquakes, the interaction between dam-foundation soil-reservoir water-ice cover, computer modeling and material properties of each section. To generalize the results, solutions should be obtained for many earthquake ground motions and different concrete gravity dam models, and the results should be evaluated together.

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