Influence of absorptive reservoir bottom on the performance of dam–reservoir-foundation coupled system

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In this article we present the performance of concrete gravity with absorptive reservoir bottom and soil–structure–fluid interaction. A two-dimensional direct coupling methodology is presented to evaluate the performances of dam–reservoir-foundation coupled system. A reflection coefficient is introduced to simulate the reservoir bottom absorption. The fundamental frequency of reservoir has a decreasing trend with increase of reflection coefficient and the responses of individual sub-systems with different reservoir bottom depend on exciting frequency. However, this effect decreases continuously with fluid–structure and soil–structure–fluid interaction.

Keywords: Absorptive reservoir bottom, added response, coupled systems, free field response, reflection coefficient.

THE characteristics of a reservoir bottom may alter the performance of dams. In most cases, the reservoir bottom is considered as rigid and the hydrodynamic pressure on adjacent dam for such cases is quite higher. Earthquake response of dams considering water–sediment–foundation interaction was determined by Lotfi[1]. The sediment layer was assumed to be viscoelastic and almost incompressible. Some researchers modelled the reservoir bottom absorption by damping boundary condition[2–5]. Bougacha and Tassoulas[6,7] modelled the sediment at reservoir bottom as fluid-filled and poroelastic solid system to determine the response of a concrete gravity dam against sinusoidal ground excitation. Dominguez *et al.*[8] analysed a system of water, viscoelastic and fluid-filled poroelastic zones of arbitrary shapes by boundary element method. The wave equation through viscoelastic material was solved for reflection coefficient at reservoir bottom[5,9]. A procedure based on acoustic reverberation technique for measuring the overall or mean reflection coefficient at reservoir bottom was proposed by Ghanaat *et al.*[10]. Influence of sediment at the reservoir bottom on dynamic behaviour of gravity dams at different ages of concrete was studied by Gogoi and Maity[11]. Based on the scaled boundary finite element method, a semi-analytical formulation in frequency domain was proposed to obtain dam responses by considering fluid and structure interaction[12]. Hence, a precise methodology which can incorporate the effects of reservoir bottom absorption is essential.

The prediction of the performance of dams will be more realistic if fluid–structure and soil–structure interactions are considered simultaneously. Lysmer and Kuhlemeyer[13] showed the importance of considering elastic soil foundation and proposed a local absorbing boundary condition for soil domain. Yazdchi *et al.*[14] studied dam-foundation system for different impedance ratios. The results indicated that the dam–foundation interaction become significant for comparatively lower impedance ratio. A similar study on dam-foundation coupled system was carried out earlier[15]. In frequency domain, a hybrid finite and boundary element method was used to analyse the gravity dam–reservoir-foundation system[2]. On the other hand, Touhei and Ohmachi[16] used this hybrid model in time domain. Responses of dam considering fluid–structure–soil against spatially varying earthquake ground motions in frequency domain were studied by several researchers[17–19]. Bayraktar *et al.*[20] used 3D solid element to simulate dam and foundation (SOLID 45) and eight-node 3D fluid element (FLUID 80) in ANSYS to model the dam, foundation and reservoir respectively. Similarly, Papazafeiropoulos *et al.*[21] studied the performance of dam–reservoir-foundation in the finite element software ABAQUS.

It is apparent from the various studies that the effect of fluid–structure–soil system is important for accurate transient responses of concrete dam. Very few studies considered these three systems in a coupled way using standard software such as ANSYS and ABAQUS. However, the effect of absorptive reservoir bottom cannot be incorporated in such software. In the present study, a computer code in MATLAB language has been developed for responses of concrete gravity dam with absorptive reservoir bottom. The study is further extended for different excitations to observe the influence of reservoir bottom absorption with and without fluid–structure and fluid–soil–structure interaction.

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Numerical modelling

Finite element modelling of dam and soil foundation

The dynamic equilibrium equation in finite element form for dam and soil foundation can be expressed as

$$M_d\ddot{d} + C_d\dot{d} + K_d d - M_d\ddot{d}_g = 0, \tag{1}$$

where M_d, K_d and C_d are mass, stiffness and damping matrix respectively. $\ddot{d}$, $\dot{d}$ and d represent the nodal accelerations, velocities and displacements respectively and $\ddot{d}_g$ is the external acceleration. In the present study, eight node rectangular elements were used to model the dam and foundation and both were assumed to be in a state of plane strain. For structural damping, simplified Rayleigh damping was considered.

$$C_d = \alpha M_d + \beta K_d, \tag{2}$$

where α and β are constants.

Truncation boundary for soil foundation: For finite element modelling of infinite soil foundation, one of the main problems is to model the boundary domain accurately. The most commonly used absorbing boundary is presented here. The present non-reflecting boundary depends on 1D wave propagation. In discretized form, the damper coefficient c_n and c_t in normal and tangential directions may be expressed as

$$c_n = A_1 r c_p, \tag{3}$$

$$c_t = A_2 r c_s, \tag{4}$$

where r is the density. The dashpot coefficient c_s and c_p in normal and tangential directions respectively, are expressed as

$$c_s = \sqrt{G/r}, \tag{5}$$

$$c_p = \sqrt{\frac{E(1-\lambda)}{(1+\lambda)(1-2\lambda)r}}, \tag{6}$$

where shear modulus is defined by G and A_1 and A_2 are effective area along the direction of wave propagation which can be expressed for isotropic medium as

$$A_1 = \frac{8}{15P}(5+2m-2m^2), \tag{7}$$

$$A_2 = \frac{8}{15P}(3+2m). \tag{8}$$

m can be expressed as

$$m = \sqrt{\frac{(1-2l)}{2(1-l)}}. \tag{9}$$

Formulation for infinite fluid domain

The hydrodynamic pressure due to the external excitation can be expressed by eq. (10). Here, the fluid is considered to be linearly compressible, inviscid and its motion is irrotational.

$$\nabla^2 P = \frac{1}{C^2}\ddot{P}, \tag{10}$$

where C is velocity of sound through water. The solution of eq. (10) with the below given boundary conditions gives the pressure distribution within the fluid domain. The geometry of reservoir with dam and soil foundation is presented in Figure 1 *a*.

(i) Boundary 1: If the surface wave is considered, the boundary condition at free end will be

$$\frac{1}{g}\ddot{P} + \frac{\partial P}{\partial y} = 0. \tag{11}$$

(ii) Boundary 2: At the interface of dam and reservoir, the pressure gradient may be expressed as

$$\frac{\partial p}{\partial n}(0, y, t) = -\rho_f b', \tag{12}$$

where b' is ground acceleration in horizontal direction, n is normal to the surface and ρ_f is the density of fluid.

Boundary 3: The effect of absorptive reservoir bottom is determined based on the report of Hall and Chopra[22]. According to their study, pressure should satisfy the condition given below.

$$\frac{\partial P}{\partial n}(x,0,t) = -\theta\dot{P}(x,0,t). \tag{13}$$

For harmonic behaviour of pressure i.e. $P(x, 0, t) = P_0(x, 0, t)e^{i\omega t}$, the above equation is expressed as

$$\frac{\partial P}{\partial n}(x,0,t) = i\omega\theta P(x,0,t), \tag{14}$$

where θ is a coefficient expressed as

$$\theta = \frac{1}{C}\left(\frac{1-\alpha}{1+\alpha}\right). \tag{15}$$

α is the frequency independent reflection coefficient.

Boundary 4: For finite element modelling of reservoir, the infinite reservoir is truncated at a certain distance and a condition proposed by Gogoi and Maity[11] has been implemented to simulate the effect of infinite reservoir.

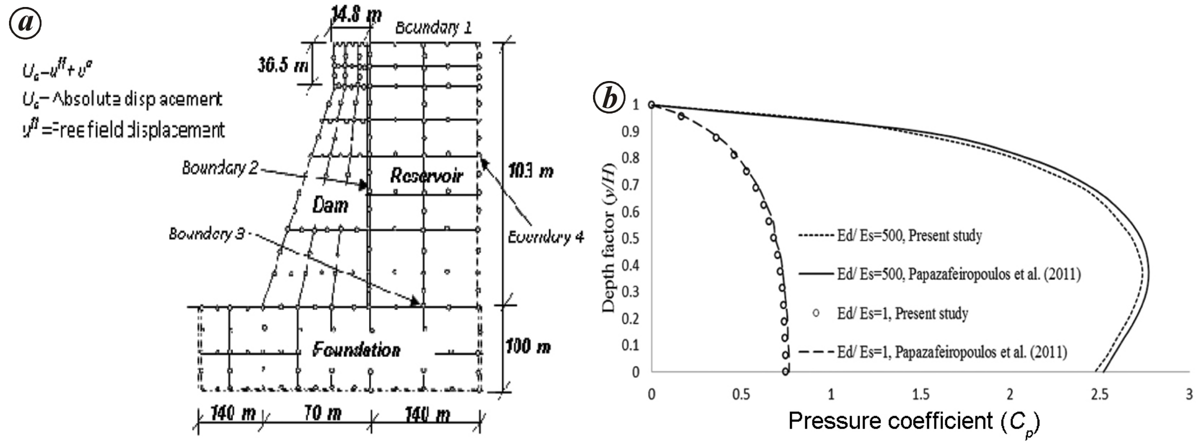

Figure 1. Geometry and hydrodynamic pressure distribution in dam–reservoir-foundation system. ***a***, Dam–reservoir-foundation system. ***b***, Hydrodynamic pressure along the dam reservoir interface.

Modelling of fluid domain: For finite element modelling, the equation of motion for fluid, i.e. eq. (10) is expressed by Galerkin method and it becomes

$$\int_{\Omega} N_j \left[\nabla^2 \sum N_j P_j - \frac{1}{C^2} \sum N_j \ddot{P}_j \right] \mathrm{d}\Omega = 0, \tag{16}$$

where N_j is shape function for the reservoir. Now, applying Green's theorem eq. (16) becomes

$$-\int_{\Omega} \left[\frac{\partial N_j}{\partial x} \sum \frac{\partial N_j}{\partial x} P_j + \frac{\partial N_j}{\partial y} \sum \frac{\partial N_j}{\partial y} P_j \right] \mathrm{d}\Omega$$

$$-\frac{1}{C^2} \int_{\Omega} N_j \sum N_j \,\mathrm{d}\Omega\, \ddot{P}_j + \int_{\Gamma} N_j \sum \frac{\partial N_j}{\partial n} \mathrm{d}\Gamma\; P_j = 0, \tag{17}$$

where j is node number and Γ is boundaries of reservoir. Equation (17) may also be expressed as

$$[\bar{T}]\{\ddot{P}\} + [\bar{V}]\{P\} = \{f\}, \tag{18}$$

where

$$[\bar{T}] = \frac{1}{C^2} \sum \int_{\Omega} [N]^T [N] \mathrm{d}\Omega, \tag{19}$$

$$[\bar{V}] = \sum \int_{\Omega} \left[\frac{\partial}{\partial x}[N]^T \frac{\partial}{\partial x}[N] + \frac{\partial}{\partial y}[N]^T \frac{\partial}{\partial y}[N] \right] \mathrm{d}\Omega, \tag{20}$$

$$[f] = \sum \int_{\Gamma} [N]^T \frac{\partial p}{\partial n} \mathrm{d}\Gamma = \{f_f\} + \{f_{fd}\} + \{f_{ff}\} + \{f_t\}. \tag{21}$$

Here the subscripts f, fd, ff and t represent the top surface of reservoir, dam–reservoir interface, reservoir–foundation interface and truncation surface respectively. Implementing all boundary conditions, i.e. eqs (11), (12) and (14) and the condition according to a previous study[11], eq. (18) is modified as

$$[T]\{\ddot{P}\} + [W]\{\dot{P}\} + [V]\{P\} = \{f_r\}, \tag{22}$$

where

$$[T] = [\bar{T}] + \frac{1}{g}[R_f], \tag{23}$$

$$\{f_r\} = -\rho_f [R_{fs}]\{a\}, \tag{24}$$

$$[W] = \frac{1}{C}[R_t], \tag{25}$$

$$[V] = [\bar{V}] + \zeta[R_t] - \mathrm{i}\omega\theta[R_{fb}], \tag{26}$$

where ς is the coefficient expressed by Gogoi and Maity[11] and

$$[R_f] = \sum \int_{\Gamma_f} [N]^T [N] \mathrm{d}\Gamma, \quad [R_{fd}] = \sum \int_{\Gamma_{fd}} [N]^T [N_d] \,\mathrm{d}\Gamma,$$

$$[R_{ff}] = \sum \int_{\Gamma_{ff}} [N]^T [N] \,\mathrm{d}\Gamma, \text{ and } [R_t] = \sum \int_{\Gamma_t} [N]^T [N] \,\mathrm{d}\Gamma.$$

Formulation of dam–reservoir-foundation coupled system

In this section, equilibrium equations of the dam, reservoir and soil foundation are coupled in such a way that they act as a single system and the coupling procedure is as follows:

The discrete dam equation with damping may be written as

$$M_d \ddot{d}_d + C_d \dot{d}_d + K_d d_d - QP - M_d \ddot{d}_g = 0, \tag{27}$$

where $[Q]$ is the coupling matrix and it arises to satisfy the compatibility condition at dam–reservoir interface and expressed as

$$\int_{\Gamma_{\mathrm{dr}}} N_{\mathrm{dr}}^T np \,\mathrm{d}\Gamma = \left(\int_{\Gamma_{\mathrm{dr}}} N_{\mathrm{dr}}^T n N_{\mathrm{dr}} \,\mathrm{d}\Gamma \right) P = QP, \tag{28}$$

where N_{dr} is interpolation function for beam element at common face of dam and reservoir. Similarly, the equation for fluid motion may be written as

$$T\ddot{P} + W\dot{P} + VP + Q^T \ddot{d}_{\mathrm{d}} - f_{\mathrm{r}} = 0. \tag{29}$$

In case of dam and reservoir as a single system, eqs (27) and (29) are coupled and expressed in eq. (30).

$$\begin{bmatrix} T & Q^T \\ 0 & M_d \end{bmatrix} \begin{Bmatrix} \ddot{P} \\ \ddot{d}_d \end{Bmatrix} + \begin{bmatrix} W & 0 \\ 0 & C_d \end{bmatrix} \begin{Bmatrix} \dot{P} \\ \dot{d}_d \end{Bmatrix} + \begin{bmatrix} V & 0 \\ -Q & K_d \end{bmatrix} \begin{Bmatrix} P \\ d_d \end{Bmatrix} = \begin{Bmatrix} f_r \\ M_d \ddot{d}_g \end{Bmatrix}. \tag{30}$$

The above equation does not include elastic foundation.

The dynamic equilibrium equations for coupled dam–reservoir-foundation may be developed in the following way.

For soil–structure interaction (SSI) problem, the formula based on added motion approach remains popular and this is due to its simplicity in formulation. Further, the method is based on simple mathematics and it produces most accurate responses when the structure behaviour is linear. The responses (D_a) of the coupled system, dam–reservoir-foundation can have two parts, one is free field responses, another is added responses. The equilibrium equation for coupled system may be expressed as follows

$$\begin{bmatrix} T & Q_s^T & Q_c^T & 0 \\ 0 & M_{ss} & M_{sc} & 0 \\ 0 & M_{cs} & M_{cc} & M_{cf} \\ 0 & 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{P} \\ \ddot{D}_s \\ \ddot{D}_c \\ \ddot{D}_{ff} \end{Bmatrix} + \begin{bmatrix} W & 0 & 0 & 0 \\ 0 & C_{ss} & C_{sc} & 0 \\ 0 & C_{cs} & C_{cc} & C_{cf} \\ 0 & 0 & C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{P} \\ \dot{D}_s \\ \dot{D}_c \\ \dot{D}_{ff} \end{Bmatrix} + \begin{bmatrix} V & 0 & 0 & 0 \\ -\begin{bmatrix} Q_s \\ Q_c \end{bmatrix} & K_{ss} & K_{sc} & 0 \\ 0 & K_{cs} & K_{cc} & K_{cf} \\ 0 & 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} P \\ D_s \\ D_c \\ D_{ff} \end{Bmatrix}$$

$$= -\begin{bmatrix} I & 0 & 0 & 0 \\ 0 & M_{ss} & M_{sc} & 0 \\ 0 & M_{cs} & M_{cc} & M_{cf} \\ 0 & 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} f_r \\ \ddot{D}_s^g \\ \ddot{D}_c^g \\ \ddot{D}_{ff}^g \end{Bmatrix}, \tag{32}$$

where the subscripts 's, ff and c' stand for nodes within the structure, nodes within the foundation and nodes at the junction of structure and soil foundation respectively and $\ddot{D}_g$ is the external acceleration vector. The different matrices at the interface of structure and soil foundation are considered to be the sum of contributions from structure (s) and soil foundation (ff), and may be defined as in eq. (33). The coupling matrix is rearranged as $Q = [[Q_s]\ [Q_c]]^T$, where $[Q_s]$ associates with the nodes of dam other than common nodes and $[Q_c]$ is associated with the common nodes at the junction of structure and soil foundation and presented in Figure 1 *a*. For obtaining the response of structure considering soil–structure–foundation interaction, first the free field and added responses are to be determined and the actual responses are obtained from eq. (34).

$$M_{cc} = M_c^d + M_c^{ff},\ C_{cc} = C_c^s + C_c^{ff} \text{ and}$$

$$K_{cc} = K_c^s + K_c^{ff}, \tag{33}$$

$$\begin{Bmatrix} \ddot{P} \\ \ddot{D}_s \\ \ddot{D}_c \\ \ddot{D}_f \end{Bmatrix} = \begin{Bmatrix} \ddot{P}^{ff} \\ \ddot{d}_s^{ff} \\ \ddot{d}_c^{ff} \\ \ddot{d}_f^{ff} \end{Bmatrix} + \begin{Bmatrix} \ddot{P}^a \\ \ddot{d}_s^a \\ \ddot{d}_c^a \\ \ddot{d}_f^a \end{Bmatrix}, \begin{Bmatrix} \dot{P} \\ \dot{D}_s \\ \dot{D}_c \\ \dot{D}_f \end{Bmatrix} = \begin{Bmatrix} \dot{P}^{ff} \\ \dot{d}_s^{ff} \\ \dot{d}_c^{ff} \\ \dot{d}_f^{ff} \end{Bmatrix} + \begin{Bmatrix} \dot{P}^a \\ \dot{d}_s^a \\ \dot{d}_c^a \\ \dot{d}_f^a \end{Bmatrix}$$

$$\text{and} \begin{Bmatrix} P \\ U_s \\ U_c \\ U_f \end{Bmatrix} = \begin{Bmatrix} P^{ff} \\ d_s^{ff} \\ d_c^{ff} \\ d_f^{ff} \end{Bmatrix} + \begin{Bmatrix} P^a \\ d_s^a \\ d_c^a \\ d_f^a \end{Bmatrix}, \tag{34}$$

where superscripts 'ff and a' define free field and added response respectively. Now, putting eq. (34) in eq. (32), the following equation is obtained.

$$\begin{bmatrix} T & Q_s^T & Q_c^T & 0 \\ 0 & M_{ss} & M_{sc} & 0 \\ 0 & M_{cs} & M_{cc} & M_{cf} \\ 0 & 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{P}^a \\ \ddot{d}_d^a \\ \ddot{d}_c^a \\ \ddot{d}_f^a \end{Bmatrix}$$

$$+\begin{bmatrix} W & 0 & 0 & 0 \\ 0 & C_{ss} & C_{sc} & 0 \\ 0 & C_{cs} & C_{cc} & C_{cf} \\ 0 & 0 & C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{P}^a \\ \dot{d}_s^a \\ \dot{d}_c^a \\ \dot{d}_f^a \end{Bmatrix}$$

$$+\begin{bmatrix} V & 0 & 0 & 0 \\ -\begin{bmatrix} Q_s \\ Q_c \end{bmatrix} & K_{ss} & K_{sc} & 0 \\ 0 & K_{cs} & K_{cc} & K_{cf} \\ 0 & 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} P^a \\ d_s^a \\ d_c^a \\ d_f^a \end{Bmatrix} = r + f, \tag{35}$$

where

$$r = -\begin{bmatrix} T & Q_s^T & Q_c^T & 0 \\ 0 & M_{ss} & M_{sc} & 0 \\ 0 & M_{cs} & M_{cc} & M_{cf} \\ 0 & 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{P}^{ff} \\ \ddot{d}_s^{ff} \\ \ddot{d}_c^{ff} \\ \ddot{d}_f^{ff} \end{Bmatrix}$$

$$-\begin{bmatrix} W & 0 & 0 & 0 \\ 0 & C_{ss} & C_{sc} & 0 \\ 0 & C_{cs} & C_{cc} & C_{cf} \\ 0 & 0 & C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{P}^{ff} \\ \dot{d}_d^{ff} \\ \dot{d}_c^{ff} \\ \dot{d}_f^{ff} \end{Bmatrix}$$

$$-\begin{bmatrix} V & 0 & 0 & 0 \\ -\begin{bmatrix} Q_s \\ Q_c \end{bmatrix} & K_{ss} & K_{sc} & 0 \\ 0 & K_{cs} & K_{cc} & K_{cf} \\ 0 & 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} P^{ff} \\ d_s^{ff} \\ d_c^{ff} \\ d_f^{ff} \end{Bmatrix}, \tag{36}$$

and

$$f = -\begin{bmatrix} I & 0 & 0 & 0 \\ 0 & M_{ss} & M_{sc} & 0 \\ 0 & M_{cs} & M_{cc} & M_{cf} \\ 0 & 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} f_r \\ \ddot{D}_s^g \\ \ddot{D}_c^g \\ \ddot{D}_f^g \end{Bmatrix}. \tag{37}$$

In our study, a mathematical model is presented to obtain the responses of gravity dam considering fluid–soil–structure interaction. Since the free field analysis is only for soil foundation, the corresponding responses for structure and adjacent reservoir are considered as zero. This implies the following corresponding changes in the responses

$$\begin{Bmatrix} \ddot{P} \\ \ddot{D}_s \\ \ddot{D}_c \\ \ddot{D}_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \ddot{d}_c^{ff} \\ \ddot{d}_f^{ff} \end{Bmatrix} + \begin{Bmatrix} \ddot{P}^a \\ \ddot{d}_s^a \\ \ddot{d}_c^a \\ \ddot{d}_f^a \end{Bmatrix}, \quad \begin{Bmatrix} \dot{P} \\ \dot{D}_d \\ \dot{D}_c \\ \dot{D}_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \dot{d}_c^{ff} \\ \dot{d}_f^{ff} \end{Bmatrix} + \begin{Bmatrix} \dot{P}^a \\ \dot{d}_s^a \\ \dot{d}_c^a \\ \dot{d}_f^a \end{Bmatrix}$$

$$\text{and } \begin{Bmatrix} P \\ D_s \\ D_c \\ D_f \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ d_c^{ff} \\ d_f^{ff} \end{Bmatrix} + \begin{Bmatrix} P^a \\ d_s^a \\ d_c^a \\ d_f^a \end{Bmatrix}. \tag{38}$$

In eq. (34), the free field responses of structure and reservoir are equal to zero because these responses are obtained by analysing the foundation only, i.e. no structure and adjacent reservoir are present in the soil foundation. Therefore, if the soil foundation experienced an earthquake motion, the responses for free field analysis are obtained by solving the following expression.

$$\begin{bmatrix} M_{cc} & M_{cf} \\ M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{d}_c^f \\ \ddot{d}_f^f \end{Bmatrix} + \begin{bmatrix} C_{cc} & C_{cf} \\ C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{d}_c^f \\ \dot{d}_f^f \end{Bmatrix}$$

$$+\begin{bmatrix} K_{cc} & K_{cf} \\ K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} d_c^f \\ d_f^f \end{Bmatrix} = -\begin{bmatrix} M_{cc} & M_{cf} \\ M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} D_c^g \\ D_f^g \end{Bmatrix}. \tag{39}$$

Using free field responses from the above equation, interaction force r from eq. (36) is calculated as

$$r = -\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & M_{ss} & M_{sc} & 0 \\ 0 & M_{cs} & M_{cc}^d & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ \ddot{u}_c^f \\ 0 \end{Bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & C_{ss} & C_{sc} & 0 \\ 0 & C_{cs} & C_{cc}^d & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\times \begin{Bmatrix} 0 \\ 0 \\ \dot{u}_c^f \\ 0 \end{Bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & K_{ss} & K_{sc} & 0 \\ 0 & K_{cs} & K_{cc}^d & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ u_c^f \\ 0 \end{Bmatrix}. \tag{40}$$

Once the interaction force, r is obtained, the added responses of the structure–soil–foundation and reservoir are determined using eq. (35) and these calculated responses are added to the free field response according to eq. (38) for absolute responses of structure considering soil–structure–fluid interaction.

Results and discussions

Validation of the present modelling

The present modelling is validated with a bench mark problem carried out by Papazafeiropoulos *et al.*[21] in which the structure and soil foundation are modelled by four-node bilinear plane strain elements and water is modelled by linear acoustic quadrilateral elements. Here, the soil foundation is considered as viscoelastic half plane and the material properties and geometry of structure, soil and fluid are considered based on the previous study[21]. The study is performed for two different moduli of elasticity of soil foundation. For reservoir, a condition proposed by Somerfeld is implemented at the truncation surface. The response along the structure–reservoir interface due to sinusoidal acceleration with the fundamental frequency of the system from the present study and reference study[21] are compared in Figure 1 *b*. The responses of our study are almost similar to that obtained by Papazafeiropoulos *et al.*[21] for $E_d/E_s = 1$. However, a little variation of the results is observed for $E_d/E_s = 500$ which is due to the different mesh size and element used in discretization of dam–reservoir-foundation system.

Performance of reservoir with absorptive bottom

In this section, the effect of reservoir bottom absorption on the performance of gravity dam considering soil–structure–fluid interaction is discussed. The geometry and elastic properties are as follows: water depth in reservoir (H_f) = 70.0 m, density = 1000 kg/m^3 and acoustic speed of water (c) = 1434 m/s respectively. Here, the elastic effect of dam adjacent to the infinite reservoir is neglected. The fundamental frequencies of reservoir at different reflection coefficients are presented in Table 1. Table 1 depicts that the natural frequency has a decreasing trend with the increase of reflection coefficient. The study is further extended for sinusoidal excitation with different frequencies, i.e. T_c/H_f. Here, the amplitude of the external acceleration is considered to be 1.0 *g*. The time history of the responses of reservoir at the heel of a rigid dam for different exciting frequencies with different reflection coefficients is shown in Figure 2. Figure 2 *c* shows that the pressure coefficient remains almost constant for different reflection coefficients at $T_c/H_f = 100$. However, for $T_c/H_f = 4.0$ and 1.0, reflection coefficient enhances the reservoir response at the heel point of dam (Figure 2 *a* and *b*).

Table 1. Effect of reservoir bottom absorption on fundamental frequency of the reservoir

Reflection coefficient	Fundamental frequency (rad/sec)
0.25	40.1
0.5	37.26
0.75	35.32
0.95	33.62
1.0	32.69

Performance of gravity dam with fluid–structure interaction and absorptive reservoir bottom

The effect of absorptive reservoir bottom on the responses of concrete gravity dam and the reservoir is studied in this section. Two-dimensional Koyna gravity with vertical upstream face is considered. The elastic properties of reservoir dam and water are as follows – dam: height (H_d) = 103.0 m, top width of dam (t_d) = 14.8 m, width of base (L_d) = 70.0, density of concrete (ρ_f) = 2415.816 kg/m^3, Poisson's ratio (ν) = 0.235, and for Rayleigh damping $\xi = 5\%$; reservoir: depth of water (H_f) = 103.0 m, velocity of sound in water (c) = 1440 m/s, density of water (ρ_d) = 1000 kg/m^3. Length of the reservoir (L_t) = 51.5 m and the condition suggested by Gogoi and Maity[11] is implemented at this artificial surface. The fluid–structure system is excited under different types of acceleration, i.e. ramp and sinusoidal with different exciting frequencies and earthquake. The graphical results plotted in Figure 3 show that the reservoir bottom

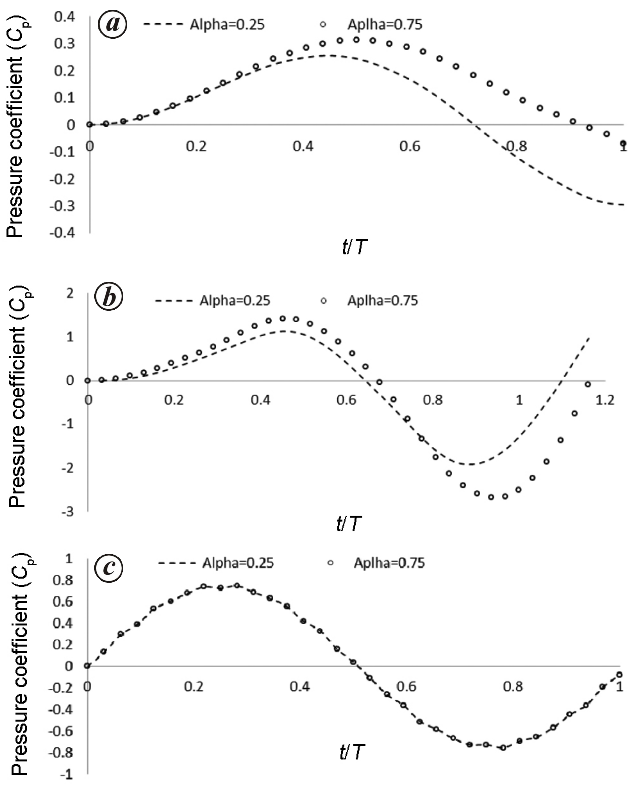

Figure 2. Variation of hydrodynamic pressure for different exciting frequencies. ***a***, For $T_c/H_f = 1$. ***b***, For $T_c/H_f = 4$. ***c***, For $T_c/H_f = 100$.

absorption has negligible effect on the responses of dam and reservoir respectively due to the application of ramp acceleration.

We also studied the sinusoidal excitation of different frequencies. The same geometry and elastic properties for the structure and water within the reservoir are considered. The fluid–structure system experiences harmonic acceleration of frequencies in different ways like (i) equal to the fundamental frequency of fluid–structure system, $\omega = 15.92$ rad/s (ii) less than fundamental frequency of fluid–structure system, $\omega = 0.877$ rad/s (iii) equal to the fundamental frequency of the reservoir, $\omega = 33.71$ rad/s and (iv) greater than the fundamental frequency of reservoir, $\omega = 87.83$ rad/s. The peak ground acceleration in this case is considered as 1.0 m/s^2.

Figures 4–5 show the effects of reflection coefficient when the coupled system experiences acceleration of different frequencies. The pressure coefficients and displacement of dam at an excitation frequency equal to the resonant frequency of dam–reservoir system, i.e. $\omega = 15.92$ rad/s are presented in graphical form in Figure 4 *a* and *b*. It is noted from these figures that pressure coefficient is increased slightly when the reflection coefficients increase (Figure 4 *a*). However, the tip displacement remains almost constant for different reflection coefficients (Figure 4 *b*). It is interesting to see that the effect of reflection coefficient is almost insignificant when the frequency of acceleration is much less than the resonant frequency of the reservoir (Figure 4 *c*–*d*). Similar comparison is made with frequency equal to and greater than resonant frequency of reservoir. Responses are plotted in Figure 5 which show that both the magnitude of hydrodynamic pressure and tip displacement reduce significantly for absorptive reservoir bottom. Thus, it may be concluded from the above parametric study that the absorptive reservoir bottom effect due to deposition of sediments should not be neglected for obtaining accurate behaviour of gravity dam with fluid–structure interaction.

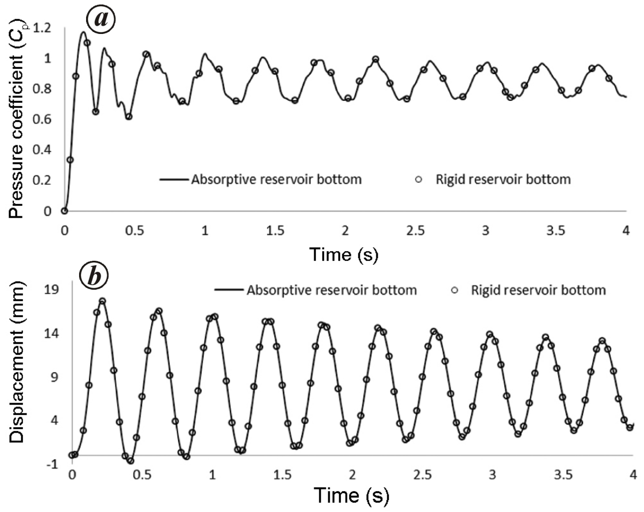

Figure 3. Responses of dam–reservoir system due to ramp acceleration. ***a***, Hydrodynamic pressure. ***b***, Tip displacement of dam.

Performance of gravity dam with fluid–structure–soil interaction and absorptive reservoir bottom

It is observed from the earlier section that the behaviour of gravity dam with absorptive reservoir bottom is frequency dependent. Further, in the previous section it is observed that the effect of absorptive reservoir bottom becomes significant when this coupled system is vibrated with frequency equal or greater than the resonant frequency of the reservoir. In the present section, the effect of reflection coefficient at the reservoir bottom is studied due to the harmonic excitation of frequency which is (i) equal to the resonant frequency of reservoir, i.e. 33.71 rad/s and (ii) greater than the resonant frequency of

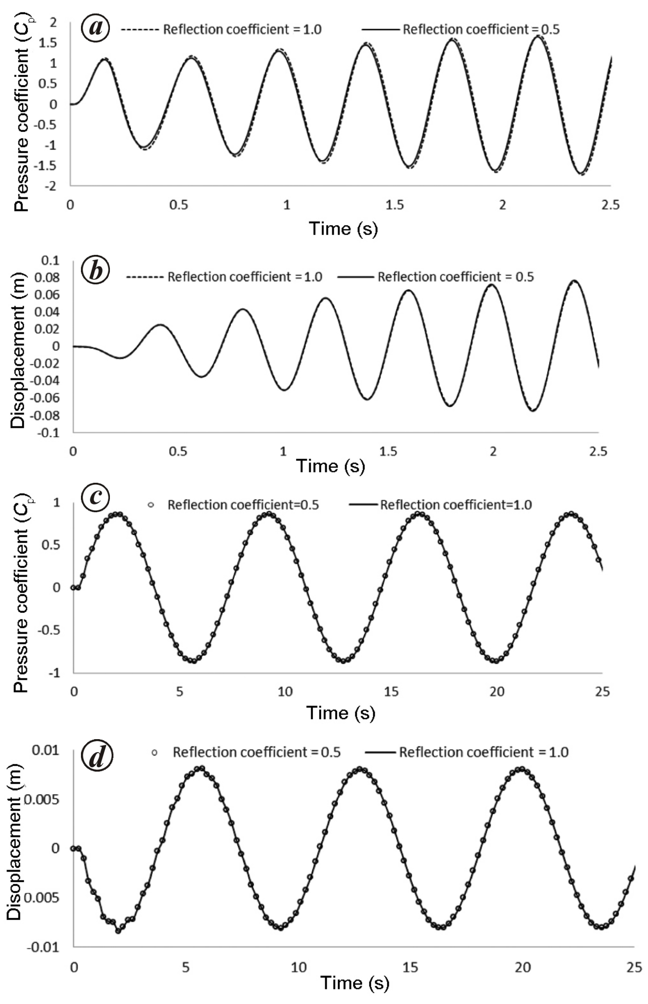

Figure 4. Responses of dam–reservoir system for exciting frequencies less than fundament frequency of reservoir. ***a***, Hydrodynamic pressure $\omega = 15.92$ rad/s. ***b***, Tip displacement $\omega = 15.92$ rad/s. ***c***, Hydrodynamic pressure $\omega = 0.877$ rad/s. ***d***, Tip displacement $\omega = 0.877$ rad/s.

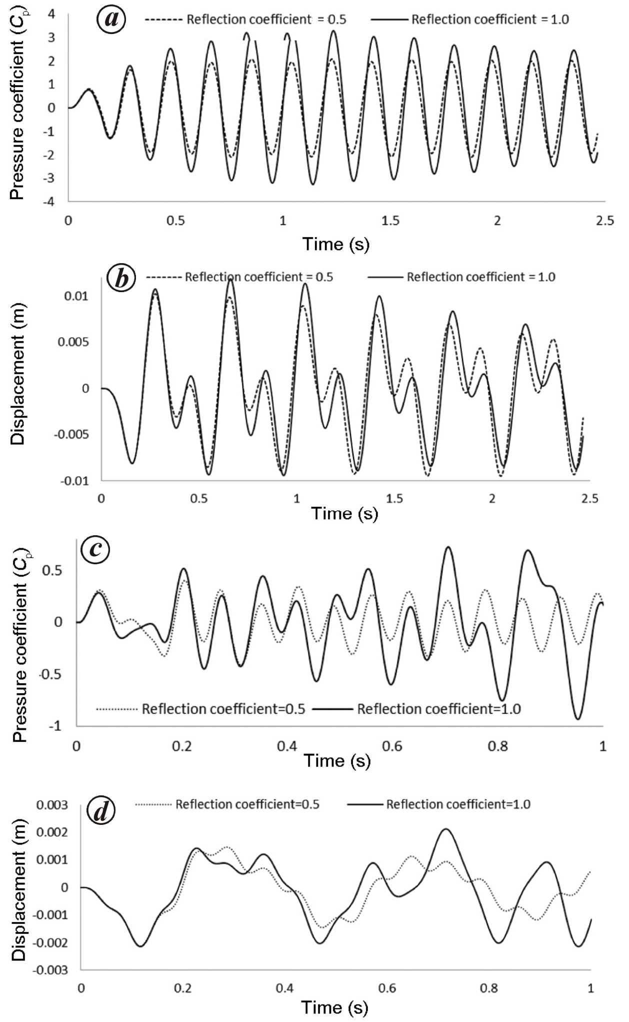

Figure 5. Responses of dam–reservoir system for exciting frequencies equal and greater than fundament frequency of reservoir. ***a***, Hydrodynamic pressure $\omega = 33.71$ rad/s. ***b***, Tip displacement $\omega = 33.71$ rad/s. ***c***, Hydrodynamic pressure $\omega = 87.83$ rad/s. ***d***, Tip displacement $\omega = 87.83$ rad/s.

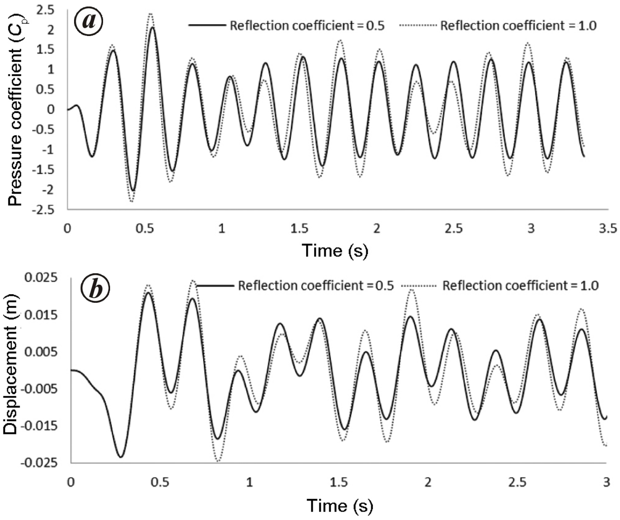

Figure 6. Responses of dam–reservoir-foundation system for $\omega = 33.71$ rad/s. ***a***, Hydrodynamic pressure. ***b***, Tip displacement.

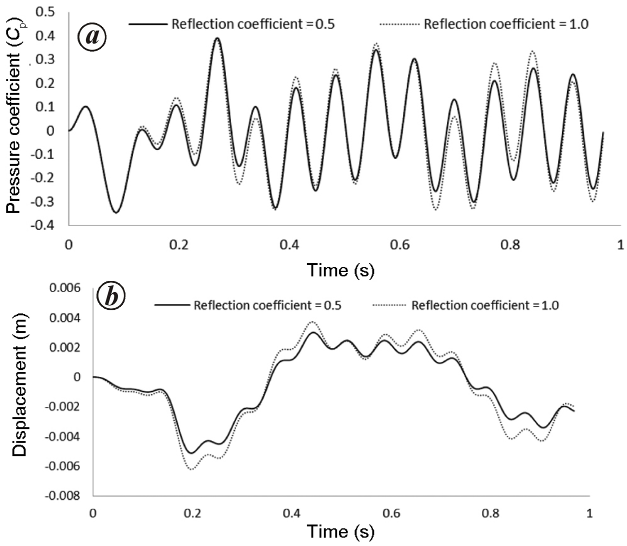

Figure 7. Responses of dam–reservoir-foundation system for $\omega = 87.83$ rad/s. ***a***, Hydrodynamic pressure. ***b***, Tip displacement.

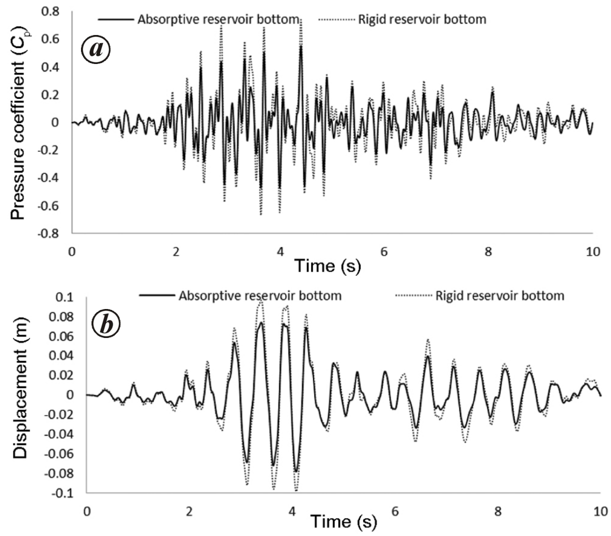

Figure 8. Hydrodynamic pressure and tip displacement for dam–reservoir-foundation system due to earthquake excitation. ***a***, Hydrodynamic pressure. ***b***, Tip displacement.

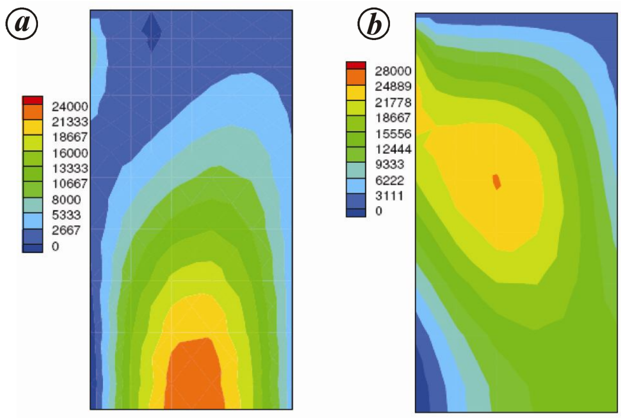

Figure 9. Contour plot of hydrodynamic pressure at $t = 4.02$ s for ***a***, Absorptive bottom; ***b***, Rigid bottom.

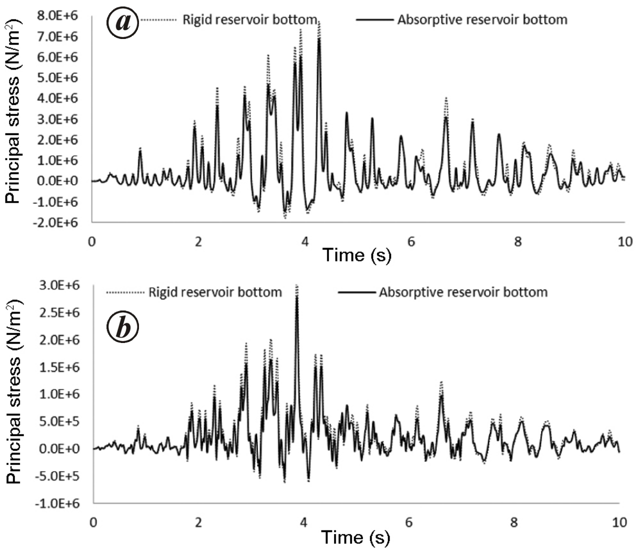

Figure 10. Major principal stress at different locations of dam. ***a***, At notch. ***b***, At heel.

reservoir, i.e. 87.83 rad/s. The geometry and typical finite element meshing is presented in Figure 1 *a*. Here, the elastic properties are as follows – Dam: Young modulus of concrete = 3.150×10^{10} N/m^2, Poisson's ratio = 0.2350, density of concrete = 2416.0 kg/m^3. Foundation: Young modulus of soil = 1.750×10^{10} N/m^2, Poisson's ratio = 0.20, density of soil = 1800 kg/m^3 and for Rayleigh damping for both structure and soil is $\xi = 5\%$. Reservoir: the acoustic wave speed = 1440 m/s, density = 1000 kg/m^3. Figures 6 and 7 show the variation of responses of dam and reservoir. A significant increase in tip displacement of dam as well as the hydrodynamic pressure is observed for both the frequencies from these figures.

The study is further extended for earthquake excitation. Here, Koyna earthquake acceleration is considered to be the external excitation and variation of tip displacement of dam and pressure coefficient at heel is presented in graphical form. It is observed from Figure 8 *a* and *b* that the responses of dam and reservoir are reduced when the coefficient is 0.50. The distribution of pressure coefficient also changes when absorptive reservoir bottom is considered (Figure 9). The major principal stresses at notch and heel are also evaluated and plotted in Figure 10 *a* and *b* respectively. These graphs depict that the maximum compressive stresses in dam reduce significantly when the reservoir bottom is considered to be absorptive. Further, the magnitude of stresses at the notch of the dam has higher value than those at the heel and it is due to stress concentration at the notch.

Conclusions

A dynamic analysis of concrete gravity dam is presented here to obtain the behaviour of gravity dam with absorptive reservoir bottom adjacent to it. In the present study, finite element based on displacement is used to model dam and foundation. However, pressure-based formulation is used to reduce the degree of freedom in reservoir domain. The coupling equation of dam–reservoir-foundation is achieved by direct approach. The main advantage of the present methodology is its computational effort. It requires less time and memory space during its operation. A reflection coefficient is introduced to simulate the absorptive condition of reservoir bottom and its effect on the dynamic performances are studied with and without soil–structure and fluid–structure interaction. Thus, it is observed that the effect of absorptive reservoir bottom is frequency-dependant. For reservoir with rigid dam, there is a considerable change in hydrodynamic pressure if the frequency of exciting is equal or greater than the resonant frequency of reservoir. Similar observation is observed at the same range of exciting frequency for dam–reservoir and dam–reservoir-foundation cases. However, there is a change in the response of dam if the exciting frequency is equal to the resonant frequency of dam–reservoir coupled system. This study further implies that the influence of absorptive reservoir bottom reduces if fluid–structure and structure-soil–fluid interactions are considered and the least effect is observed for dam–reservoir-foundation case.

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