Coupled Systems Mechanics, *Vol. 8, No. 5 (2019) 393-414*
DOI: https://doi.org/10.12989/csm.2019.8.5.393

Seismic analysis of dam-foundation-reservoir coupled system using direct coupling method

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(Received June 15, 2019, Revised September 24, 2019, Accepted September 25, 2019)

Abstract. This paper presents seismic analysis of concrete gravity dams considering soil-structure-fluid interaction. Displacement based plane strain finite element formulation is considered for the dam and foundation domain whereas pressure based finite element formulation is considered for the reservoir domain. A direct coupling method has been adopted to obtain the interaction effects among the dam, foundation and reservoir domain to obtain the dynamic responses of the dam. An efficient absorbing boundary condition has been implemented at the truncation surfaces of the foundation and reservoir domains. A parametric study has been carried out considering each domain separately and collectively based on natural frequencies, crest displacement and stress at the neck level of the dam body. The combined frequency of the entire coupled system is very less than that of the each individual sub-system. The crest displacement and neck level stresses of the dam shows prominent enhancement when coupling effect is taken into consideration. These outcomes suggest that a complete coupled analysis is necessary to obtain the actual responses of the concrete gravity dam. The developed methodology can easily be implemented in finite element code for analyzing the coupled problem to obtain the desired responses of the individual sub-domains.

Keywords: finite element method; coupled system; dam-foundation-reservoir interaction; direct coupling method; earthquake analysis; absorbing boundary conditions

1. Introduction

Accurate seismic responses of a concrete gravity dam cannot be obtained through the dynamic analysis of the dam alone. The responses depend on the mutual interactions among the dam and it's underneath foundation and upstream reservoir domains. When a dam is to be constructed on a soft soil the flexibility of the foundation domain drastically modifies the dynamic responses of the dam. Reservoir water present at the upstream face of the dam generates hydrodynamic pressure during earthquakes. When elasticity of the dam is considered then this hydrodynamic pressure get significantly changes due to the interaction among the dam and the reservoir domains. A complete coupling among these three domains namely the dam, foundation and reservoir domain will

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http://www.techno-press.org/?journal=csm&subpage=8 ISSN: 2234-2184 (Print), 2234-2192 (Online)

provide the accurate responses of a concrete gravity dam under earthquake motion. Hence, to obtain actual dynamic behavior of the concrete gravity dam under seismic conditions, complete interaction among the dam, foundation and reservoir domains need to be considered. Dam-foundation, dam-reservoir and dam-foundation-reservoir interaction generally comes under the soil-structure interaction (SSI), fluid-structure interaction (FSI) and soil-fluid-structure interaction (SFSI) analysis respectively.

Related to the dam-foundation coupled system, it is generally observed that when a large structure likes concrete gravity dam has to be constructed on a relatively soft soil medium in seismically active zones then consideration of dynamic soil-structure interaction (SSI) phenomenon is highly necessary. Kramer (1996) pointed out that for this type of analysis, the base motion of the structure will not be the same with the free field ground motion. Here, the foundation is unable to maintain the uniformity of deformations as produced by free field motion. Also, the seismic response of the structure would provide deformation to the supporting soil. The entire process is termed as SSI where, the soil and structure domain mutually influences the responses of the each other. There are two coupling approaches namely indirect coupling and direct coupling approach to obtain the interactive responses of a coupled system. The indirect coupling approach was initially inspired from the work carried out by Felippa and Park (1980) on staggered solution procedure for solving verity of coupled field dynamic problem. Rizos and Wang (2002) formulated a partitioned algorithmic technique in the context of SSI analysis in time domain. Theoretically, in indirect coupling method structure and foundation domains are treated as two separate sub-systems and coupling is established at the dam-foundation interface iteratively. Recent studies carried out by Jharomi *et al.* (2007, 2009) pointed out that the staggered solution approach should be considered in SSI analysis with great care, since obtaining a converge solution sometimes becomes very difficult issue and also results a time consuming process. On the other hand, the direct coupling method was first studied by Wolf (1985). In direct coupling method the structure and the soil part near to the structure is modeled in monolithic manner and the combined system is analyzed in a single step in each time step. Hence, that direct coupling approach is more efficient in terms of computational time than the iterative method considered. There are several studies that point out the concept of free-field motion input (Clough and Penzein, 1975; Clough and Chopra 1979) and added motion based formulation (Ibrahimbegovic and Wilson, 1990, 1992) approach of Soil-structure interaction under earthquake loading condition. Ibrahimbegovic and Wilson, (1990, 1992) introduced the natural base isolation concept to capture the local non-linearity effect at the dam-foundation interface and uplifting and sliding of the dam at its base in the added motion formulation of the dam-foundation coupled system. Their proposed formulation is beneficial as it can consider the release of the potential stress due to the allowance of sliding and uplifting phenomena at the base. Reddy *et al.* (2008), Burman *et al.* (2012) and Mandal and Maity (2016) successfully implemented the direct coupling approach in dam-foundation coupled analysis problems. Their proposed algorithm was simple to implement in a finite element (FE) code. One of the major computational challenges that arise while implementing FEM in infinite soil domain is the spurious wave reflections from the truncated soil boundaries. Some researchers considered implementation of infinite elements to treat the spurious reflection of wave [Su and Wang (2013)] in the dynamic soil-structure interaction analysis. Though for a finite element programming the present authors [Mandal and Maity (2016)] had implemented successfully, the cone (spring-dashpot) type absorbing boundary conditions suggested by Kellezi, (2000).

Regarding the reservoir effect on the concrete gravity dam, initially the dam-reservoir interface was treated as rigid. Added mass approach proposed by Westergaard (1933), is generally used for this simplified assumption. But, this simplified assumption is not valid when the elasticity of the dam is considered in the analysis, and then these hydrodynamic pressures on the upstream face of the dam get significantly changes. This happens due to the coupled behavior of the dam and the reservoir domains. Similar to the dam-foundation interaction, dam-reservoir interaction can also be carried out by direct and iterative coupling method. Iterative coupling on the dam-reservoir system may be found in the studies carried out by Maity and Bhattacharya (2003). Zeinkiewicz *et al* (2005) addressed both the coupling procedure in the chapter of coupled systems in his book on the finite element method. Sami and Lotfi (2007) attempted to obtain the coupled responses of the dam-reservoir coupled systems with the help of coupled and decoupled modal analysis. The analysis procedure of 2-D fluid structure interaction using FEM may also be found in the study carried out by Mitra and Sinhamahapatra (2008). From more complex computational point of view Kassiotis *et al.* (2010) proposed a novel coupling approach between the solid body and fluid with free surface flow. They had discritized the solid domain using finite elements and fluid domain using finite volume approach, and moreover they used partition strategy with direct force-motion transfer algorithm to capture the interaction effects and large deformation of the solid body. This methodology would be very demanding to capture the large deformation of the dam body. In a study carried out by Miquel and Bouaanani (2013) suggested a novel technique by modifying the original earthquake acceleration to directly take care the complex fluid-structure interaction effect on the dam responses. In a recent review article published by Mandal and Maity (2015) has pointed out that between these two analyses approaches, being iterative in nature the responses obtained in the indirect coupling highly dependent on the flexibility of the structure. Similar to the infinite soil domain, appropriate absorbing boundary condition also need to be provided at the truncated boundaries of the infinite reservoir domain while analyzing the dam-reservoir coupled system using the finite element method. In fluid domains, boundary conditions proposed by Sommerfeld (1949), Sharan (1992) and Gogoi and Maity (2006) are generally preferred for time domain analysis. Out of these three, the latter two are dependent on the excitation frequency. Sami and Lotfi (2012) proposed H-W (Hagstrom-Warbutron) boundary condition for dam-reservoir interaction. It is recently, Khazaee and Lotfi (2015) proposed the implementation technique of perfectly matched layer in transient analysis of dam-reservoir systems. Hadzalic *et al.* (2018, 2019) addressed one interesting issue in their recent studies on the progressive localized failure of a dam-reservoir coupled system due to the porous cohesive nature of the dam. In their formulation they have tried to assess the influence of the internal pore pressure on the ultimate failure mode with fully saturated cracks present in the porous dam body.

Coupling of the entire dam-foundation and reservoir domain is necessary to obtain the most accurate seismic responses of the gravity dams. Kucukarslan (2003) attempted to solve the three coupled systems numerically by implementing dual reciprocity boundary element method for the reservoir and foundation domain and finite element method for the dam domain in time domain. The responses that had been obtained were close to the FEM-FEM coupled system. Mohammadi *et al.* (2009) had compared the Eulerian and Lagrangian approach of analysis in dam-foundation-reservoir coupling analysis. Papazafeiropoulos *et al.* (2011) performed an analytical and numerical comparative study on the complete dam-foundation-reservoir coupled system. The authors had used ABAQUS commercial software to perform the finite element analysis and concluded that incorporation of the complex geometries of the dam and various material properties of the dam and foundation domain FEM analysis is more robust in nature. Hariri-Arbedili *et al.* (2016) had attempted to obtain responses of a concrete gravity dam considering input excitation mechanism. There the authors have modeled the coupled system by Lagangian and Eulerian formulation; the study also point out the importance of different parameters considered in the analysis procedure on the dam responses. It is very recently that Chopra and his coworkers (see, Løkke, A., & Chopra, A. K, 2017, 2018 and 2019) proposed a direct finite element approach for nonlinear analysis of semi bounded dam-foundation reservoir system. In their proposed method they have pointed out that frequency domain analysis of the complete coupled dam-foundation-reservoir system using sub-structure method is not capable to capture the nonlinear responses of the dam under strong earthquake ground motion, but direct finite element approach can do. Their proposed method can be effectively implemented to the commercial software packages for studying propagation of cracks inside the dam. Recently, Gorai and Maity (2019) have studied the influence of the near field and far field ground motion on the responses of the concrete gravity dam. They have followed the direct coupling approach to analyze the coupled system.

In the present study we investigate the seismic behavior of a concrete gravity dam through a complete coupling with the foundation and the reservoir domains using direct coupling methodology. The dam and foundation domain are modeled using displacement based finite element formulation and pressure based formulation is considered for the reservoir domain. In case of the semi-infinite soil domain, a newly proposed cone type absorbing boundary condition (Mandal and Maity, 2016) has been considered at the truncated faces. At the truncated face of the reservoir domain, efficient absorbing boundary condition has been implemented. Keeping in mind the two domain coupled system, the coupling of the three domain comprised of the dam-foundation and the reservoir has been established. In this methodology, the interactive forces will get exchanged at the interfaces among the different domains. The present coupling methodology has been validated with the existing literatures. The natural frequencies of the coupled system has been obtained and compared with individual domains and the any two domain coupled systems. A parametric study has been performed to obtain the influence of the other sub-domains on the dynamic responses of the concrete gravity dams. The seismic responses of the dam-foundation coupled system at the salient positions are obtained considering the effect of the reservoir water. The contour plots are also obtained to point out the most stresses regions in the coupled systems and the stresses at the dam body has been compared for individual case and coupled cases.

2. Interaction through direct coupling method

In the direct coupling method the coupled domain is solved in a single step considering the entire system at a time. In the present study, the entire dam-foundation-reservoir coupled system is analyzed using direct coupling approach. Before introducing the complete dam-foundation-reservoir interaction formulation, dam-foundation and dam-reservoir interaction are discussed in brief. The finite element mesh with eight nodded iso-parametric elements and geometry of the Koyna dam and its surrounded reservoir and foundation domain are shown in Fig.1.

2.1 Dam-foundation interaction

A brief description of the direct coupling method has been provided in this section. The absolute responses of the coupled system are assumed to be sum of free field and added responses. Free field responses are obtained assuming that no structure is present over the foundation domain. The added responses are those, which are found out carrying coupled dam-foundation interaction system. The Koyna dam foundation system has been chosen for the present study as shown in

Table 1 Property matrices considered for dam-foundation interaction

	Mass	Damping	Stiffness
Dam	$M_d = \begin{bmatrix} M_{dd} & M_{di} \\ M_{id} & M_{ii}^d \end{bmatrix}$	$C_d = \begin{bmatrix} C_{dd} & C_{di} \\ C_{id} & C_{ii}^d \end{bmatrix}$	$K_d = \begin{bmatrix} K_{dd} & K_{di} \\ K_{id} & K_{ii}^d \end{bmatrix}$
Foundation	$M_f = \begin{bmatrix} M_{ii}^f & M_{if} \\ M_{fi} & M_{ff} \end{bmatrix}$	$C_f = \begin{bmatrix} C_{ii}^f & C_{if} \\ C_{fi} & C_{ff} \end{bmatrix}$	$K_f = \begin{bmatrix} K_{ii}^f & K_{if} \\ K_{fi} & K_{ff} \end{bmatrix}$

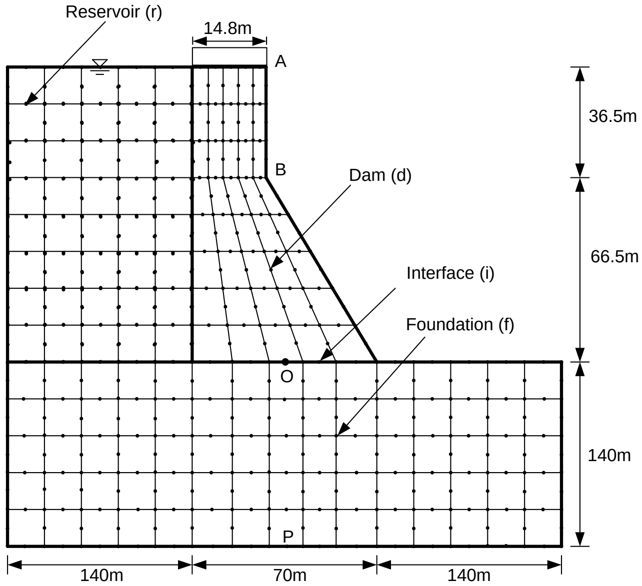


Fig. 1 Koyna dam with reservoir and foundation domain

Fig.1. The dam-foundation coupled system is divided into three sets of nodal locations such as, the dam (*d*), interface (*i*) and foundation (*f*). Initially, the free field motions are obtained from the dynamic equation of motion of the foundation domain (Eq. (1))

$$M_f \ddot{v}(t) + C_f \dot{v}(t) + K_f(t) = f_{ff}(t) \tag{1}$$

where, M, C and K are the mass, damping and stiffness matrices respectively. Subscript ‘f’ is indicating the foundation domain. The free field displacement, velocity and the acceleration vectors are designated as $v(t)$, $\dot{v}(t)$ and $\ddot{v}(t)$ respectively and $f_{ff}(t)$ is the far-field boundary loading.

With the addition of a structure to the foundation domain, a complete structure-foundation system is formed. The equations of motion for the complete system exposed to the same far field boundary loading $f_{ff}(t)$ can be stated as

$$[M_d + M_f]\{\ddot{v}(t) + \ddot{u}(t)\} + [C_d + C_f]\{\dot{v}(t) + \dot{u}(t)\} + [K_d + K_f]\{v(t) + u(t)\} = f_{ff}(t) \tag{2}$$

where, M_d, C_d and K_d are the mass, damping and stiffness matrices of the dam domain respectively. The added field displacement, velocity and the acceleration vectors are designated as

$u(t)$, $\dot{u}(t)$ and $\ddot{u}(t)$ respectively and other notations are the same as in Eq. (1). The dynamic property matrices namely mass, damping and stiffness for the dam and foundation domain are shown in Table 1. Here, the same three identifiers for dam, interface and foundation are chosen for the three parts of the coupled system.

Simplifying Eq. (2), the following expression may be obtained

$$\begin{aligned}&\left[M_d + M_f\right]\ddot{v}(t) + \left[M_d + M_f\right]\ddot{u}(t) + \left[C_d + C_f\right]\dot{v}(t) + \left[C_d + C_f\right]\dot{u}(t)\\&+\left[K_d + K_f\right]v(t) + \left[K_d + K_f\right]u(t) = f_{ff}(t)\end{aligned} \tag{3}$$

$$\begin{aligned}&[M]\ddot{u}(t) + [C]\dot{u}(t) + [K]u(t) + [M_d]\ddot{v}(t) + [C_d]\dot{v}(t) + [K_d]v(t)\\&= f_{ff}(t) - [M_f]\ddot{v}(t) - [C_f]\dot{v}(t) - [K_f]v(t)\end{aligned} \tag{4}$$

where, M, C and K are the mass, damping and stiffness of the total coupled system. The mass, damping and stiffness matrices at the interface level are evaluated by adding together the same property matrices coming from the structure and foundation sides as follows

$$M_{ii} = M_{ii}^d + M_{ii}^f \quad C_{ii} = C_{ii}^d + C_{ii}^f \quad K_{ii} = K_{ii}^d + K_{ii}^f \tag{5}$$

Inserting Eq. (1) in Eq. (4), the following expression is obtained

$$M\,\ddot{u}(t) + C\,\dot{u}(t) + K\,u(t) = -M_d\ddot{v}(t) - C_d\dot{v}(t) - K_d v(t) \tag{6}$$

The dynamic equilibrium equation stated in Eq. (6) may be rewritten in matrix form as follows

$$\begin{aligned}&\begin{bmatrix} M_{dd} & M_{di} & 0 \\ M_{id} & M_{ii} & M_{if} \\ 0 & M_{fi} & M_{ff} \end{bmatrix}\begin{Bmatrix} \ddot{u}_d(t) \\ \ddot{u}_i(t) \\ \ddot{u}_f(t) \end{Bmatrix} + \begin{bmatrix} C_{dd} & C_{di} & 0 \\ C_{id} & C_{ii} & C_{if} \\ 0 & C_{fi} & C_{ff} \end{bmatrix}\begin{Bmatrix} \dot{u}_d(t) \\ \dot{u}_i(t) \\ \dot{u}_f(t) \end{Bmatrix} + \begin{bmatrix} K_{dd} & K_{di} & 0 \\ K_{id} & K_{ii} & K_{if} \\ 0 & K_{fi} & K_{ff} \end{bmatrix}\begin{Bmatrix} u_d(t) \\ u_i(t) \\ u_f(t) \end{Bmatrix} =\\&-\begin{bmatrix} M_{dd} & M_{di} & 0 \\ M_{id} & M_{ii}^d & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} 0 \\ \ddot{v}_i(t) \\ \ddot{v}_f(t) \end{Bmatrix} - \begin{bmatrix} C_{dd} & C_{di} & 0 \\ C_{id} & C_{ii}^d & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} 0 \\ \dot{v}_i(t) \\ \dot{v}_f(t) \end{Bmatrix} - \begin{bmatrix} K_{dd} & K_{di} & 0 \\ K_{id} & K_{ii}^d & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} 0 \\ v_i(t) \\ v_f(t) \end{Bmatrix}\end{aligned} \tag{7}$$

Interaction is only possible at the dam-foundation interface; hence, Eq. (7) may be simplified as

$$\begin{aligned}&\begin{bmatrix} M_{dd} & M_{di} & 0 \\ M_{id} & M_{ii} & M_{if} \\ 0 & M_{fi} & M_{ff} \end{bmatrix}\begin{Bmatrix} \ddot{u}_d(t) \\ \ddot{u}_i(t) \\ \ddot{u}_f(t) \end{Bmatrix} + \begin{bmatrix} C_{dd} & C_{di} & 0 \\ C_{id} & C_{ii} & C_{if} \\ 0 & C_{fi} & C_{ff} \end{bmatrix}\begin{Bmatrix} \dot{u}_d(t) \\ \dot{u}_i(t) \\ \dot{u}_f(t) \end{Bmatrix} + \begin{bmatrix} K_{dd} & K_{di} & 0 \\ K_{id} & K_{ii} & K_{if} \\ 0 & K_{fi} & K_{ff} \end{bmatrix}\begin{Bmatrix} u_d(t) \\ u_i(t) \\ u_f(t) \end{Bmatrix} =\\&-\begin{bmatrix} 0 & M_{di} & 0 \\ 0 & M_{ii}^d & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} 0 \\ \ddot{v}_i(t) \\ 0 \end{Bmatrix} - \begin{bmatrix} 0 & C_{di} & 0 \\ 0 & C_{ii}^d & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} 0 \\ \dot{v}_i(t) \\ 0 \end{Bmatrix} - \begin{bmatrix} 0 & K_{di} & 0 \\ 0 & K_{ii}^d & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} 0 \\ v_i(t) \\ 0 \end{Bmatrix}\end{aligned} \tag{8}$$

Solution of Eq. (8) provides the added motion for the entire system. The total response of the coupled system is evaluated by adding the added motion responses with the free field motion responses of the system as follows

$$\begin{Bmatrix} U_d(t) \\ U_i(t) \\ U_f(t) \end{Bmatrix} = \begin{Bmatrix} 0 \\ v_i(t) \\ v_f(t) \end{Bmatrix} + \begin{Bmatrix} u_d(t) \\ u_i(t) \\ u_f(t) \end{Bmatrix};\ \begin{Bmatrix} \dot{U}_d(t) \\ \dot{U}_i(t) \\ \dot{U}_f(t) \end{Bmatrix} = \begin{Bmatrix} 0 \\ \dot{v}_i(t) \\ \dot{v}_f(t) \end{Bmatrix} + \begin{Bmatrix} \dot{u}_d(t) \\ \dot{u}_i(t) \\ \dot{u}_f(t) \end{Bmatrix};\ \begin{Bmatrix} \ddot{U}_d(t) \\ \ddot{U}_i(t) \\ \ddot{U}_f(t) \end{Bmatrix} = \begin{Bmatrix} 0 \\ \ddot{v}_i(t) \\ \ddot{v}_f(t) \end{Bmatrix} + \begin{Bmatrix} \ddot{u}_d(t) \\ \ddot{u}_i(t) \\ \ddot{u}_f(t) \end{Bmatrix} \tag{9}$$

The main assumption in this model is that the input motions at the level of the base rock are not considered to be altered by the presence of the dam (Leger and Boughoufalah 1989). The spatial variation of the free field ground motion is neglected in the present formulation, as most of the cases sufficient information's regarding these are mostly unavailable.

2.2 Dam-reservoir interaction

In the direct coupling method of dam-reservoir system, the dam and the reservoir domain are considered as a single entity. This single entity is solved at a time in each time step. Hence, computational time required for this method is generally less compared to the indirect coupling method. The equation of motion of the dam domain is expressed as follows

$$M_d \ddot{u}_d + C_d \dot{u}_d + K_d u_d - Rp - M_d \ddot{U}_g = 0 \tag{10}$$

The coupling matrix R in Eq. (10) comes into picture to satisfy the compatibility condition at the dam-reservoir interface and may be expressed as

$$\int_{\Gamma_s} N_d^T np d\Gamma = \left(\int_{\Gamma_s} N_d^T n N_r d\Gamma \right) p = Rp \tag{11}$$

where, n is the unit normal vector to the dam-reservoir interface. N_d and N_r are the shape functions of the dam and reservoir respectively. The equation of motion of the fluid domain may be expressed as

$$E\ddot{p} + A\dot{p} + Gp + R^T \ddot{u}_d - F_l = 0 \tag{12}$$

Both the Eqs. (10) and (12) are coupled and mathematically define the equation of motion of the coupled system. In matrix form, these two equations may be expressed as

$$\begin{bmatrix} E & R^T \\ 0 & M_d \end{bmatrix} \begin{Bmatrix} \ddot{p} \\ \ddot{u}_d \end{Bmatrix} + \begin{bmatrix} A & 0 \\ 0 & C_d \end{bmatrix} \begin{Bmatrix} \dot{p} \\ \dot{u}_d \end{Bmatrix} + \begin{bmatrix} G & 0 \\ -R & K_d \end{bmatrix} \begin{Bmatrix} p \\ u_d \end{Bmatrix} = \begin{Bmatrix} F_l \\ M_d \ddot{U}_g \end{Bmatrix} \tag{13}$$

2.3 Dam-foundation-reservoir interaction

Similar to the dam-foundation interaction analysis, the complete dam-foundation-reservoir analysis is carried out by dividing the dam-foundation system into three different parts, namely the dam, interface and foundation. The degrees of freedom of these three parts are designated with subscripts'*d*', '*i*' and '*f*' respectively. Here, also the added motion approach is considered and total motion is assumed to be sum of free field and added motion.

$$\begin{Bmatrix} \ddot{P} \\ \ddot{U}_d \\ \ddot{U}_i \\ \ddot{U}_f \end{Bmatrix} = \begin{Bmatrix} \ddot{P}^{ff} \\ \ddot{u}_d \\ \ddot{u}_i \\ \ddot{u}_f \end{Bmatrix} + \begin{Bmatrix} \ddot{P}^a \\ \ddot{v}_d \\ \ddot{v}_i \\ \ddot{v}_f \end{Bmatrix}; \quad \begin{Bmatrix} \dot{P} \\ \dot{U}_d \\ \dot{U}_i \\ \dot{U}_f \end{Bmatrix} = \begin{Bmatrix} \dot{P}^{ff} \\ \dot{u}_d \\ \dot{u}_i \\ \dot{u}_f \end{Bmatrix} + \begin{Bmatrix} \dot{P}^a \\ \dot{v}_d \\ \dot{v}_i \\ \dot{v}_f \end{Bmatrix}; \quad \begin{Bmatrix} P \\ U_d \\ U_i \\ U_f \end{Bmatrix} = \begin{Bmatrix} P^{ff} \\ u_d \\ u_i \\ u_f \end{Bmatrix} + \begin{Bmatrix} P^a \\ v_d \\ v_i \\ v_f \end{Bmatrix} \tag{14}$$

Here, the interaction among the foundation and reservoir domain is also considered in a similar way of dam-reservoir coupled system. The governing equation of the reservoir domain stated in Eq. (12) is slightly modified for this purpose.

$$E\ddot{p}+A\dot{p}+Gp+R^T\ddot{u}_d+Q^T\ddot{u}_f-F_l=0 \tag{15}$$

The coupling matrix R in Eq. (15) defines interaction between the dam and reservoir system and expressed mathematically in Eq. (11). The coupling matrix Q indicates the interaction between the foundation and reservoir system and expressed mathematically as

$$\int_{\Gamma_s} N_f^T npd\Gamma=\left(\int_{\Gamma_s} N_f^T nN_r d\Gamma\right)p=Qp \tag{16}$$

The equation of motion of the foundation domain will get modified to the following form

$$M_f\ddot{u}_f+C_f\dot{u}_f+K_f u_f-Qp-M_f\ddot{U}_f=0 \tag{17}$$

Now, utilizing the equations stated in Eqs. (6), (15) and (17), the equation of motion of dam-foundation-reservoir coupled system is derived with the help of free field and added motion field. The boundary effect of the reservoir domain (F_l) is implemented separately for the coupled system. The matrix based equation for the direct coupling method is follows

$$\begin{aligned}&\begin{bmatrix}E & R^T & 0 & Q^T\\ 0 & M_{dd} & M_{di} & 0\\ 0 & M_{id} & M_{ii} & M_{if}\\ 0 & 0 & M_{fi} & M_{ff}\end{bmatrix}\begin{Bmatrix}\ddot{P}^a\\ \ddot{u}_d\\ \ddot{u}_i\\ \ddot{u}_f\end{Bmatrix}+\begin{bmatrix}A & 0 & 0 & 0\\ 0 & C_{dd} & C_{di} & 0\\ 0 & C_{id} & C_{ii} & C_{if}\\ 0 & 0 & C_{fi} & C_{ff}\end{bmatrix}\begin{Bmatrix}\dot{P}^a\\ \dot{u}_d\\ \dot{u}_i\\ \dot{u}_f\end{Bmatrix}+\begin{bmatrix}G & 0 & 0 & 0\\ -R & K_{dd} & K_{di} & 0\\ 0 & K_{id} & K_{ii} & K_{if}\\ -Q & 0 & K_{fi} & K_{ff}\end{bmatrix}\begin{Bmatrix}P^a\\ u_d\\ u_i\\ u_f\end{Bmatrix}=\\ &-\begin{bmatrix}E & R^T & 0 & Q^T\\ 0 & M_{dd} & M_{di} & 0\\ 0 & M_{id} & M_{ii} & M_{if}\\ 0 & 0 & M_{fi} & M_{ff}\end{bmatrix}\begin{Bmatrix}\ddot{P}^f\\ \ddot{v}_d\\ \ddot{v}_i\\ \ddot{v}_f\end{Bmatrix}-\begin{bmatrix}A & 0 & 0 & 0\\ 0 & C_{dd} & C_{di} & 0\\ 0 & C_{id} & C_{ii} & C_{if}\\ 0 & 0 & C_{fi} & C_{ff}\end{bmatrix}\begin{Bmatrix}\dot{P}^f\\ \dot{v}_d\\ \dot{v}_i\\ \dot{v}_f\end{Bmatrix}-\begin{bmatrix}G & 0 & 0 & 0\\ -R & K_{dd} & K_{di} & 0\\ 0 & K_{id} & K_{ii} & K_{if}\\ -Q & 0 & K_{fi} & K_{ff}\end{bmatrix}\begin{Bmatrix}P^f\\ v_d\\ v_i\\ v_f\end{Bmatrix}+\begin{Bmatrix}F_l\\ 0\\ 0\\ 0\end{Bmatrix}\end{aligned} \tag{18}$$

Through the coupling matrix R, interaction between the dam and reservoir domain established in the complete dam-foundation-reservoir coupled system. The interaction among the foundation and the reservoir domains is neglected in this study. A numerical technique is introduced to solve the entire coupled system. In Eq. (18), the free field responses of the dam and reservoir domains are set to be zero as the free field motion are obtained by analyzing the foundation domain alone. Hence, the parts corresponding to the reservoir and dam are neglected in the equation as follows

$$\begin{aligned}&\begin{bmatrix}E & R^T & 0 & Q^T\\ 0 & M_{dd} & M_{di} & 0\\ 0 & M_{id} & M_{ii} & M_{if}\\ 0 & 0 & M_{fi} & M_{ff}\end{bmatrix}\begin{Bmatrix}\ddot{P}^a\\ \ddot{u}_d\\ \ddot{u}_i\\ \ddot{u}_f\end{Bmatrix}+\begin{bmatrix}A & 0 & 0 & 0\\ 0 & C_{dd} & C_{di} & 0\\ 0 & C_{id} & C_{ii} & C_{if}\\ 0 & 0 & C_{fi} & C_{ff}\end{bmatrix}\begin{Bmatrix}\dot{P}^a\\ \dot{u}_d\\ \dot{u}_i\\ \dot{u}_f\end{Bmatrix}+\begin{bmatrix}G & 0 & 0 & 0\\ -R & K_{dd} & K_{di} & 0\\ 0 & K_{id} & K_{ii} & K_{if}\\ -Q & 0 & K_{fi} & K_{ff}\end{bmatrix}\begin{Bmatrix}P^a\\ u_d\\ u_i\\ u_f\end{Bmatrix}=\\ &-\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & M_{dd} & M_{di} & 0\\ 0 & M_{id} & M_{ii} & M_{if}\\ 0 & 0 & M_{fi} & M_{ff}\end{bmatrix}\begin{Bmatrix}0\\ 0\\ \ddot{v}_i\\ \ddot{v}_f\end{Bmatrix}-\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & C_{dd} & C_{di} & 0\\ 0 & C_{id} & C_{ii} & C_{if}\\ 0 & 0 & C_{fi} & C_{ff}\end{bmatrix}\begin{Bmatrix}0\\ 0\\ \dot{v}_i\\ \dot{v}_f\end{Bmatrix}-\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & K_{dd} & K_{di} & 0\\ 0 & K_{id} & K_{ii} & K_{if}\\ 0 & 0 & K_{fi} & K_{ff}\end{bmatrix}\begin{Bmatrix}0\\ 0\\ v_i\\ v_f\end{Bmatrix}+\begin{Bmatrix}F_l\\ 0\\ 0\\ 0\end{Bmatrix}\end{aligned} \tag{19}$$

Now, the interaction among the dam and foundation domains happens only at the dam foundation interface. Utilizing the equivalence nature of the matrices the following simplification can be achieved.

$$
\begin{bmatrix} E & R^T & 0 & Q^T \\ 0 & M_{dd} & M_{di} & 0 \\ 0 & M_{id} & M_{ii} & M_{if} \\ 0 & 0 & M_{fi} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{P}^a \\ \ddot{u}_d \\ \ddot{u}_i \\ \ddot{u}_f \end{Bmatrix} + \begin{bmatrix} A & 0 & 0 & 0 \\ 0 & C_{dd} & C_{di} & 0 \\ 0 & C_{id} & C_{ii} & C_{if} \\ 0 & 0 & C_{fi} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{P}^a \\ \dot{u}_d \\ \dot{u}_i \\ \dot{u}_f \end{Bmatrix} + \begin{bmatrix} G & 0 & 0 & 0 \\ -R & K_{dd} & K_{di} & 0 \\ 0 & K_{id} & K_{ii} & K_{if} \\ -Q & 0 & K_{fi} & K_{ff} \end{bmatrix} \begin{Bmatrix} P^a \\ u_d \\ u_i \\ u_f \end{Bmatrix} =
$$
$$
-\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & M_{di} & 0 \\ 0 & 0 & M_{ii}^d & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ \ddot{v}_i \\ 0 \end{Bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & C_{di} & 0 \\ 0 & 0 & C_{ii}^d & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ \dot{v}_i \\ 0 \end{Bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & K_{di} & 0 \\ 0 & 0 & K_{ii}^d & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} 0 \\ 0 \\ v_i \\ 0 \end{Bmatrix} + \begin{Bmatrix} F_l \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{20}
$$

The matrix equation stated in Eq. (20) is directly solved using Newmark beta average acceleration method to obtain the added responses in the complete coupled system. The total responses of the coupled system are evaluated from the following expressions.

$$
\begin{Bmatrix} \ddot{P} \\ \ddot{U}_d \\ \ddot{U}_i \\ \ddot{U}_d \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \ddot{U}_i^{ff} \\ \ddot{U}_f^{ff} \end{Bmatrix} + \begin{Bmatrix} \ddot{P}^a \\ \ddot{U}_d^a \\ \ddot{U}_i^a \\ \ddot{U}_f^a \end{Bmatrix} ; \quad \begin{Bmatrix} \dot{P} \\ \dot{U}_d \\ \dot{U}_i \\ \dot{U}_d \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ \dot{U}_i^{ff} \\ \dot{U}_f^{ff} \end{Bmatrix} + \begin{Bmatrix} \dot{P}^a \\ \dot{U}_d^a \\ \dot{U}_i^a \\ \dot{U}_f^a \end{Bmatrix} ; \quad \begin{Bmatrix} P \\ U_d \\ U_i \\ U_d \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ U_i^{ff} \\ U_f^{ff} \end{Bmatrix} + \begin{Bmatrix} P^a \\ U_d^a \\ U_i^a \\ U_f^a \end{Bmatrix} \tag{21}
$$

3. Truncation boundary conditions

In a dam-foundation-reservoir coupled system, one of the major challenges is the incorporation of a suitable boundary condition at the truncated boundaries of the infinite foundation and reservoir domain. In the present study two different kind of absorbing boundary conditions are implemented at the foundation and reservoir domains. In case of the foundation domain, frequency independent cone type local absorbing boundary condition is implemented. In this boundary a parallel combination of spring and dashpots are attached to the boundary nodes in horizontal and vertical degrees of freedoms as shown in Fig 2. The present authors have extensively studied the

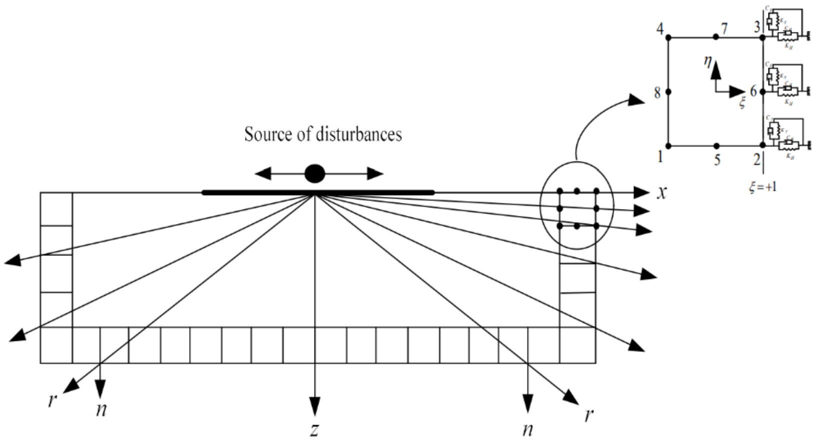


Fig. 2 Implementation of cone boundary condition along truncation boundaries of the soil domain

suitability of such kind of boundary condition in dam-foundation coupled system in their previous study (Mandal and Maity 2016). Readers are referred to Mandal and Maity (2016) for detail implementation procedure.

In case of the reservoir domain, it is found that the absorbing boundary condition proposed by Gogoi and Maity (2006) is the most suitable for time domain analysis. According to Gogoi and Maity (2006) the boundary condition at the truncation face is defined as

$$\frac{\partial p}{\partial n}(L,y,t)=\left(\zeta_m-\frac{1}{c}\right)\dot{p} \quad \text{and} \quad \zeta_m=-\frac{i\sum_{m=1}^{\infty}\frac{\lambda_m^2 I_m}{\beta_m}e^{(-k_m x)}(\psi_m)}{\Omega c\sum_{m=1}^{\infty}\frac{\lambda_m^2 I_m}{\beta_m k_m}e^{(-k_m x)}(\psi_m)} \tag{22}$$

Readers are referred to Gogoi and Maity, (2006) for detail variable definitions and implementation procedure.

4. Numerical investigations and results

The numerical responses are obtained through several coupled problem analysis. This section has been divided into three main section namely, validation study, seismic responses of the Koyna dam and parametric study considering the coupled system with several sub-domains to obtain the influence of those in the seismic responses of the dam.

4.1 Validation study

The proposed coupling methodology has been validated with the existing literatures. Interactions among dam-foundation, dam-reservoir and dam-foundation-reservoir systems are validated in the next sub-sections respectively.

4.1.1 Dam-foundation system

Dam foundation coupled system has been validated with the model dam problem considered by Yazdchi *et al.* (1999). All the relevant data are taken from that study. The responses are also compared with two other reported studies for various impedance ratios (E_f/E_d, i.e., the ratio of modulus of elasticity of foundation to modulus of elasticity of the dam) and tabulated in Table 2. Slight variations in the responses are observed due to different coupling methodology and boundary conditions.

Table 2 Maximum horizontal crest displacements (mm)

Impedance ratio E_f/E_d	Yazdchi *et al.* (1999)	Reddy *et al.* (2008)	Burman *et al.* (2012)	Present method
0.5	6.89	8.60	6.75	7.72
	-7.53	N/A	-8.62	-8.08
4.0	4.11	3.90	4.09	3.73
	-3.70	N/A	-4.70	-3.66

(N/A- Data not available in aforementioned paper)

Table 3 Validation study of the dam-reservoir coupled system

Mode Number	Time period(s)		Percentage (%) Variation
	Sami and Lotfi (2007)	Present Algorithm	
1	0.3178	0.3194	0.51
2	0.1544	0.1549	0.33

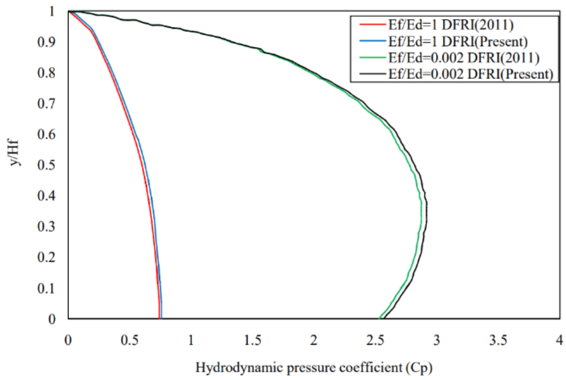


Fig. 3 Hydrodynamic pressure along dam-reservoir interface

4.1.2 Dam-reservoir system

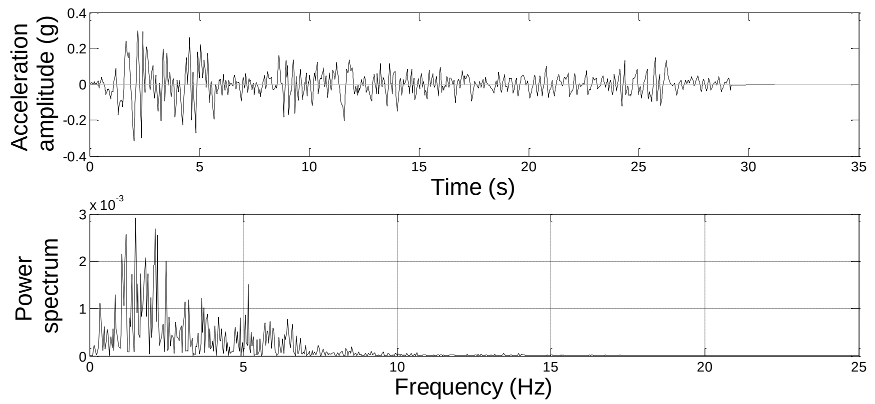
Dam reservoir coupled system has been validated with the model dam problem considered by Sami and Lotfi (2007). The time periods for the first two modes are compared and close agreement is achieved with the above mentioned literature.

4.1.3 Dam-foundation-reservoir system

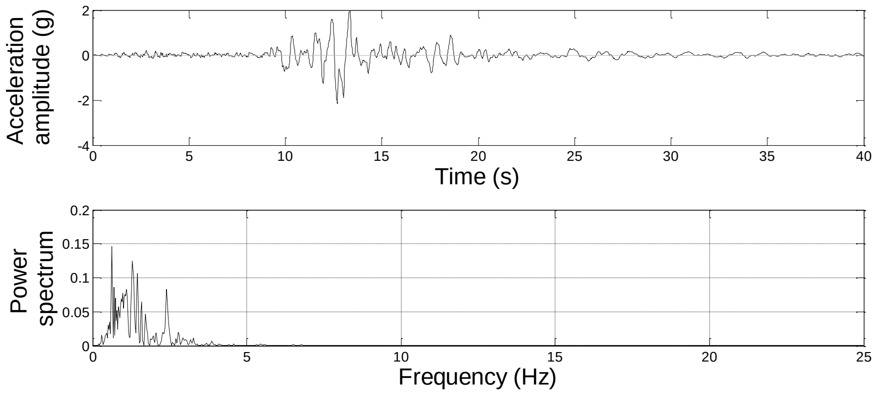
The developed computer code for the analysis of dam-foundation-reservoir coupled system is validated with a benchmark problem carried out by Papazaferiopoulos *et al.* (2011). All the relevant data are considered from the above-mentioned study. The present study is carried out for two different impedance ratios i.e. E_f/E_d ratios. The distribution of the hydrodynamic pressure along the dam reservoir interface due to harmonic loading are obtained for two different impendence ratios like E_f/E_d = 1 and E_f/E_d = 0.002. Here, DFRI represents dam-foundation-reservoir interaction obtained by Papazaferiopoulos *et al.* (2011). Similarly, DFRI (present) represents the dam-foundation-reservoir interaction using the present method. It is observed from Fig. 3 that the hydrodynamic pressure distributions have minor discrepancy with the literature for both the cases. This discrepancy occurs may be due to the different mesh size and type of element considered in the discretization of the dam-foundation-reservoir domain.

4.2 Seismic responses of the concrete gravity dam

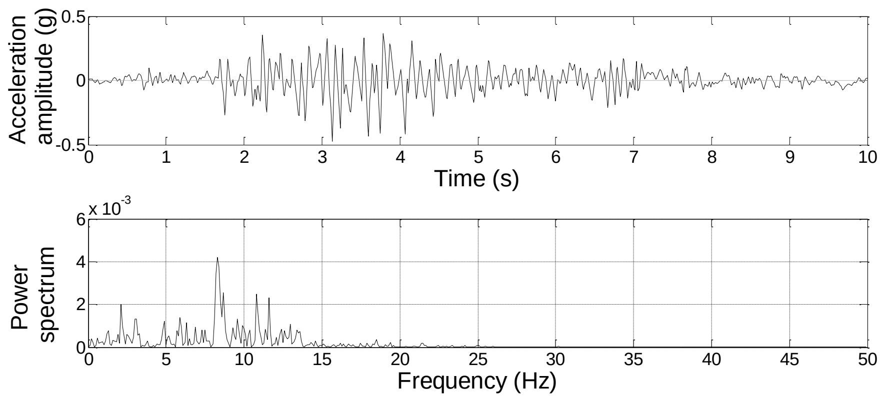
The dynamic dam-foundation-reservoir interaction (DFRI) analyses of existing dams have been carried out using the direct coupling approach. Three earthquake ground motions namely El-Centro Earthquake (1940), Loma Prieta Earthquake (1989) and Koyna earthquake (1967) have been considered for the analysis. All the three ground motions along with their frequency contents are shown in Fig. 4(a), 4(b) and 4(c) respectively. Once the validation of the proposed direct



(a) El-Centro Earthquake (1940) Ground Motion



(b) Loma Prieta Earthquake (1989) Ground Motion



(c) Koyna Earthquake (1967) Ground Motion

Fig. 4 (a) El-Centro Earthquake (1940) Ground Motion, (b) Loma Prieta Earthquake (1989) Ground Motion and (c) Koyna Earthquake (1967) Ground Motion

coupling approach for analyzing the dam-foundation-reservoir is done, the coupling methodology has been used to analyze the existing dams. Koyna dam has been considered for the detail numerical study and the seismic responses obtained from the coupled system are also verified with the Pine Flat Dam.

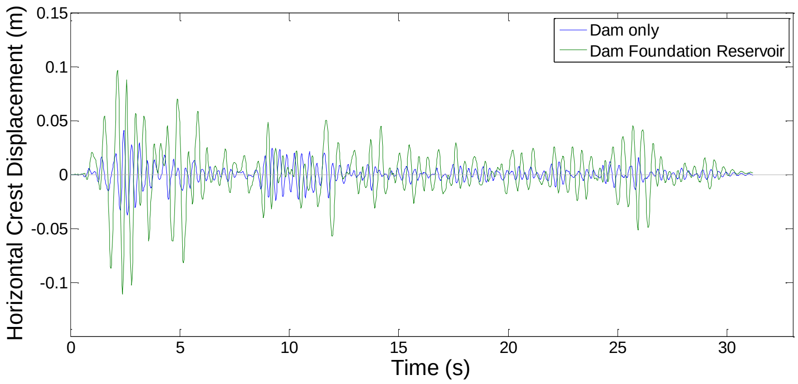


Fig. 5 Crest displacement of Koyna dam for El-Centro Earthquake

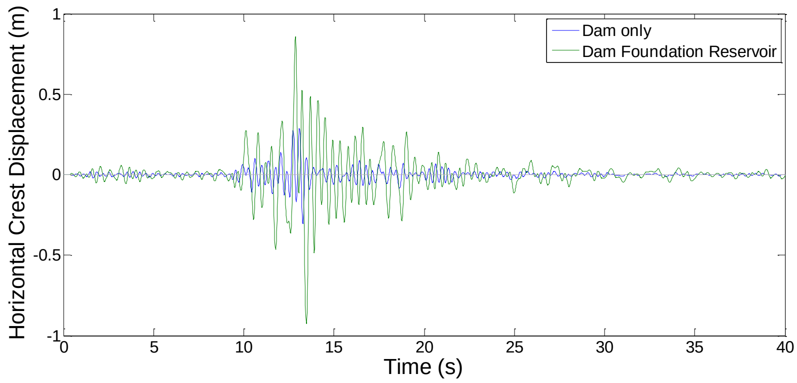


Fig. 6 Crest displacement of Koyna dam for Loma Prieta Earthquake

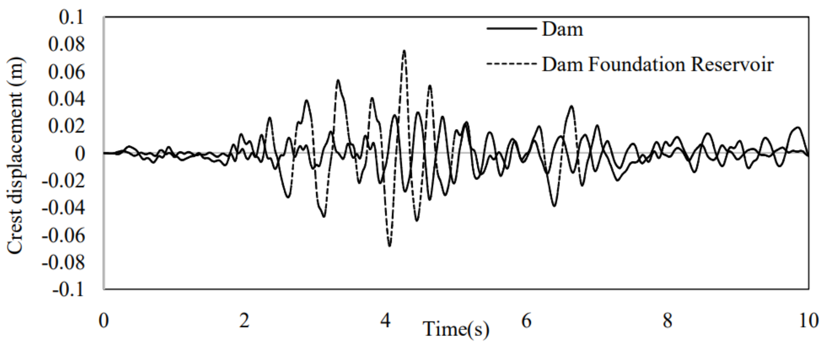


Fig. 7 Crest displacement of Koyna dam for Koyna Earthquake

4.2.1 Seismic responses of Koyna Dam

The geometry of the dam-foundation-reservoir coupled system has been shown in Fig. 1. The Young's modulus, Poisson's ratio and mass density of dam and foundation body are considered from the study carried out by Mandal and Maity (2016). The acoustic wave speed and the unit weight of the reservoir water are considered as 1440 m/s and 9.81 kN/m^3. In order to achieve sufficient accuracy under external loading the optimum mesh grading for the dam domain has been considered as 5×8 ($N_h \times N_v$) (Fig. 1).

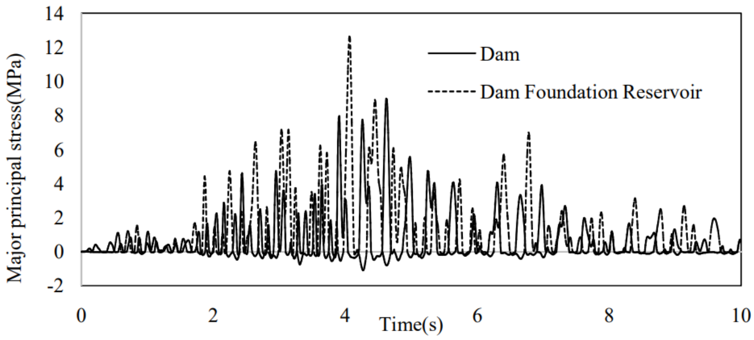


Fig. 8 Major principal stress histories at the neck of Koyna dam for Koyna Earthquake

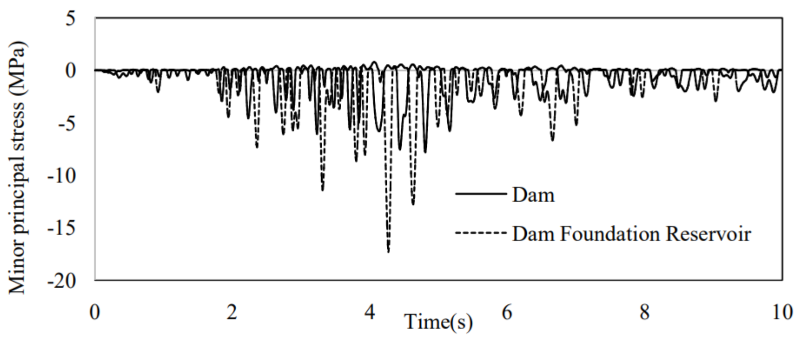


Fig. 9 Minor principal stress histories at the neck of Koyna dam for Koyna Earthquake

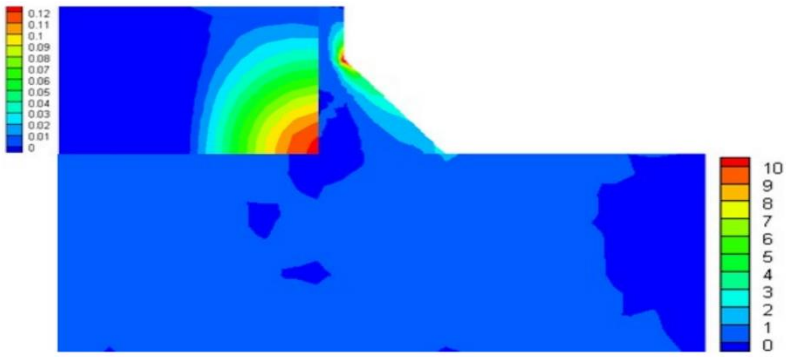


Fig. 10 Major principal stress (MPa) and hydrodynamic pressure coefficient contours of Koyna dam for Koyna Earthquake

The Horizontal crest displacement histories of the dam are obtained for these three earthquake ground motions and shown in Figs. 5-7 respectively. In all the cases it is observed that consideration of the interaction effect in the analysis has drastically enhanced the responses. The major and minor principal stresses at the neck of the Koyna dam are obtained for Koyna earthquake alone and plotted in Figs. 8-9. The hydrodynamic effect of the reservoir water has also been considered in the coupling analysis as mentioned in section 2.3. The dam-foundation-reservoir interaction results are also compared with the responses of the dam alone in Figs. 5-9. Contour plots of the major and minor principal stresses of Koyna dam under Koyna earthquake

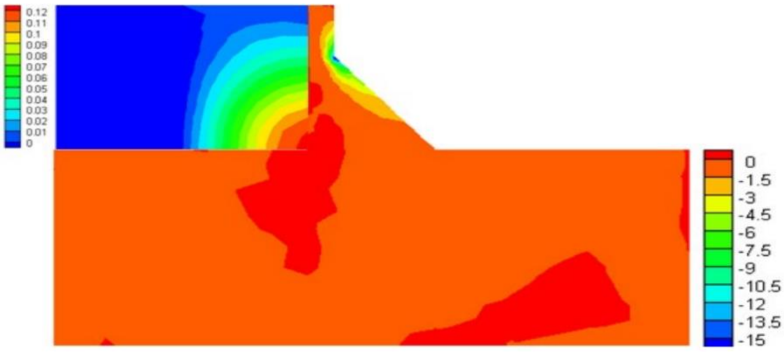


Fig. 11 Minor principal stress (MPa) and hydrodynamic pressure coefficient contours of Koyna dam for Koyna Earthquake

ground motion are plotted along with the hydrodynamic pressure coefficients in Figs. 10-11. The pressure contours are obtained when the maximum magnitude of stresses reach at the neck level.

4.2.2 Seismic responses of the Pine Flat dam

The geometry and the material properties considered for Pine Flat Dam are taken from the

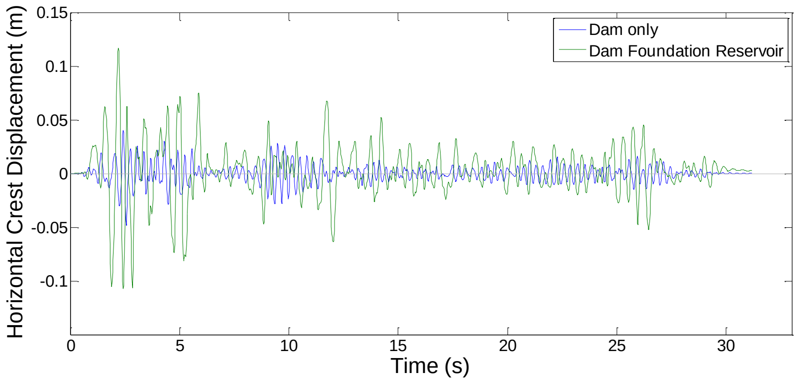


Fig. 12 Crest displacement of Pine Flat dam for El-Centro Earthquake

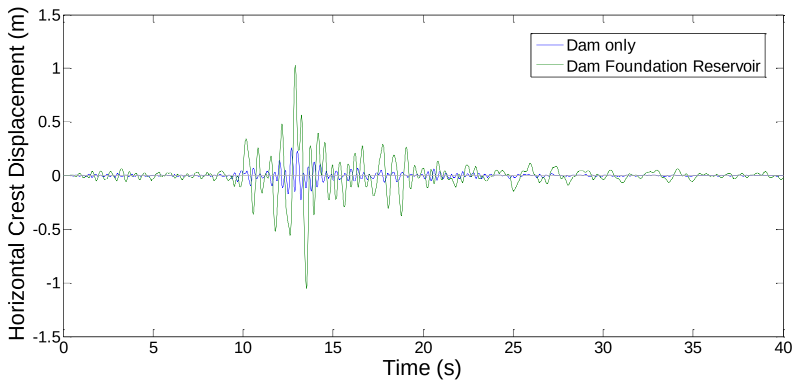


Fig. 13 Crest displacement of Pine Flat dam for Loma Prieta Earthquake

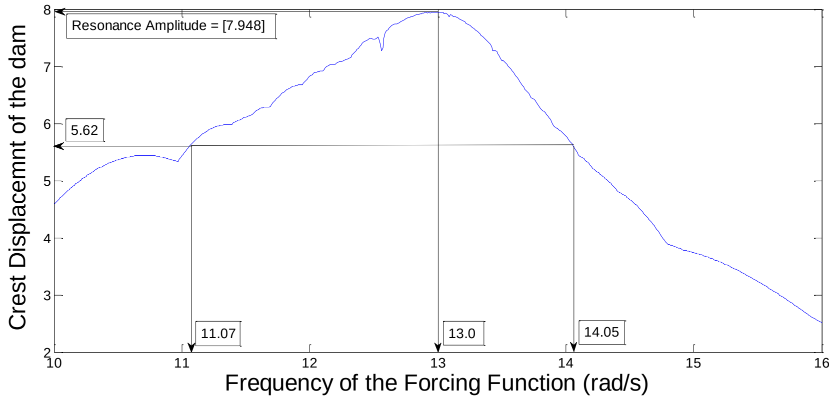


Fig. 14 Crest displacement response spectrum of Koyna Dam considering Coupled dam-foundation-reservoir system

study conducted by Sami and Lotfi (2007). The crest displacement responses of the Pine Flat dam are obtained for El Centro and Loma Prieta Earthquake ground motions. The responses are compared with the coupled system responses and shown in Figs. 12-13 respectively.

4.3 Numerical identification of the effective viscous damping of the coupled system

Forced harmonic half-power bandwidth test has been carried out for numerical identification of the effective viscous damping of the coupled systems. A sinusoidal ground motion with a series of incremental frequencies (10 rad/s to 16 rad/s with an increment of 0.01 rad/s) and amplitude is equal to 'g' (i.e., 9.81 m/s2) has been considered for analysis. The response of the crest displacement has been considered as the response output for which the response spectrum is obtained for the considered series of incremental frequencies. Then finally from the crest displacement response spectrum the effective viscous damping ratio is determined using the standard half-power bandwidth test method (Chopra, 2007). The response spectrum of the crest displacement has been shown in Fig. 14. Two frequencies (w_b =14.05 rad/s and w_a = 11.07 rad/s) are considered from Fig. 14 where the crest displacement response spectrum value is equal to $\frac{1}{\sqrt{2}}$ times of the resonance amplitude (i.e., 7.948). Hence, the effective viscous damping ratio from half power bandwidth method may be obtained approximately as

$$\xi \cong \frac{w_b - w_a}{2w_r} = \frac{(14.05 - 11.07)}{2 \times 13.05} = 0.1146 = 11.46\%$$

4.4 Parametric study

4.4.1 Comparisons based on natural frequencies

In this section, first five natural frequencies (Hz) of different components and their coupled system are compared in Table 4. It is observed from tabular results that the fundamental frequencies are decreased if dam, foundation and reservoir domains are coupled to each other. Among the coupled systems, the dam-foundation-reservoir system has the lowest frequencies.

Table 4 Comparison of first five natural frequencies (Hz)

Dam only	Foundatiuon Only	Reservoir Only	Dam-Foundation	Dam-Reservoir	Dam-Foundation-Reservoir
2.91	3.02	3.50	2.14	2.33	2.07
7.83	5.34	6.22	2.73	3.50	2.28
11.94	5.68	10.49	4.41	6.22	3.62
15.95	5.98	10.89	5.12	7.83	4.57
24.41	6.28	11.68	5.50	10.49	5.26

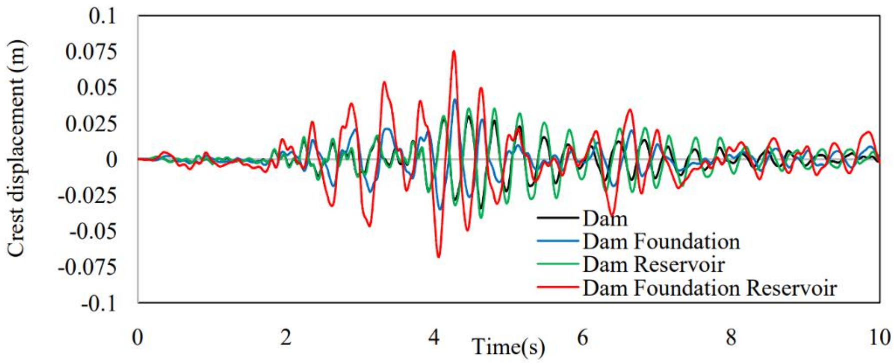


Fig. 15 Comparison of the horizontal tip displacement of Koyna dam

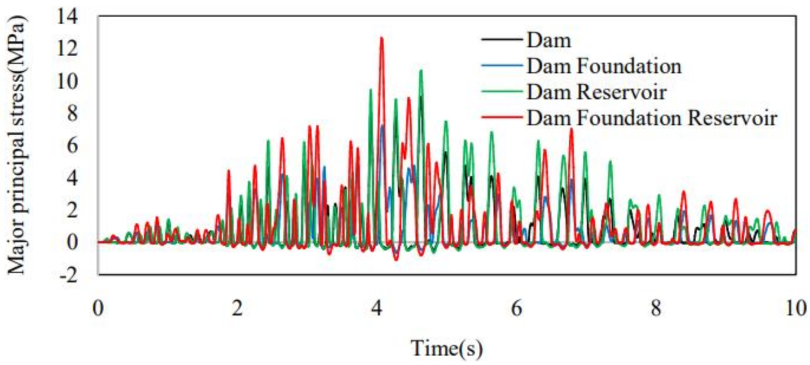


Fig. 16 Comparison of the major principal stress at the neck of the Koyna dam

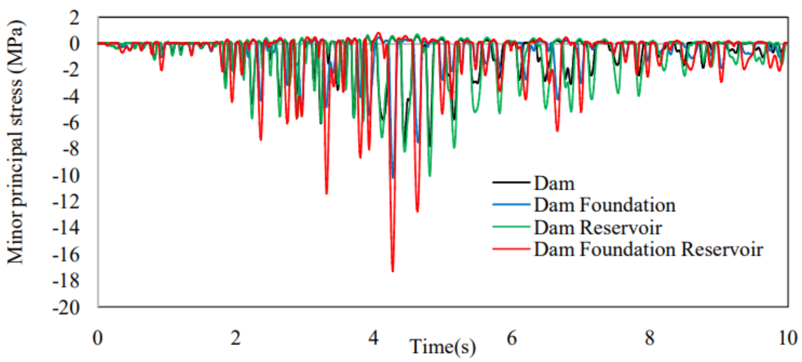
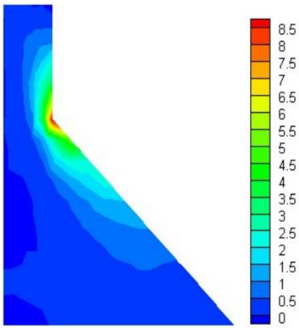
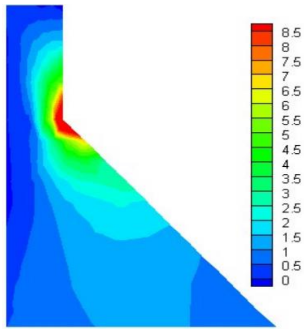


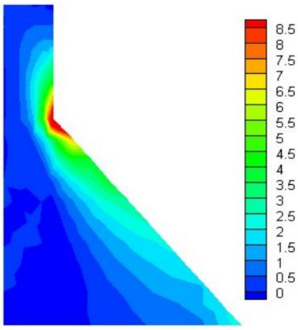
Fig. 17 Comparison of the minor principal stress at the neck of the Koyna dam



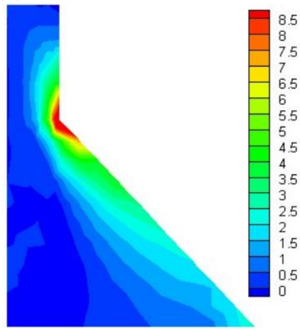
(a) Only dam



(b) Dam reservoir Interaction

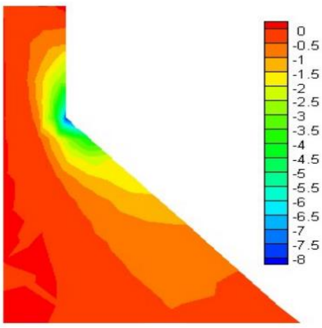


(c) Dam-foundation interaction

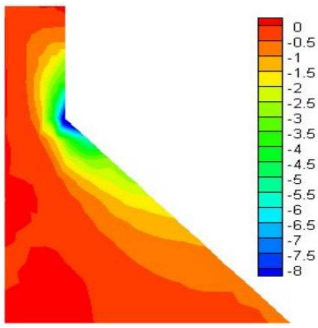


(d) Dam-foundation-reservoir interaction

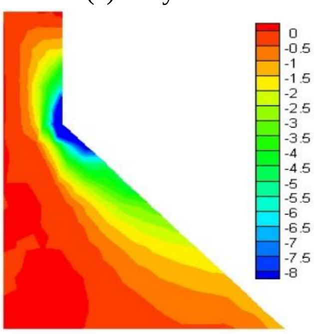
Fig. 18 Contour of major principal stress of the Koyna dam



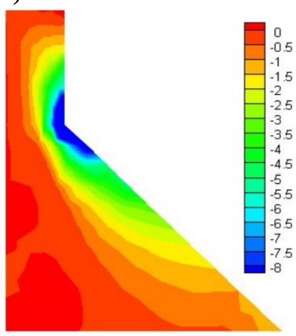
(a) Only dam



(b) Dam reservoir Interaction



(c) Dam-foundation interaction



(d) Dam-foundation-reservoir interaction

Fig. 19 Contour of minor principal stress of the Koyna dam

4.4.2 Comparisons based on seismic responses

A parametric study based on the seismic responses at the salient points of the dam has also been carried out by analyzing Koyna dam under Koyna Earthquake ground motion. The horizontal crest displacements of the dam are obtained for the cases considering the dam alone, dam-foundation coupled system, dam-reservoir coupled system and the complete dam-foundation-reservoir system. The four time history responses are plotted in Fig. 15. It is observed that the crest displacement enhances if the foundation and reservoir domains are coupled with the dam domain and maximum value of displacement is observed when the complete dam-foundation-reservoir system are coupled. Major and minor principal stress history responses at the neck of the dam also get alters with the consideration of the coupling effects as shown in Figs. 16-17 respectively. It is observed that the maximum major and minor principal stresses increase when the three systems are coupled together. This signifies the importance of consideration of the flexible nature of the foundation and the influence of the adjacent reservoir in the seismic analysis of dam.

The stress contours for principal stresses (MPa) of dam are plotted in Figs. 18-19. All the major and minor principal stress contours are obtained when the neck level stresses reach its maximum value. It is observed from the stress contours that incorporation of the foundation and reservoir domain in the analysis of dam changes the distribution of the stresses within the dam body considerably. Considering all the cases, it is noticed that the major principal stress and minor principal stresses reach their maximum magnitudes when the coupled effect of dam-foundation-reservoir is considered.

5. Conclusions

The present paper comprises of the mathematical formulations and finite element solutions of the dam-foundation-reservoir coupled system. Complete coupling among the dam, foundation and reservoir domains are achieved through direct coupling method. The theoretical formulation and finite element implementation techniques of each coupled system are addressed in detail. The implementation of recently developed cone (spring-dashpot) type absorbing boundary condition in the truncated faces of the semi-infinite foundation domain is discussed. The implementation of frequency dependent truncation boundary condition at the truncated face of infinite reservoir domain is also discussed. The responses obtained from each of the coupled systems are validated numerically with the existing literatures. Finally, the complete dam-foundation-reservoir domain is studied in detail for the assessment of the necessity for considering interaction effect among the dam-foundation and reservoir domain. Three different earthquake ground motions containing entirely different frequency contents have been chosen for the analysis of the coupled system and two concrete gravity dams are considered for the present study. The crest displacement histories are obtained and each case it has been observed that ignoring the foundation flexibility and reservoir interaction affects greatly under estimate the seismic responses. The stress histories obtained are also depicted that when the complete coupling among the dam-reservoir-foundation domain is considered then the stresses at the neck level get increases. The viscous damping ratio of the coupled system is numerically identified with the help of half power bandwidth method. Parametric studies are carried out on the basis of natural frequencies and the seismic responses. The complete coupled system shows lowest natural frequency among all other coupled or individual sub-systems. The parametric studies in terms of seismic responses also show that consideration of the coupled effect among the several domains enhances the responses. The present coupling methodology is limited to linear analysis though it can be utilized for preliminary assessment of the dam responses and the hydrodynamic pressures arises on the upstream face of the dam considering complete interaction effects of dam-foundation and reservoir domain. Under strong earthquake ground motion, the development of neck level crack and its propagation need to be addressed with proper nonlinear analysis schemes. For large overall motion of the dam with free surface flow of the reservoir subjected to strong earthquake ground motion more advanced coupling strategies (Kassiotis *et al.* 2010) can be followed. In the complete dam-foundation-reservoir coupled system one can incorporate the uplifting and sliding phenomena at the dam base (Ibrahimbegovic and Wilson, 1990, 1992) for more realistic responses of the dam by reducing the potential stresses through formation of fracture. Propagation of saturated cracks in a porous dam body (Hadzalec *et al.* 2018, 2019) due to the continuous contact with reservoir water at the upstream face of the dam can also be included in the present coupled algorithm to quantify structural safety of the dam.

Acknowledgments

The authors are thankful to the three reviewers for their suggestions to improve the quality of the manuscript in the peer review process.

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