*ICOLD Symposium on Sustainable Development of Dams and River Basins, 24th - 27th February, 2021, New Delhi*

# A FINITE ELEMENT FRAMEWORK FOR THE SEISMIC ANALYSIS OF CONCRETE GRAVITY DAMS CONSIDERING FLUID-STRUCTURE-SOIL INTERACTION

**SOUMYA GORAI AND DAMODAR MAITY**
*Department of Civil Engineering, Indian Institute of Technology Kharagpur, West Bengal, India*

## ABSTRACT

*Seismic safety of concrete gravity dams in the areas of high seismicity is of great concern in recent times. This article presents a dynamic analysis of concrete gravity dams considering fluid-structure-soil interaction under strong ground motions. Two-dimensional numerical modeling of dam-reservoir-foundation system is carried out using finite element method in a GUI based MATLAB algorithm. Dam and foundation domain is developed using displacement based formulation whereas modeling of reservoir domain is performed using pressure based formulation. Interaction of reservoir with dam and foundation is taken care by direct coupling methodology. Time history analysis is carried out under real earthquake ground motion. Seismic response of the dam, reservoir and foundation, with and without interaction between those respective domains, are evaluated to study the influence of reservoir and foundation on the behaviour of dam. It is revealed that seismic behaviour of concrete gravity dam is significantly altered when interaction with reservoir and foundation is considered. Hydrodynamic pressure of the reservoir and stress distribution in foundation are also affected due to the fluid-structure-soil interaction.*

**Keywords :** *Concrete gravity dams, Finite element method, Fluid-structure-soil interaction, Earthquake analysis, Time history analysis.*

## 1. INTRODUCTION

Earthquakes play an important role in design and proper functioning of dams. Ground shaking is considered as main hazard for large dams. Concrete gravity dams are massive structures, constructed across a river or stream to hold the flow of water to control floods. The retained water is utilized for farming, water supply, electricity generation, recreation, etc. Engineers had started designing dams at 1930s using Pseudo-static method. In this method, the earthquake activity is represented using a seismic coefficient. Because of large uncertainties in ground motion intensity of strong earthquakes, pseudo-static method is not entirely reliable for designing dams in earthquake prone areas. There are few cases where large concrete dams experienced several level of damages in past earthquakes, such as, Hsinfengking dam (earthquake in China, 1962) (Hariri-Ardebili, 2016), Koyna dam (Koyna earthquake, 1967) (Mridha & Maity, 2014), Sefid Rud buttress dam (Manjil earthquake, 1990). Much developments have been taken place in the area of numerical analysis of dams since last century, and hence Pseudo-static method has been considered obsolete in current scenario. There are several factors that should be taken care during numerical analysis of concrete gravity dams. Those critical factors are (i) complex geometry of dam, (ii) interaction with reservoir, (iii) compressibility of water, (iv) interaction with foundation, (v) effect of sloshing waves, (vi) Implementation of appropriate boundary condition for energy dissipation. From initially proposed Pseudo static method to well-known FEM and FEM-BEM hybrid approach, researchers have developed and implemented various methods for analysis of concrete gravity dams under seismic excitation. FEM has become more popular over the years for its straightforwardness. Chopra and his co-workers (Chopra et al, 1969; Chopra & Chakrabarti, 1972) have carried out some pioneering work in the field of earthquake engineering of concrete gravity dams. It was explicitly revealed that interactive forces from reservoir affect the deformation and stresses in concrete gravity dam (Chopra & Chakrabarti, 1973). Eulerian technique (Chopra & Chakrabarti, 1981; Hall & Chopra, 1982; Maity & Bhattacharyya, 1999) is utilized by most researchers for modeling of reservoir in which the unknown field variable is taken as dynamic pressure in governing differential equation. On the contrary, the structure is modeled by displacement based technique. Energy dissipation at the truncation end of the reservoir have carefully been tackled by various researchers introducing suitable boundary condition in time domain (Sharan, 1987; Maity & Bhattacharyya, 1999; Gogoi & Maity, 2006) or in frequency domain (Samii & Lotfi, 2012). The boundary condition proposed by Gogoi & Maity (2006) is most advanced and give appropriate results for any excitation frequency. Another complicated issue in numerical analysis is the appropriate modeling of semi-infinite soil domain which should not be neglected. Wave propagation through soil domain is a critical factor which is looked upon extensively over the decades. Cone boundary condition (Meek & Wolf, 1993; Kellezi, 2000; Mandal & Maity, 2016a) is proven to be most appropriate for wave propagation through soil domain and appropriate mechanism for prevention of wave reflection from boundary. Interaction between dam, reservoir and foundation can be enforced by two approaches, namely, indirect coupling and direct coupling. Iterative scheme is followed in indirect coupling (Gogoi & Maity, 2007; Burman et al, 2011) which require more computational time. Whereas, direct coupling (Mandal & Maity, 2016b; Gorai & Maity, 2019) requires less computational time but special efforts. Nonlinear behaviour of concrete and soil during strong earthquakes has also been investigated by few researchers. However, a complete and straightforward framework for seismic analysis of concrete gravity dams combining all important factors is not yet well established.

This study deals with a numerical investigation on dynamic behaviour of concrete gravity dams considering fluid-soil-structure interaction using finite element method. Free and forced vibration analysis are performed on three domains; dam, reservoir, foundation, and sub-systems considering interaction between them. A real time earthquake record is selected for time history analysis. Results are presented in terms of displacement, stresses of dam, dynamic pressure in reservoir and stress distribution in foundation.

## 2. METHODOLOGY

### 2.1 Numerical modeling of dam-reservoir-foundation system

Finite element method is adopted for numerical formulation of the coupled system. Numerical analysis of the coupled system is performed in a GUI based MATLAB program. The unknown variable in formulation of dam and foundation is considered displacement. Whereas, pressure is taken as unknown variable in reservoir. The dam and foundation is assumed to be in the state of plane strain. Interaction between structure (dam & foundation) and fluid (reservoir) domain is enforced by direct coupling methodology with the help of a coupling term. Radiation of energy at the boundaries of reservoir and foundation is considered by implementing suitable artificial non-reflecting boundary conditions. Energy dissipation at the bed of the reservoir is also taken into account. Sloshing wave effects at the free surface of the reservoir is not considered. The global equilibrium equation of which is solved to calculate the response of coupled system is as follows,

$$\begin{bmatrix} E & \rho_f Q_d^T & \rho_f (Q_{dc}^T + R_{fc}^T) & \rho_f R_f^T \\ 0 & M_{dd} & M_{dc} & 0 \\ 0 & M_{cd} & M_{cc} & M_{cf} \\ 0 & 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{P} \\ \ddot{U}_d \\ \ddot{U}_c \\ \ddot{U}_f \end{Bmatrix} + \begin{bmatrix} A & 0 & 0 & 0 \\ 0 & C_{dd} & C_{dc} & 0 \\ 0 & C_{cd} & C_{cc} & C_{cf} \\ 0 & 0 & C_{fc} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{P} \\ \dot{U}_d \\ \dot{U}_c \\ \dot{U}_f \end{Bmatrix} +$$

$$\begin{bmatrix} G & 0 & 0 & 0 \\ -Q_d & K_{dd} & K_{dc} & 0 \\ -(Q_{cd} + R_{cf}) & K_{cd} & K_{cc} & K_{cf} \\ -R_f & 0 & K_{fc} & K_{ff} \end{bmatrix} \begin{Bmatrix} P \\ U_d \\ U_c \\ U_f \end{Bmatrix} = - \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & M_{dd} & M_{dc} & 0 \\ 0 & M_{cd} & M_{cc} & M_{cf} \\ 0 & 0 & M_{fc} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{U}_i^g \\ \ddot{U}_d^g \\ \ddot{U}_c^g \\ \ddot{U}_f^g \end{Bmatrix} \qquad ...(1)$$

The description of specific terms and finite element modeling can be found in the study of Mandal & Maity (2016b) and Gorai & Maity (2019). The geometry of Koyna dam, Maharashtra (Figure 1) is considered for numerical application. The size of the foundation domain is considered to be extended up to a distance equal to the height of dam ($H_0$) in downstream and upstream direction, and in vertical direction beneath the dam. Spring-dashpots are attached at three sides of foundation domain to represent the cone type boundary condition. The depth of reservoir water is considered as $H_r - 0.95H_0$. The length of the reservoir is also truncated at a distance equal to the height of dam, and non-reflecting boundary condition (Gogoi & Maity, 2006) is implemented at the boundary. Absorption of longitudinal waves at reservoir bottom due to sedimentary material is also considered by reflection coefficient. (Gogoi & Maity, 2007). The material properties are selected as follows: elastic modulus of concrete = $31\times10^9$ N/m$^2$, Poisson's ratio of concrete = 0.2, unit weight of concrete = 2643 kg/m$^3$, acoustic wave speed in water = 1440 m/s, mass density of water = 1000 kg/m$^3$, elastic modulus of soil = $16.86\times10^9$ N/m$^2$, Poisson's ratio of soil = 0.18, unit weight of soil = 2701 kg/m$^3$. 5% material damping is considered for dam and foundation domain. 8-noded isoparametric elements are used for discretization of different domains. A mesh sensitivity study is also performed to fix an optimum mesh. The geometry and finite element model of dam-reservoir-foundation coupled system is shown in Figure 2.

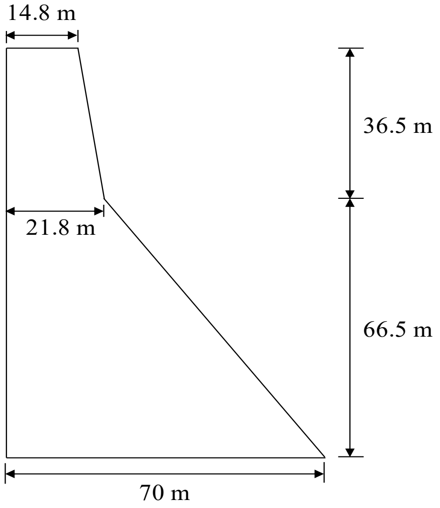


**Figure 1** : Geometry of Koyna dam

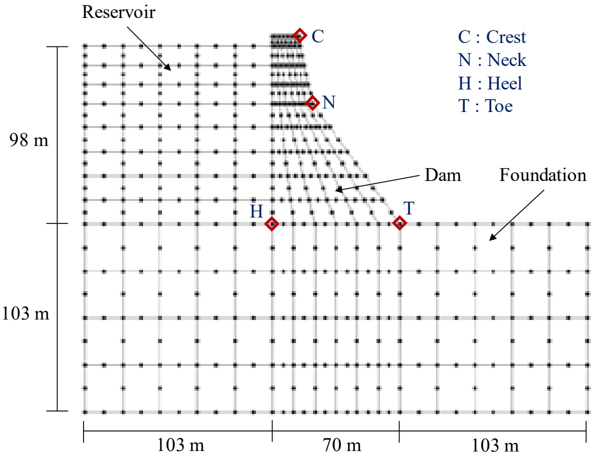


**Figure 2** : Finite element model of dam-reservoir-foundation system

## 2.2 Analysis Scheme

The Newmark-beta method (average acceleration) is chosen for performing time history analysis. As the truncation boundary condition of the reservoir is frequency dependent, Wavelet Transformation (Heidaria & Salajegheh, 2009) of seismic excitation is carried out for capturing time-wise frequency distribution of non-stationary earthquake signal.

## 3. ANALYSIS AND RESULTS

The ground motion record (component N175E) at the station Pacoina Dam (downstream) during Northridge Earthquake is selected as earthquake excitation. The acceleration time history is scaled to a PGA level 0.24g (Figure 2) according to the zone factor of Zone IV as specified in Indian Standard 1893: 2016. Forced vibration analysis is carried out on six different domains and sub-systems, such as (i) dam, (ii) reservoir, (iii) foundation, (iv) dam-reservoir, (v) dam-foundation, (vi) dam-reservoir-foundation. Prior to the forced vibration analysis natural frequencies (Table 1) of different domains and sub-systems are evaluated. It is observed that interaction with reservoir and foundation decreases the natural frequency, and the dam-reservoir-foundation system shows the least natural frequencies among all the domains and subsystems. The scaled acceleration time history as shown in Figure 3 is applied as external seismic excitation in only horizontal direction for time history analysis.

**Table 1** : Natural frequencies (Hz) of different domains and sub-systems.

| Mode no. | Dam | Foundation | Reservoir | Dam-foundation | Dam-reservoir | Dam-reservoir-foundation |
|---|---|---|---|---|---|---|
| 1st | 3.21 | 1.63 | 3.49 | 1.46 | 2.70 | 1.33 |
| 2nd | 8.49 | 1.91 | 7.82 | 1.69 | 3.83 | 1.53 |
| 3rd | 10.97 | 2.28 | 10.48 | 2.12 | 7.09 | 2.03 |

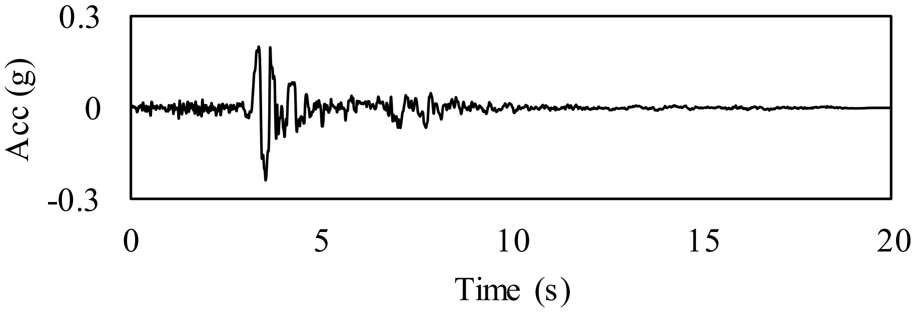


**Figure 3** : Scaled acceleration time history at the station Pacoina dam (downstream), Northridge earthquake

Relative horizontal displacement histories at the crest (node C) of the dam for different subsystems are obtained and shown in Figure 4 with positive sign indicate downstream deflection. It can be observed that interactive forces from foundation and reservoir increase the deflection of the dam. Highest relative horizontal crest displacement is occurred when interaction of reservoir and foundation are considered together. Figure 5 and Figure 6 show the major principal stress (tensile) history at heel (node H) and neck (node N) for different sub-systems, respectively. It is clearly noticeable that heel region experience lowest tensile stress in empty reservoir and rigid base condition. As the deformation of the dam is increased with the inclusion of interactive force from reservoir and foundation, tensile stress at heel is also enhanced. The heel region experience maximum tensile stress in the system dam-reservoir-foundation. Neck region experience highest tensile stress for the system dam-foundation. Tensile stress at heel reaches maximum value at the time instant 3.74 sec in the dam-reservoir-foundation system. Hence, hydrodynamic pressure distribution in reservoir at the time instant 3.74 sec for different sub-systems is shown in Figure 7. It is clearly observed alteration in pressure happens due to coupling with dam and foundation domain. Negative pressure occurs for the system reservoir and dam-reservoir, whereas positive pressure occurs for dam-reservoir-foundation system at the same time instant. When analysis of reservoir is performed, dam and foundation domain are considered rigid.

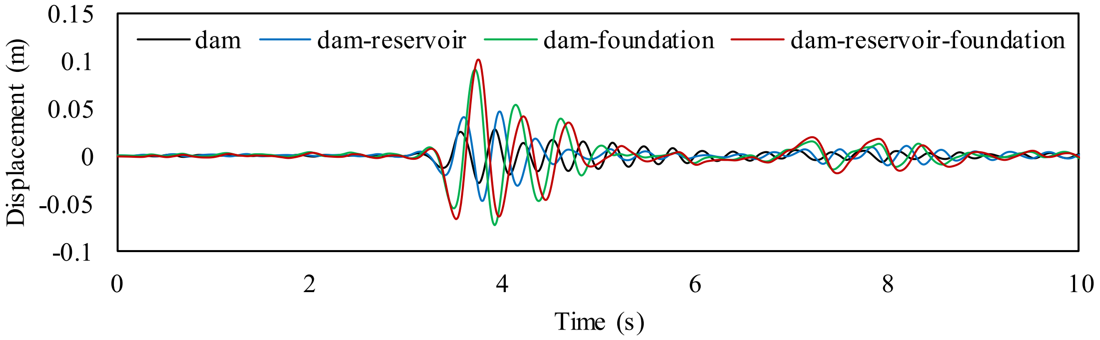


**Figure 4** : Relative horizontal crest displacement histories for different sub-systems

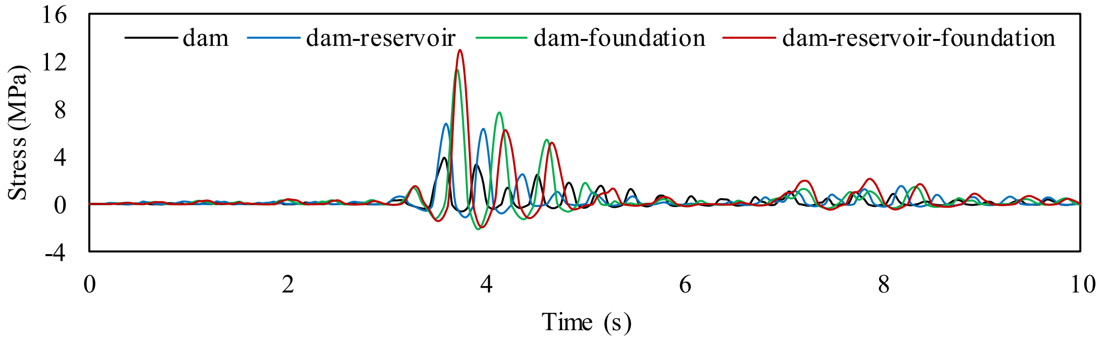


**Figure 5** : Major principal stress history at heel for different sub-systems

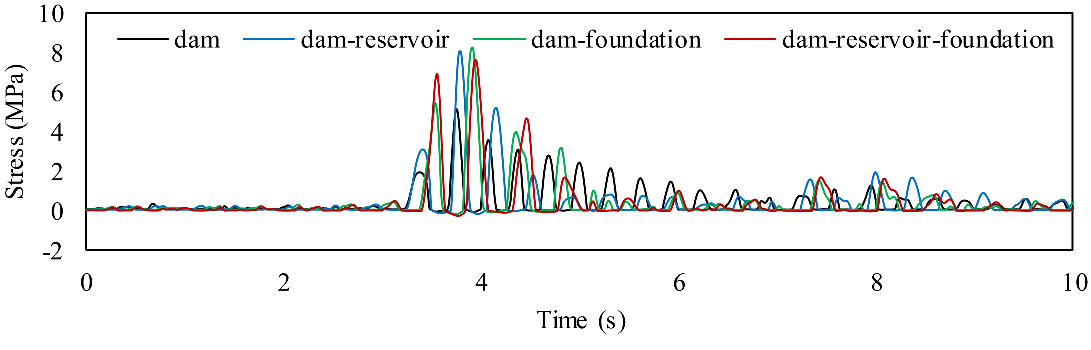
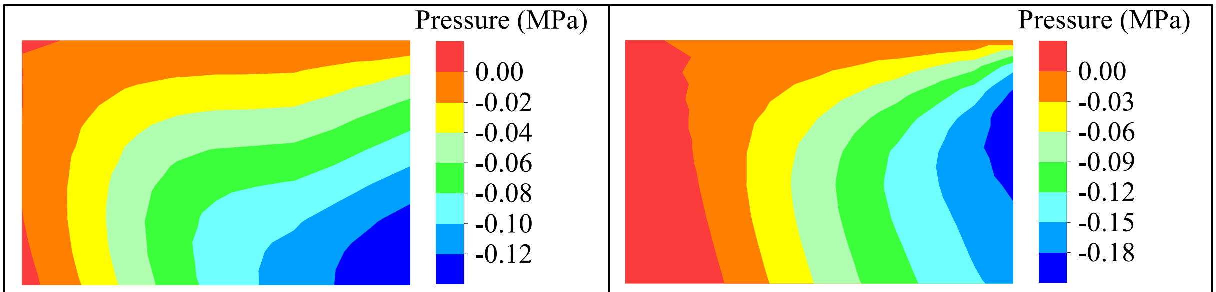


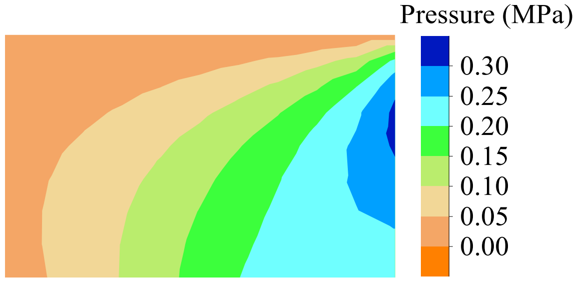
**Figure 6** : Major principal stress history at neck for different sub-systems

Maximum values of displacement and stresses at salient regions of concrete gravity dam for different systems are listed in Table 2. Minor principal stress signifies the compressive stress. It is clearly observed that when interaction effect of reservoir and foundation is considered the maximum horizontal crest displacement (0.1 m) is increased by 257% as compared to the case (0.028 m) of empty reservoir and rigid base condition. It is also revealed that foundation flexibility drastically increases the deflection of the dam. Hydrodynamic effect of the reservoir at the upstream side considerably increases the tensile stress at heel. The heel region experiences a tensile stress of 12.9 MPa in the system dam-reservoir-foundation which is 228% higher than the value of tensile stress at heel (3.93 MPa) when only the dam domain is considered. The major and minor principal stress contour of foundation at the same time instant 3.74 sec for different sub-systems are shown in Figure 8 which clearly indicate interaction with reservoir and dam considerably change the stresses in foundation. The foundation domain is analyzed in the absence dam and reservoir, and in that case the stresses in foundation do not vary much over the domain (Figure 8a). However, when the dam is considered highest tensile stress occurs just beneath the heel, and highest compressive stress occurs beneath the toe (Figure 8).



(a) reservoir

(b) dam-reservoir

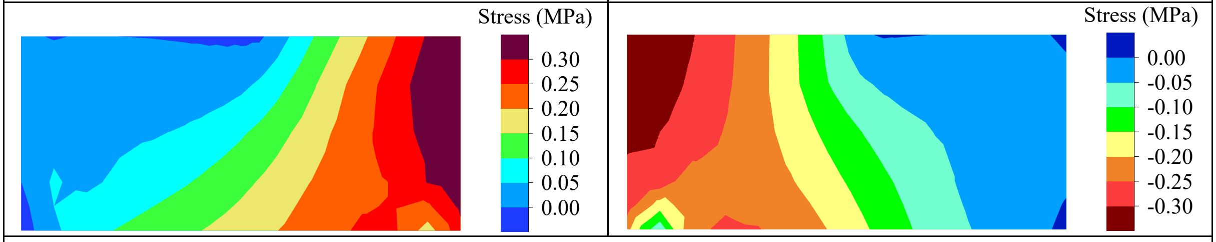


(c) dam-reservoir-foundation

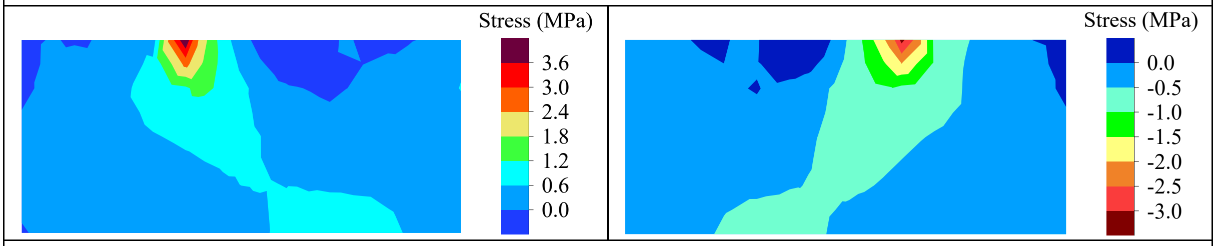
**Figure 7** : Distribution of hydrodynamic pressure in reservoir for different sub-systems

Major principal stress

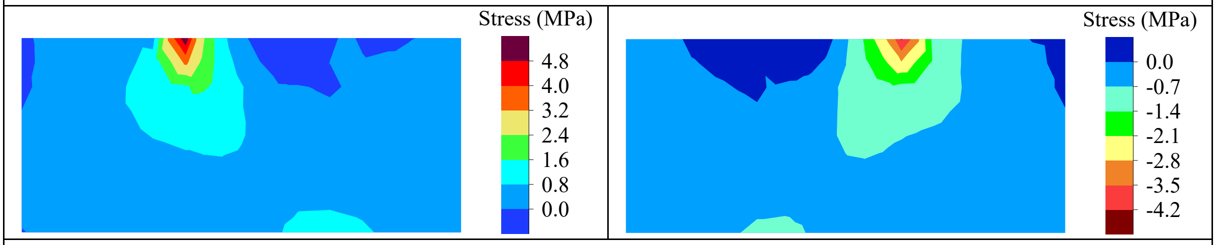
Minor principal stress



(a) foundation



(b) dam-foundation



(c) dam-reservoir-foundation

**Figure 8** : Major and minor principal stress contour of foundation domain for different sub-systems

**Table 2** : Maximum value of seismic response quantities at salient regions of the dam

| Sub-systems | Relative horizontal displacement (m) | Major Principal stress (MPa) | | | Minor principal stress (MPa) | | |
|---|---|---|---|---|---|---|---|
| | *crest* | *heel* | *neck* | *toe* | *heel* | *neck* | *toe* |
| Dam | 0.028 | 3.93 | 5.08 | 0.9 | 3.44 | 4.94 | 1.15 |
| Dam-reservoir | 0.047 | 6.81 | 8.02 | 1.79 | 6.86 | 7.88 | 1.81 |
| Dam-foundation | 0.09 | 11.21 | 8.23 | 7.09 | 10.42 | 7.6 | 9.04 |
| Dam-reservoir-foundation | 0.1 | 12.9 | 7.61 | 6.76 | 9.84 | 9.76 | 10 |

## 4. CONCLUSIONS AND SUMMARY

Free and forced vibration analysis of concrete gravity dams is performed considering fluid-structure-soil interaction in finite element framework. Seismic behaviour of an existing or newly proposed concrete gravity dam can be assessed through the modeling and analysis procedure discussed here. It is revealed that natural frequency of dam-reservoir-foundation coupled system is significantly reduced as compared to the value obtained when the domains are considered separately. Time history analysis under a real time earthquake motion reveals that consideration of coupling effect of reservoir and foundation significantly enhances the crest displacement and stresses in dam. Dynamic pressure in reservoir and stresses in foundation is also greatly affected due to the interaction forces coming from other domains.

## REFERENCES

Burman, A., Maity, D., Sreedeep, S. & Gogoi, I. 2011. Long-term influence of concrete degradation on dam–foundation interaction. *International Journal of Computational Methods* 8(3): 397–423.

Chakrabarti, P. & Chopra, A. K. 1973. Earthquake analysis of gravity dams including hydrodynamic interaction. *Earthquake Engineering & Structural Dynamics* 2: 143–160.

Chopra, A. K. & Chakrabarti, P. 1981. Earthquake analysis of concrete gravity dams including dam-water- foundation rock interaction. *Earthquake Engineering and Structural Dynamics* 9: 363–383.

Chopra, A. K., & Chakrabarti, P. 1972. The earthquake experience at koyna dam and stresses in concrete gravity dams. *Earthquake Engineering & Structural Dynamics* 1: 151–164

Chopra, A., Wilson, E. & Farhoomand, I. 1969. Earthquake analysis of reservoir-dam systems. *Proceedings of the 4th World Conference on Earthquake Engineering*, Santiago, Chille.

Gogoi, I. & Maity, D. 2006. A non-reflecting boundary condition for the finite element modeling of infinite reservoir with layered sediment. *Advances in Water Resources*, 29: 1515–1527

Gogoi, I. & Maity, D. 2007. Influence of sediment layers on dynamic behavior of aged concrete dams. *Journal of Engineering Mechanics* 133(4): 400–413.

Gorai, S. & Maity, D. 2019. Seismic response of concrete gravity dams under near field and far field ground motions. *Engineering Structures* 196: 109292.

Hall, J. & Chopra, A. 1982. Two-dimensional dynamic analysis of concrete gravity and embankment dams including hydrodynamic effects. *Earthquake Engineering & Structural Dynamics* 10:305–332.

Hariri-Ardebili, M.A. 2016. Concrete dams: From failure modes to seismic fragility. *Encyclopedia of Earthquake Engineering* 00:1–26.

Heidaria, A. & Salajegheh, E. 2009. Wavelet analysis for processing of earthquake records. *Asian Journal of Civil Engineering* 10(4): 397–408.

Kellezi, L. 2000. Local transmitting boundaries for transient elastic analysis. *Soil Dynamics and Earthquake Engineering* 19(7): 533–547

Maity, D. & Bhattacharyya, S. K. 1999. Time-domain analysis of infinite reservoir by finite element method using a novel far-boundary condition. *Finite Elements in Analysis and Design* 32:85–96.

Mandal, A. & Maity, D. 2016a. Finite element analysis of dam-foundation coupled system considering cone-type local non-reflecting boundary condition. *Journal of Earthquake Engineering* 20: 428–446

Mandal, K. K. & Maity, D. 2016b. Transient response of concrete gravity dam considering dam-reservoir-foundation interaction. *Journal of Earthquake Engineering* 00: 1–23

Meek, J. W. & Wolf, J. P. 1993. Why cone models can represent the elastic half-space. *Earthquake Engineering and Structural Dynamics* 22: 759–771

Mridha, S. & Maity, D. 2014. Experimental investigation on nonlinear dynamic response of concrete gravity dam-reservoir system. *Engineering Structures* 80:289–297

Samii, A. & Lotfi, V. 2012. Application of H-W boundary condition in dam-reservoir interaction problem. *Finite Elements in Analysis and Design* 50: 86–97.

Sharan, S. K. 1987. Time-domain analysis of infinite fluid vibration. *International Journal for Numerical Methods in Engineering* 24: 945–958.