

# Improving Seismic Performance of Concrete Gravity Dams Considering Hydrodynamic Effect and Soil-Structure Interaction

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**Abstract**— A gravity dam is a solid structure, made of concrete or masonry, constructed across a river to create a reservoir on its upstream. The theory behind gravity dams is that their own weight should be sufficient to withstand the hydrostatic pressures affecting them. Gravity dams are very important structures. The collapse of a gravity dam due to earthquake ground motion may cause an extensive damage to property and life losses. Therefore, the proper design of gravity dams is an important issue in dam engineering. In this study 2D dam-reservoir-foundation system is considered using finite element modeling (ABAQUS) to investigate the effects of the upstream side angle and the cross section changes in the dam structure on seismic damages during the Koyna earthquake. For this purpose, we firstly created a model to verify the failure mechanism of the Koyna dam, then changed the dam geometry for other models. Also, viscous dashpot boundaries were used to prevent the return of seismic waves into the models, which increased the speed of creating models compared to the common infinite element boundaries in Abaqus. Finally, it was observed that the dam with a trapezoidal shape and upstream side angle experienced minor damage compared to other shapes. Therefore, to reduce the effects of earthquakes in concrete gravity dams, it is advised to use the downward water force through an upstream angle to minimize the heel damages and avoid changing the cross-section of the dam as much as possible.

**Keywords**— Concrete Gravity Dam, Soil-Structure Interaction, Finite Element Modelling, CDP Model, Modal Analysis, Earthquake Ground Motion.

## 1. INTRODUCTION

A gravity dam is a solid structure, made of concrete or masonry, constructed across a river to create a reservoir on its upstream. The theory behind gravity dams is that their own weight should be sufficient to withstand the hydrostatic pressures affecting them. Gravity dams are very important structures. The collapse of a gravity dam due to earthquake ground motion may cause an extensive damage to property and life losses. Therefore, the proper design of gravity dams is an important issue in dam engineering. An integral part of this procedure is to accurately estimate the dam earthquake response. The prediction of the actual response of a gravity dam subjected to earthquake is a very complicated problem. It depends on several factors such as dam-foundation interaction, dam-water interaction, material model used and the analytical model employed. In fluid-structure interaction one of the main problems is the identification of the hydrodynamic pressure applied on the dam body during earthquake excitation. During the recent years, the seismic behavior of concrete gravity dams was in the center of consideration of dam engineers. Numerous researches have been conducted in order to determine how the dams behave against the seismic loads. Many achievements were obtained in the process of analysis and design of concrete dams including dam-reservoir-foundation interaction during an earthquake [1].

The response of concrete gravity dams subjected to seismic loading is a combined effect of the interaction analyses [2]. There are the reservoir and dam structure interaction and the foundation-dam interaction. The inertia effect between the dam and the reservoir, causes the hydrodynamic forces on the dam, can be modeled in the finite element system by added mass approach or inserting the water element interaction in the model [3].

In the present study, we investigated the effects of the upstream side angle and the cross section changes in dam structure on seismic damages during Koyna earthquake. For this purpose, we first created a model to verify the failure mechanism of the Koyna dam, then changed the dam geometry for other models using finite element software (Abaqus).

## 2. MATERIALS AND METHODS

### 2.1. Koyna Dam

Koyna Dam is a 103 m high concrete gravity dam, situated on the Koyna River in the south-western region of India. In figure 1 the Koyna dam can be observe. Its wall is 853 m long and the dam has a capacity of 310 million m<sup>3</sup>. Construction of the dam began in 1954 and ended in 1963 [4]. The dam was constructed to abate monsoon flood waters, provide irrigation water to the east and provide power to the west.



Fig. 1. Koyna dam

### 2.2. Ground Motions

For this study, the horizontal acceleration record of 1967 Koyna earthquake have been Used. The record is shown in figure 2. The peak horizontal accelerations is 0.474 g with 10 sec time duration.

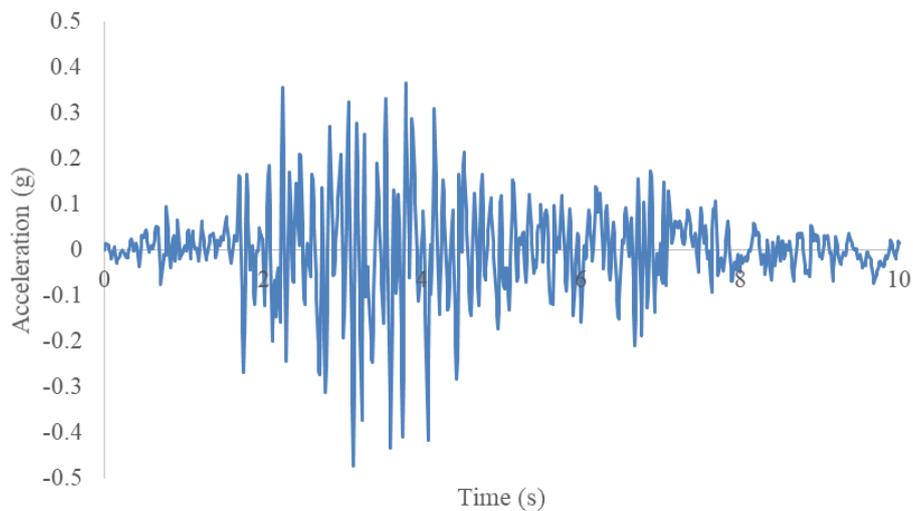


Fig. 2. Horizontal component of Koyna earthquake on December 11, 1967

### 2.3. Numerical Modelling

Koyna concrete dam that is situated in Maharashtra is selected as a case study for this paper. The dam has been analyzed using two-dimensional plane strain formulations. The time history analyses are performed by ABAQUS software throughout this study. Prior to the dynamic simulation, the model is subjected to gravity loading and hydrostatic pressure along the dam-reservoir interface. In the analyses these loads are specified in two consecutive static steps. For the dynamic analysis, in the third step the horizontal acceleration is applied to the model using an implicit step. Chopra et al. (1980) and Vargas et al. (1989) gave all the material properties of dam, foundation, and reservoir of Koyna dam [5, 6]. Parameters of the reservoir water are; bulk modulus  $K_w = 2070$  MPa, and mass density  $\rho_w = 1000$  kg/m<sup>3</sup>. The foundation material is assumed to be linearly elastic. The foundation parameters are; elastic modulus  $E_f = 21600$  MPa, mass density  $\rho_f = 0$  kg/m<sup>3</sup>, and Poisson's ratio  $\nu_f = 0.33$ . And CDP model is used for calculation damages induced in dam during excitation. Here we investigate three different dam with same elevation to capture the effects of geometry on damage pattern induced by earthquake, in figure 3 their geometry can be seen.

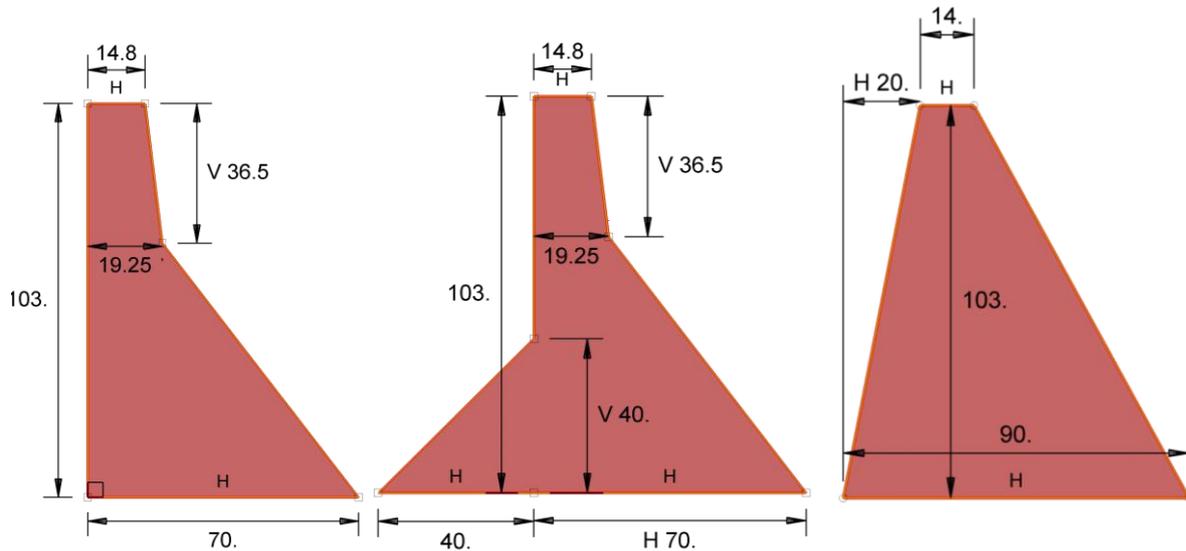


Fig. 3. Geometry of three different dam

2.3.1. Concrete materials

CDP Concrete model is one of the possible constitutive models to predict the behavior of concrete. It describes the constitutive behavior of concrete by introducing the scalar damage variables [7]. The tensile and compressive responses of concrete can be characterized by CDP in figure 4.

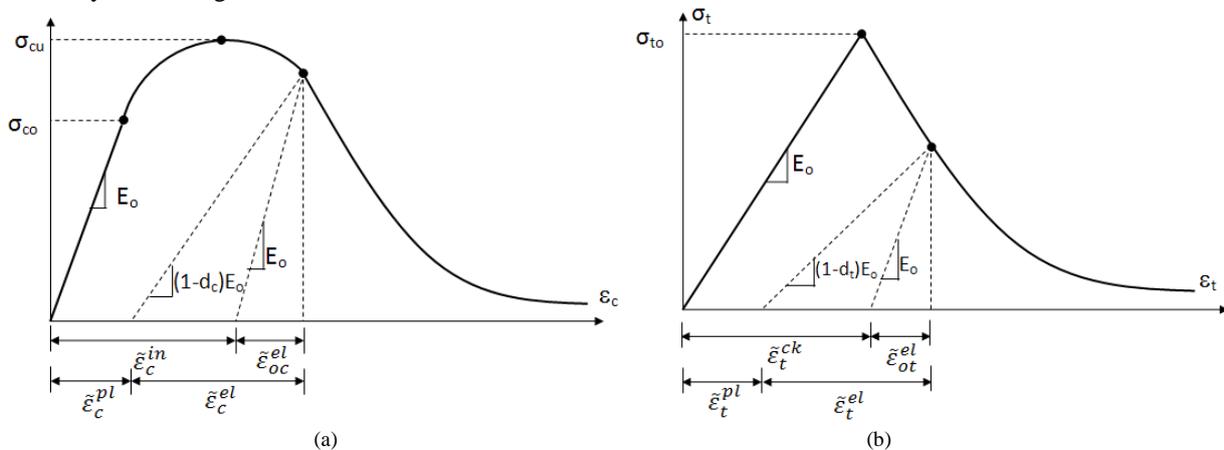


Fig. 4. The behavior of concrete under axial compressive (a) and tension (b) strength [14]

As shown figure 4, the unloaded response of the concrete specimen seems to be weakened because the elastic stiffness of the material appears to be damaged or degraded. The degradation of the elastic stiffness on the strain-softening branch of the stress-strain curve is characterized by two damage variables,  $d_t$  and  $d_c$ , which can take values from 0 to 1. The value of 0 represents the undamaged material whereas the value of 1 represents the total loss of strength.  $E_0$  is the initial (undamaged) elastic stiffness of the material, and  $\epsilon_c^{pl}$ ,  $\epsilon_t^{pl}$ ,  $\epsilon_c^{in}$ ,  $\epsilon_t^{in}$  are the compressive plastic strain, tensile plastic strain, compressive inelastic strain, and the tensile inelastic strain, respectively. The stress-strain relations under the uniaxial tension and compression are taken into account in Eq. (1) and Eq. (2) as;

$$\sigma_t = (1 - d_t) \cdot E_0 \cdot (\epsilon_t - \epsilon_t^{pl}) \quad (1)$$

$$\sigma_c = (1 - d_c) \cdot E_0 \cdot (\epsilon_c - \epsilon_c^{pl}) \quad (2)$$

In this study, we used the CDP model for the dam structure to calculate the failure process in the concrete. In Table 1, the CDP parameters for dam structure are presented [5, 6].

Table. 1. Parameters used in the CDP model for numerical calculations

Density (kg/m <sup>3</sup> )	Poisson's ratio	Young's modulus (MPa)	Dilation Angle	Compressive yield stress (MPa)	Tensile yield stress (MPa)
2643	0.2	31513	36.31	24.1	2.9

Also in figure 5 the tensile behavior of the concrete for CDP model is shown.

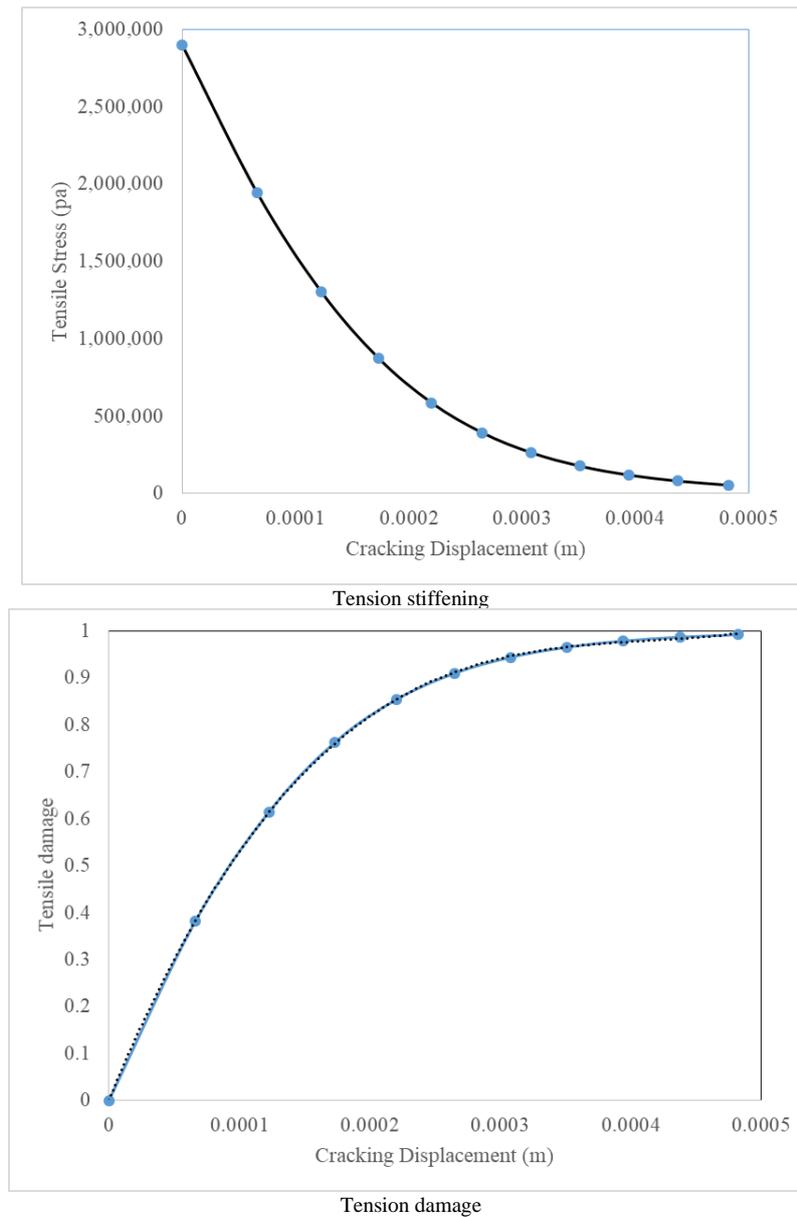


Fig. 5. Tensile material properties of concrete

2.3.2. Damping

Damping can be defined as the loss of energy within a vibrating or a cyclically loaded system, usually dissipated in the form of heat. The damping ratio is commonly used in geotechnical engineering as a measure for energy dissipation during dynamic or cyclic loading. Classical Rayleigh damping is viscous damping which is proportional to a linear combination of mass and stiffness. The Rayleigh damping method can be expressed as [8];

$$C = \alpha M + \beta K$$

Where M and K are the mass and stiffness matrices respectively and  $\alpha$  and  $\beta$  are damping coefficients.  $\alpha$  decides the influence of mass on system damping. The bigger  $\alpha$  is, the higher the damping of low-frequency vibration is;  $\beta$  decides the influence of stiffness on system damping. The bigger  $\beta$  is, the higher the damping of high-frequency vibration is. And defined as;

$$\alpha = \frac{2f_1f_2\xi}{f_1 + f_2} \quad \beta = \frac{2\xi}{f_1 + f_2}$$

Where  $f_1$  is the first natural frequency,  $f_2$  is the second natural frequency. To extract natural frequencies of the dam, modal analyses needs to be done. It is generally accepted that dams have damping ratios of about 2–5%. The material damping ratio  $\zeta$  was chosen with a value of 3 %.

2.3.3. Modal analysis

Natural frequency, time period, and mode shape were specified for the gravity dam models based on the Abaqus software. The first natural frequency for three dam models in this study are shown in figure 6.

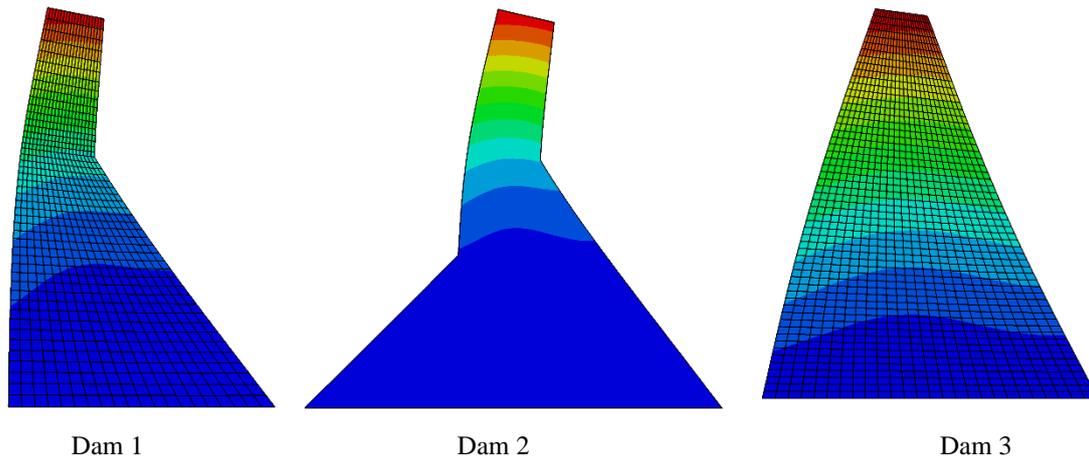


Fig. 6. Modal shapes of all 3 dams for first mode

The first four frequencies of all three dams are illustrated in figure 7 using a bar chart. It can be seen that, almost all three dams have same natural frequencies. Using modal analyses results the damping coefficients were calculated.

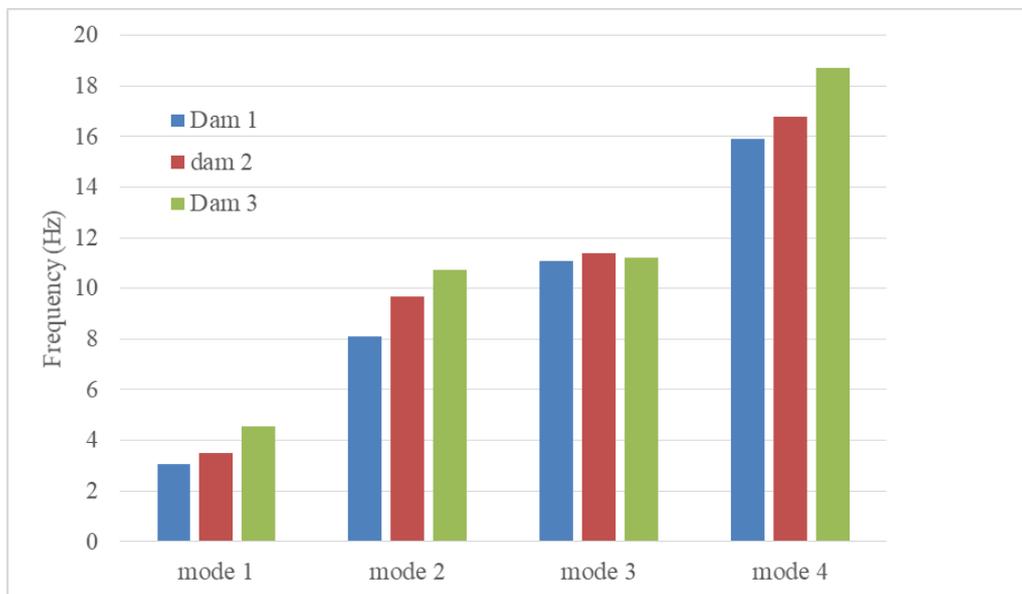


Fig. 7. The modal frequencies for three different dam

Table 2 shows the first four natural frequencies of the dam 1 model (Koyna dam) and compares them with the results obtained by Chopra and Chakrabarti [9]. The comparisons of the results indicates a validity for the present numerical model.

Table 2. A comparison of first four natural frequencies from the FE model with the literature for Koyna dam (dam 1)

Mode number	Natural frequency (Hz)		
	Reference [9]	The present work	Error (%)
1	3.002	3.0638	2
2	7.953	8.0902	1.7
3	10.848	11.072	2
4	15.640	15.89	1.5

### 2.3.4. Absorbing boundaries

In the present study two different kind of absorbing boundary conditions are implemented at the foundation domain. To evaluate both method efficiency and choose the better method for rest of modeling.

#### Viscous dash pot boundaries

A way to eliminate waves propagating outward from the structure is to use Lysmer boundaries [10]. This method consists of simply connecting dashpots to all degrees of freedom of the boundary nodes and fixing them on the other end. Lysmer boundaries are derived for an elastic wave propagation problem in a one-dimensional semi-infinite bar. The damping coefficient  $C_x$  of the dash pot equals;

$$C_x = A\rho c$$

Where A is the cross sectional area of the bar,  $\rho$  is the mass density and c the wave velocity that has to be selected according to the type of wave that has to be absorbed (shear wave velocity  $C_s$  or compressional wave velocity  $C_p$ ). In the figure 8, viscous dashpot boundaries are shown at both sides of the foundation.

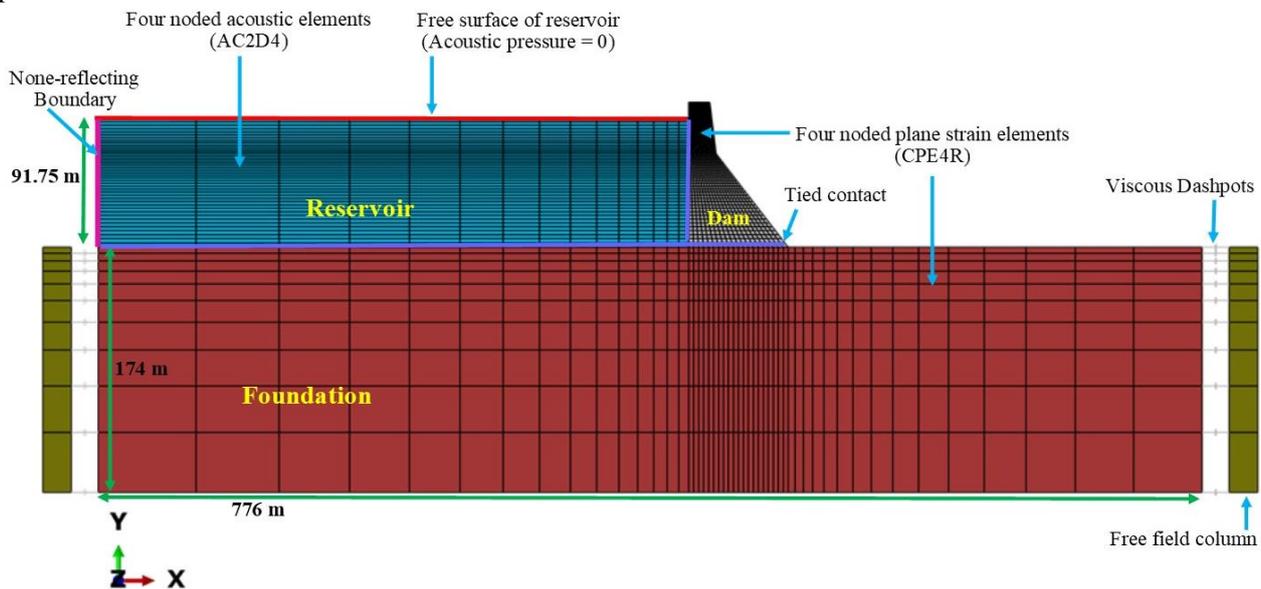


Fig. 8. Model conditions, element type and meshing for model dam 1 by considering the viscous dashpot boundaries at sides of the foundation

#### Infinite element boundaries

As shown in figure 9, CINPE4 infinite elements were used (4-node bilinear plane strain rigid continuum infinite elements) at the bottom and the lateral sides of the foundation to prevent seismic reflection waves back to the gravity dam. These boundaries are created by changing the inp file for each model.

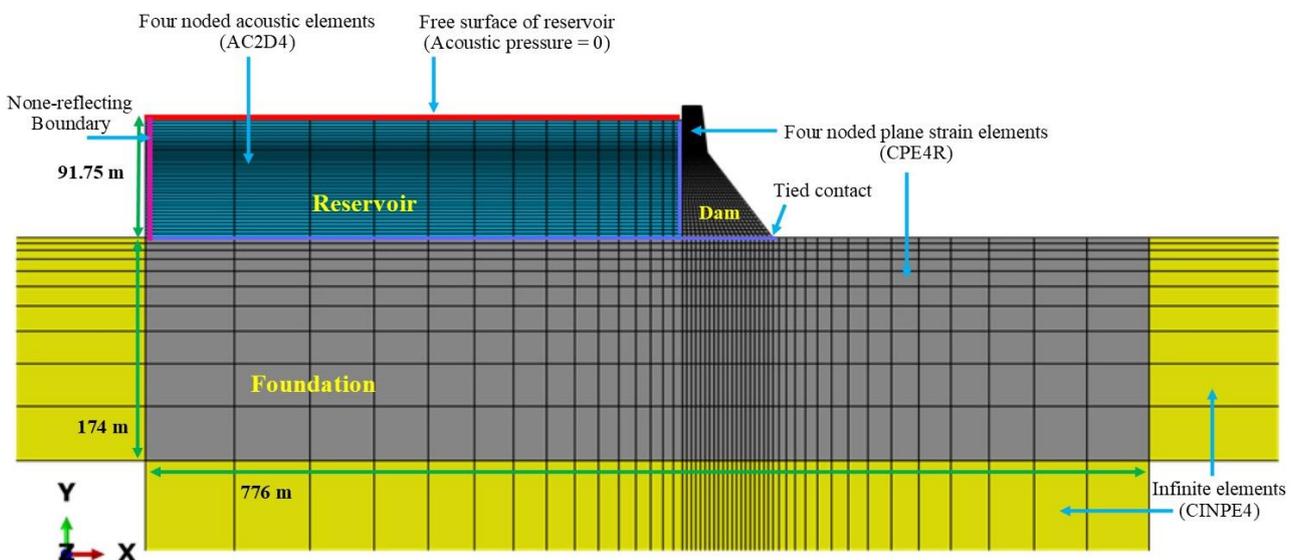


Fig. 9. Model conditions, element type and meshing for model dam 1 (koyna dam) by considering the infinite element boundaries at sides and bottom of foundation

*Results for different boundaries*

From figure 10 it is evident that both models gives almost same damage pattern for Koyna dam and the results are close to the Calayir et al [11] model. Although, for creating infinite element boundaries it needs to do some changes in the inp file and in every model these changes must be repeated. According to this fact we decided to continue with viscous dashpot boundaries to make the modeling process faster. In this part we also did validate our base model for Koyna dam destruction. In other models we just replace the concrete dam with different geometry instead Koyna dam, and all other parameters are same as before.

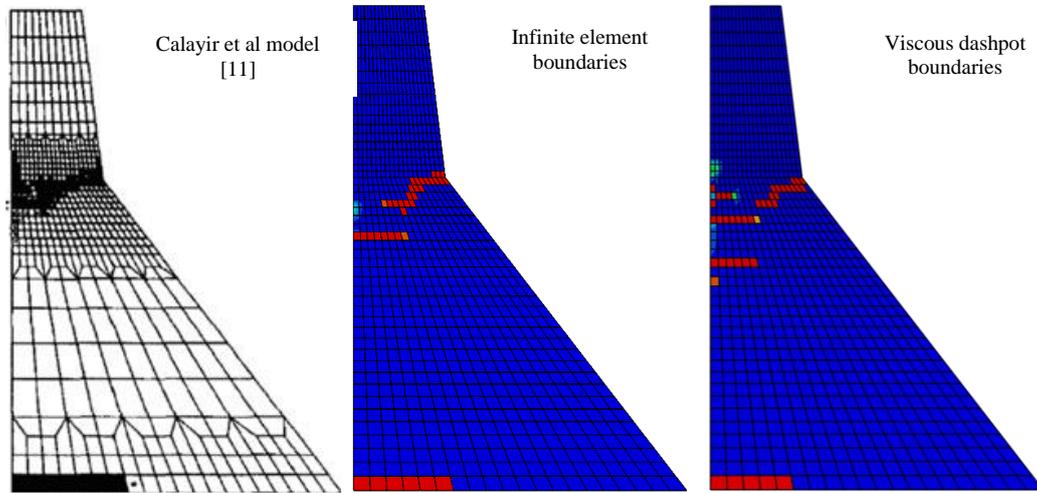


Fig. 10. Comparison of the Koyna dam model (dam 1) with different boundaries to the FEM results from Calayir et al [11]

3. RESULTS AND DISCUSSIONS

3.1. Damages in Dam

The constitutive model used here simulates the tensile damage patterns. The parameter DAMAGET is shown in figures 11–13 for all three dams. If DAMAGET = 1.0 it means, the concrete completely failed with tensile crack and the described material model for that element cannot be consider.

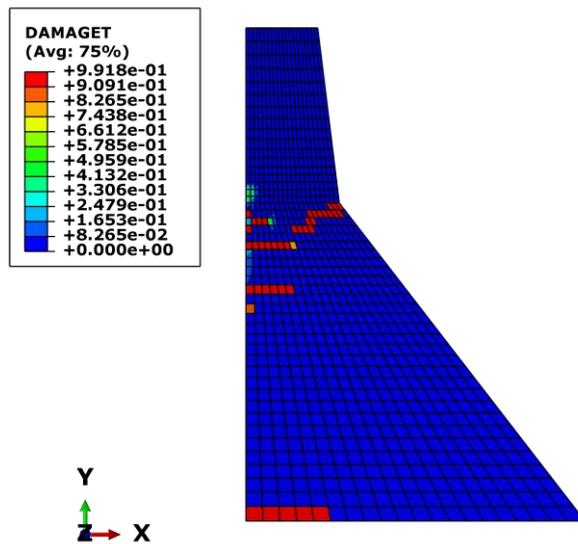


Fig. 11. Tensile damage pattern for dam 1 (koyna dam)

The described material model simulates the tensile damage patterns in the Koyna concrete dam (dam 1) reasonably well. Chopra and Chakrabarti (1971) [12]; Chopra and Chakrabarti (1973) [9]; Jansen (2012) [13] observed the same damage pattern in the Koyna dam.

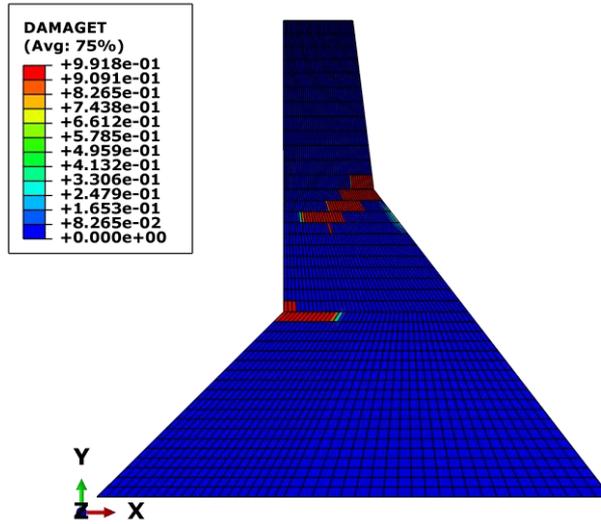


Fig. 12. Tensile damage pattern for dam 2 (just upstream angle)

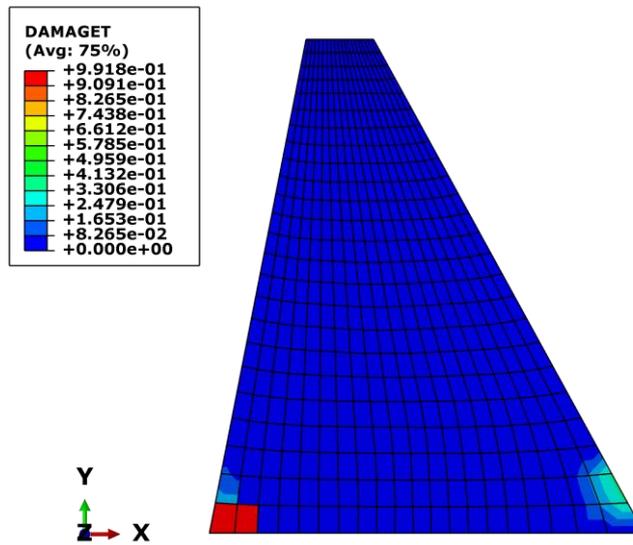


Fig. 13. Tensile damage pattern for dam 3 (with upstream angle and no cross section change)

By looking at damage pattern in all tree dam it can be found that, damages occur at zones in which cross section has changed. And it can be understood that by giving a slight angle for upstream side of the dam, the downward force of water won't let the heel to start cracking.

### 3.2. Displacement

Crest horizontal displacement for the dam finite element models during the Koyna earthquake are illustrated in figure 14. The negative displacement value represents the movement toward the upstream direction.

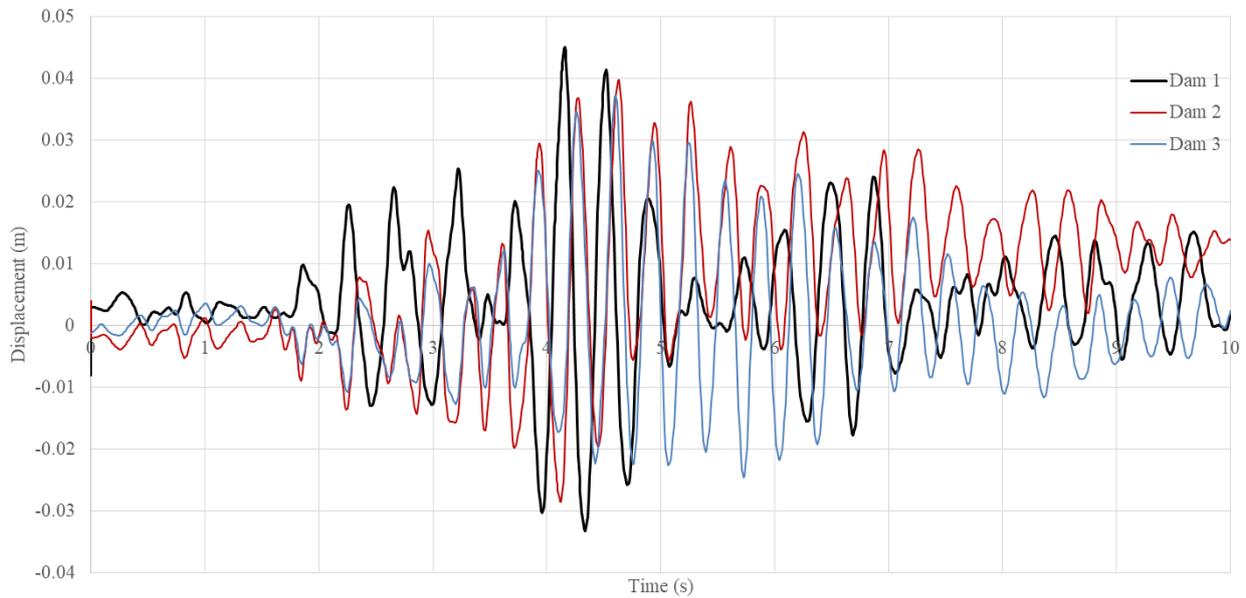


Fig. 14. Dam crest horizontal displacement during Koyna earthquake for all three models

It can be seen that dam with more damage moves with more amplitude. Dam 1 and dam 2 moves with more amplitude compare to the dam 3, because more damages occurred in them. Accordingly, both dam 1 and 2 has residual horizontal displacements. Dam 3 has no residual displacement since it remain almost in total health. Hydrostatic and hydrodynamic pressure of the reservoir make all dams tend to move downstream side. In figure 15 hydrodynamic pressure of the reservoir can be seen during the earthquake.

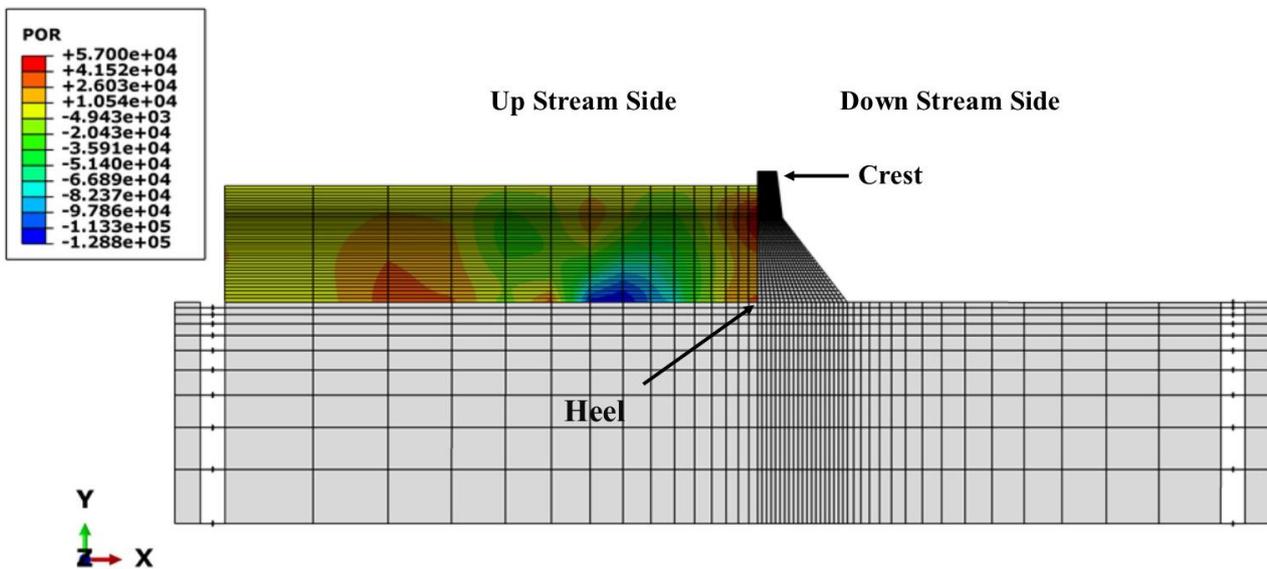


Fig. 15. Reservoir Hydrodynamic pressure during Koyna Excitation

#### 4. CONCLUSIONS

The earthquake response of concrete gravity dam-reservoir-foundation system has been investigated with emphasis on the nonlinear behavior associated with concrete tensile damage. Firstly verification of the dam model for Koyna dam was done, and then, Three different dam model including Koyna dam were created to observe the dam behavior under Koyna earthquake. In all dams we consider cross section changes and upstream side angle on damage pattern, and it was found that upstream angle helped to prevent heel damage by acting downward force because of water weight. Also, cross section changing make the zones critical, and in all these zones tensile damage happened. In the third dam model with no cross section change, tensile damage didn't showed up. And because of the upstream angle, the heel damages decreased dramatically.

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