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Seismic analysis of Fractured Koyna Concrete Gravity Dam

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Abstract. Seismic analysis of a fractured dam is a generally complex problem. This paper presents an earthquake behavior investigation of a fractured concrete gravity dam considering dam-reservoir--foundation rock interaction. The Koyna dam profile, located in India, is adopted in this study. The nonlinear finite element analyses are conducted taking into account empty and full reservoir cases, to exhibit the hydrodynamic effect of reservoir water on the dam earthquake response. The hydrodynamic pressure is modeled by fluid finite elements based on a Lagrangian approach. Transient analyses take into account material and connection nonlinearity. Drucker-Prager model is employed in nonlinear analyses for the dam concrete and foundation rock. The structural crack between the top and bottom blocks of the dam is presented by surface-to-surface contact elements based on Coulomb's friction law in order to simulate the behavior of contact joints and deformation of blocks. The distribution of horizontal displacements and principal stresses along the dam height is investigated for empty and full reservoir cases.The failure processes of two potential failure modes of cracked dam, i.e, the separation and sliding of top block during an earthquake, are examined.

Key words: Fractured dam, contact elements, finite element method, failure, Lagrangian approach, seismic analysis

1. Introduction

Dams are complex structures because of their size, significance to the economy, and strategic importance. The increasing demand for water supply, irrigation and clean hydroelectric power, gives great interest in the construction of new dams. One of the most crucial issues in the engineering area is the concrete dams seismic safety, because the earthquake activity may hurt the proper operation of these vital infrastructures and cause catastrophic damage that triggers significant loss of human life and property. Emergence, expansion, and merger coalescence of cracks in concrete are the

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main factors contributing to the seismic failure and damage of such structures (Mridha and Maity 2014). Nonlinear numerical models, which can forecast crack initiation and propagation through the dam body, have attracted significant research interest in the dam engineering field and are frequently used for assessing the seismic performance of these structures as a result of the growing concern regarding the seismic safety of concrete dams.

India's Koyna dam sustained damage as a result of a strong earthquake of magnitude 6.5 that impacted the region on December 11, 1967 and had its epicenter extremely close to the dam. The non-overflow section's higher monoliths, which are 103 m high, experienced severe distress during this earthquake. In the area of elevation of 66.5 m, where the downstream slope abruptly changes, structural cracking of the dam's concrete occurred on both upstream and downstream faces (Report of the committee of experts 1968).

On the monolith's upstream and downstream sides, there was a roughly horizontal crack at elevation of 66.5 m. On either side of the primary crack, there were smaller cracks visible. In addition, leakage from a number of the fissures was found, leading to a complete breach of the dam. At time of planning, designing, and dam building, the site was thought to be seismically stable. However, by taking into account horizontal earthquake forces equal to 0.05 times the weight, seismic procedures were performed in the dam design. It is necessary to reevaluate the dam seismic provision in event of a strong earthquake and as a result of the damage it causes to the dam.

Several studies (Chopra and Chakrabarti 1972, Saini et al 1972) based on the linear analysis demonstrated that during powerful earthquakes the dam would experience large tensile stresses that were greater than the strength of the concrete. Following these, a great deal of non-linear analysis has been done to forecast the emergence and spread of cracks. The employed model can be varied of an approach to other according to how the cracks are modeled.

The approach of discrete cracks represents the crack by dividing the nodes that belong to its flanks. Skrikerud and Bachmann (1986) used the maximum tensile strength criterion to simulate the Koyna dam crack propagation under strong earthquakes using discrete crack approach integrated in a finite element program. Pekau et al (1995) and Batta and Pekau (1996) studied the development of discrete and multiple cracks in the dam using the boundary element model, which was also based on linear fracture mechanics.

Another method is the so-called smeared crack approach, in which the materials characteristics in cracking zone are changed to simulate the physical discontinuity caused by cracks in the system. Using the method of finite elements, the analysis of impact of cracking on Koyna dam's response was investigated by a lot of researchers (Haghani et al 2021, Hariri-Ardebili and Seyed-Kolbadi 2015, Mirzabozorg and Ghaemian 2005, Pal 1976, Pirooznia 2019) with release stress once the tensile stress attained a critical value. Non-linear fracture mechanics models that take into account the behavior of strain softening in the fracture region have also been presented

by various investigators (Ayari and Saouma 1990, Calayir and Karaton 2005, Parvathi et al 2021), while other researchers (Ghrib and Tinawi 1995, Lee and Fenves 1998, Omidi et al 2013) have contributed by including damage mechanics in such analysis.

All of these works have shown that 1967 Koyna earthquake caused cracks to form on both faces. And most recently, they have stated that the dam-section is expected to be penetrated by the cracks near the downstream slope. Splitting the dam into two completely separate blocks implies that the top block stability needs to be carefully studied because it is anticipated that cracks will travel through the non-overflow sections. When the studying the problem in 1974, Saini and Krishna (1973) assumed that no sliding would occur and assumed that the top block would behave as a solid body, ignoring the interaction prob between the upper and lower blocks after adopting a horizontal crack. Their findings demonstrated that the top part remained stable under these presumptions and that an overturning of the top profile would not happen under subsequent ground motion of a similar amount.

Due to the size of the top block, the interaction between the two parts canhave a significant impact on dam behavior. Recent studies indicate that the upper block may slip along the upper face of the lower block, whose length is constrained. The interaction pattern would then alter taking into account that the block interface area will reduce the relations of contact with the upper block sliding. In the past years, there has been significant advancement in continuum and discontinuous media methods, such as distinct element methods (DEM) (Cundall 1971, Pekau and Yuzhu 2004) and discontinuous deformation analysis (DDA) (Shi and Goodman 1985, 1989), making it easier to study the fractured dams stability in powerful earthquakes while taking the aforementioned factors into account. El-Aidi and Hall (1989) used the finite element method to analyze how the Pine Dam behaved in the presence of penetrated cracks, but the scope of their analysis was constrained by the continuum's slight deformations. Discontinuous media methods must be used in order to model the failure process of damaged dam.

Research on the impact of hydrodynamic pressure on the dynamic behavior of dams first appeared in the 1930s (Zangar and Haefeli 1952, Zienkiewicz and Nath 1963). Numerous researchers have used Eulerian and Lagrangian approaches (Altunisik and Sesli 2015, Calayir et al 1996, Kalateh 2019, Ouzandja et al 2017, Shu et al 2022, Wang et al 2020) to study the dynamic response of dam-reservoir systems. One of the most significant forces in the design of dams, hydrodynamic force, was treated as deterministic in these studies.

The finite element method is used in the present paper to reveal the earthquake response of the cracked Koyna concrete gravity (CG) dam. Two-dimensional (2D) dam-foundation rock and dam-reservoir-foundation rock finite element models are employed in analyses by using ANSYS software (2018). Lagrangian approach is utilized to exhibit the hydrodynamic pressure effect of reservoir water on dam seismic behavior. Material and contact nonlinearity are considered in transient analyses. The Drucker-Prager model (1952) is taken in materially nonlinear response for dam con-

crete and foundation rock. The structural crack between the top and bottom blocks of the dam is modeled by 2D contact elements based on Coulomb's friction law to simulate the separation and sliding behavior of contact joints and deformation of dam blocks.

2. Lagrangian Formulation of Dam-reservoir-foundation Rock System

The adopted formulation for the dam-reservoir-foundation rock system is based on Lagrangian approach (Calayir and Dumanoğlu 1993, Wilson and Khalvati 1983). The displacements serve as unknown variables for both the fluid and structure domains in this approach. The fluid is presumed to be linear elastic, irrotational and inviscid. The stress-strain relationships for a 2D fluid element can be given as:

$$\begin{Bmatrix} P \\ P_x \\ P_y \end{Bmatrix} = \begin{bmatrix} C_{11} & 0 & 0 \\ 0 & C_{22} & 0 \\ 0 & 0 & C_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_v \\ W_x \\ W_y \end{Bmatrix}, \tag{1}$$

where P, C_{11} and ε_v are, respectively, the pressure, bulk modulus and volumetric strain of fluid; P_x and P_y are corresponding rotational stresses; C_{22} and C_{33} are constraint parameters; W_x and W_y are the rotations about the cartesian axis x and y, respectively. In the stress-strain relationships in Eq. (1), the rotations and constraint parameters are introduced to impose the fluid's irrotationality using the penalty method (Bathe 1996, Zienkiewicz and Taylor 1989).

The sloshing effect, a term used to describe the impact of small amplitude free surface waves, is considered in the analysis. The pressure at the fluid's free surface is caused by the sloshing effect and is given by:

$$P = -\gamma_w u_{fn}, \tag{2}$$

where u_{fn} is the normal component of the free surface displacement and γ_w is the fluid's weight density. The discrete form of Eq. (2) describes the pressure at the initial free surface level (water at rest). The reference (Calayir and Dumanoğlu 1993) provides a detailed formulation of the Lagrangian finite element formulation for the simulation of the dam-reservoir-foundation rock system.

3. Numerical Model Description

3.1. Koyna Dam

Koyna CG dam (Fig. 1) is one of biggest dams in India's Maharashtra province. It is a rubble concrete dam built on Koyna River. This dam plays a vital role of flood control during the monsoon season and is associated with a 1960 MW hydroelectric plant.

It was designed as a straight gravity dam measuring 103 m height and 853 m long. It has 14.8 m thick at the crest and 70 m thick at the base of the highest section,



Fig. 1. Koyna dam view

with a sharp change in slope on the downstream face at the level of 66.5 m. The dam was constructed of monolithic sections of 15.2 m wide, with a 91.4 m wide overflow spillway located in the center of the structure. The natural reservoir water height is 91.75 m. Cross-section dimensions of dam body are presented in Fig. 2.

3.2. Material Properties

Koyna dam was constructed mainly of rubble concrete. The mechanical properties of dam-reservoir-foundation rock system are summarized in Table 1. The materially nonlinear characteristics of investigated system are determined according to the Drucker-Prager model (1952) (see Table 1). The tensile and compressive strengths of the dam concrete are 2.41 MPa and 24.1 MPa, respectively.

Table 1. Material properties adopted in numerical analyses (Huang 2011, Sarkar et al 2007)

Material properties	Material		
	Koyna dam	Foundation rock	Reservoir fluid
Modulus of elasticity (MPa)	31030	16860	2070
Poisson's ratio	0.2	0.18	0.49
Mass density (kg/m^3)	2643	2701	1000
Cohesion(MPa)	–	0.6	–
Angle of internal friction (°)	–	41	–
Dilatation angle (°)	36.31	–	–

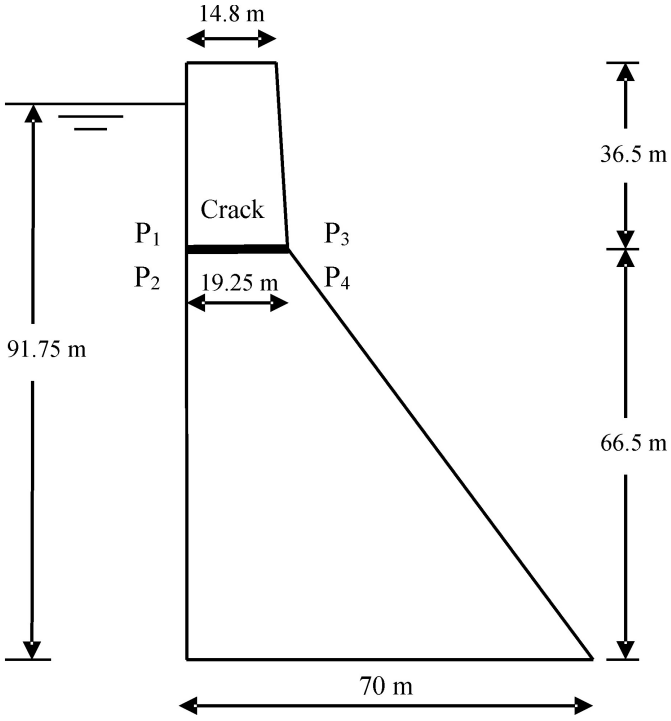


Fig. 2. Cross-section of Koyna concrete gravity dam

3.3. Finite Element Models

A discretization by 2D finite elements is used to represent the dam-reservoir-foundation rock coupled system (Fig. 3). Solid finite elements (Plane182) are employed to model the dam and foundation rock. The solid domain model has 532 elements; of which 272 elements are used for the foundation domain and 240 elements are used for the dam. Fluid finite elements (Fluid79) are considered to model the reservoir water, resulting in 336 elements. Calculating the hydrostatic pressures and issues involving fluid-solid interactions are particularly well suited to the fluid element (ANSYS software 2018). The hydrodynamic effect of the reservoir fluid is formulated by using a Lagrangian approach (Calayir and Dumanoğlu 1993, Wilson and Khalvati 1983) based on the principle of compatibility and equilibrium at nodes along fluid-structure interfaces. This approach considers that the fluid is assumed to be linearly elastic, incompressible, inviscid and irrotational. The damping ratio of 5% is used in finite element analyses. At the dam-reservoir interaction interface, the coupling element length is set to 1 mm. The principal objective of the couplings is to maintain equality of displacements between two reciprocal nodes when they are pointed in the same direction as the interface. After the initial loading condition, which is a gravity load and hydrostatic pressure, fixed boundary conditions are considered at nodes located

in the lateral ends and bottom of the foundation rock. Free limits of water reservoir are fixed in the horizontal direction.

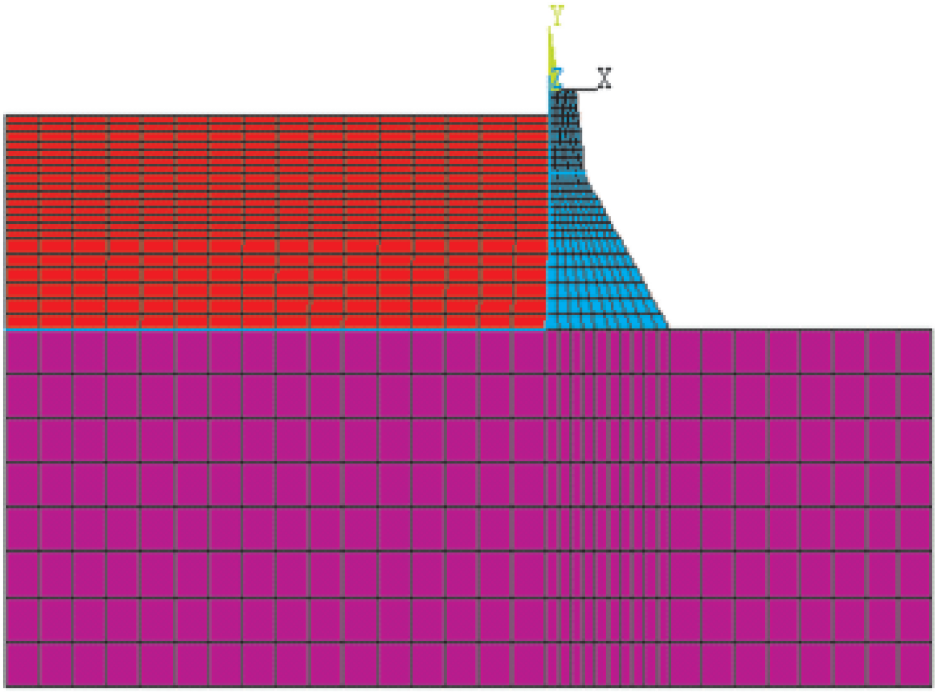


Fig. 3. Finite element discretization of the Koyna dam-reservoir-foundation rock system

The points P1 and P2 (see Fig. 2) are located at the crack's left end and are part of the top and bottom blocks, respectively, and likewise the points P3 and P4 are located at the right end of the crack (see Fig. 2). Since the crack completely divided the dam profile into two separate sections, their behavior is represented by 2D surface-to-surface contact elements based on Coulomb's friction law. These contact elements create a contact pair between a target surface (Targe169) and a contact surface (Conta172), resulting in 10 contact-target element pairs.

3.4. Modeling of Structural Fracture Between Dam Blocks

In December 11, 1967, the Koyna dam, which is located in India, sustained the development of cracks as a result of a strong earthquake. The non-overflow section's higher monoliths, which are 103 m high, were subjected to severe distress during this earthquake. In the zone of level of 66.5 m, where the downstream slope abruptly changes, horizontal structural fracture of the dam's concrete occurred on both the upstream and downstream faces.

After this seismic event, the dam system becomes divided into polygonal blocks by joints. The joints between contact blocks are modeled by contact elements based on Coulomb's friction law to simulate the sliding and separation behavior of contact joints. The contact model defined between top and bottom blocks of the dam are represented by normal (K_n) and shear (K_s) stiffness. "Standard" contact model, which permits the sliding and separation of joints is considered in this study.

Although test values for K_n and K_s stiffness, which present the crack elastic properties, were lacking, it was assumed that they had an isotropic behavior and that their stiffness was equal to 2×109 Pa/m, or roughly a fifteenth of the elastic modulus of the concrete blocks.

4. System Seismic Response

The current work shows the seismic performance of the Koyna dam subjected to stream and vertical direction acceleration components of 1967 Koyna earthquake during a period of 10 s (Fig. 4). The empty and full reservoir cases are taken into consideration in the numerical simulations. The material and contact nonlinearity are considered in the different analyses. The acceleration and displacement response spectra of stream direction and vertical components of 1967 Koyna earthquake for 5% damping are also shown in Figs. 5 and 6, respectively. The time interval of acceleration record is 0.005 sec. The horizontal displacements, principal stress components and dam failure analysis are presented.

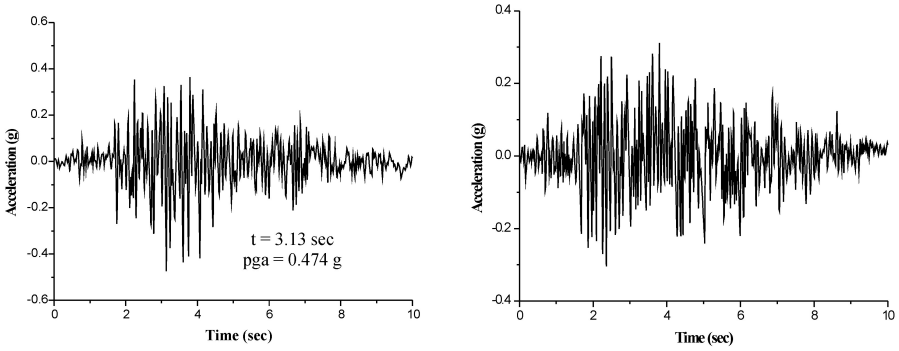


Fig. 4. 1967 Koyna earthquake acceleration records: (a) Stream direction component; and (b) Vertical component

4.1. Modal Analysis

The modal analysis results of some natural frequencies of Koyna dam vibration modes are summarized in Table 2 for empty and full reservoir cases. As can be seen in this

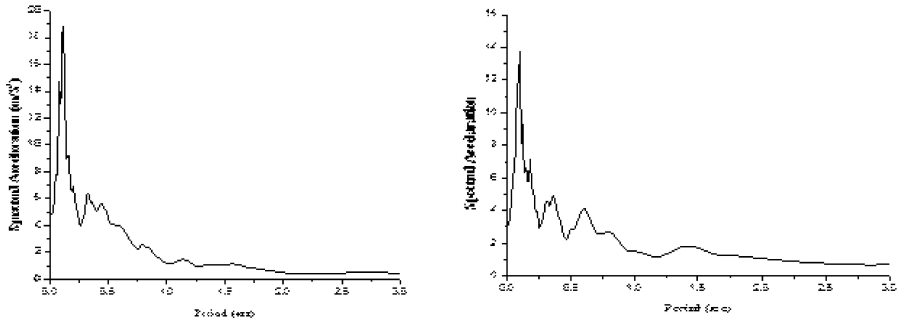


Fig. 5. Acceleration response spectra of 1967 Koyna earthquake for 5% damping: (a) Stream direction component; and (b) Vertical component

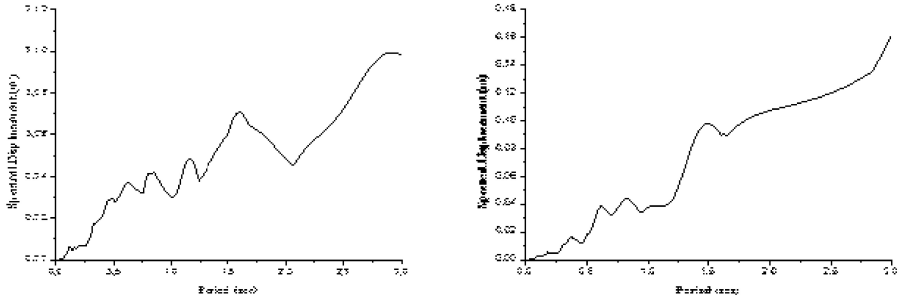


Fig. 6. Displacement response spectra of 1967 Koyna earthquake for 5% damping: (a) Stream direction component; and (b) Vertical component

table, the natural frequencies decrease in the full reservoir case due to the effect of dam-reservoir interaction.

Table 2. Natural frequencies of Koyna dam-reservoir-foundation rock system

Mode number	Empty reservoir case		Full reservoir case	
	Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)
1	3.06	0.33	1.97	0.51
2	3.64	0.27	3.02	0.33
3	4.56	0.22	3.32	0.30

Fig. 7 depicts the chosen mode shapes (the color contours present the normalized displacement vectors). It is noted that the top block of the dam is more exposed to

separation and sliding at the level of structural crack in empty reservoir case compared to full reservoir case.

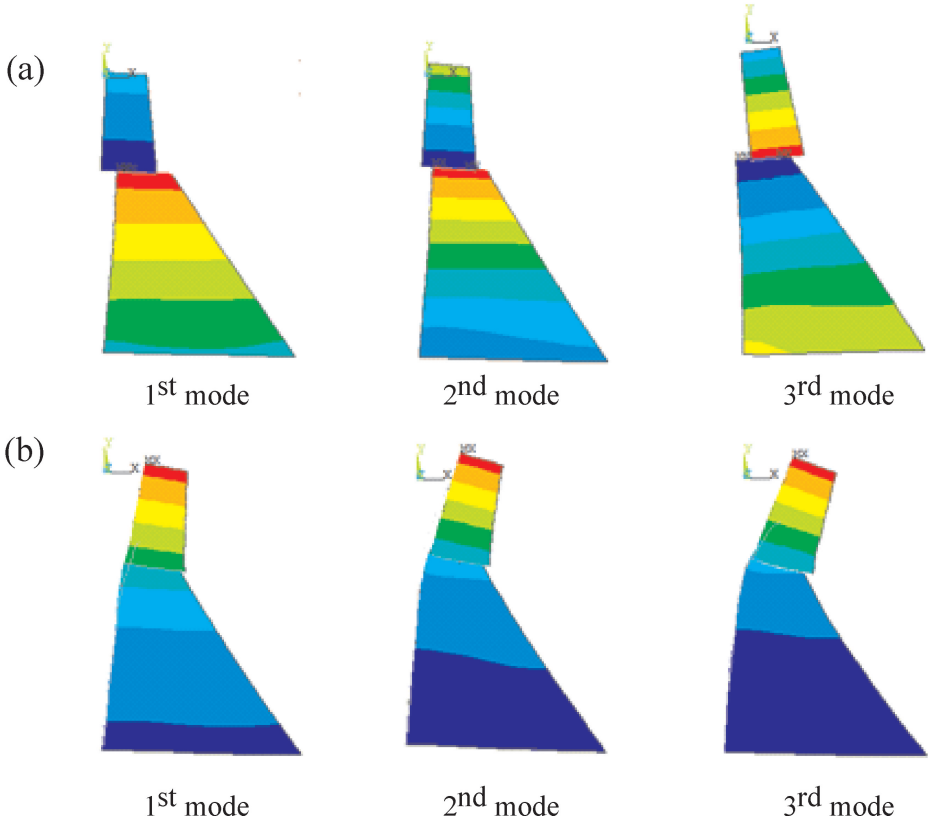


Fig. 7. Mode shapes of Koyna dam: (a) Empty reservoir case; and (b) Full reservoir case

4.2. Seismic Analysis

4.2.1. Displacements

The distribution of maximum horizontal displacements along dam height in upstream direction is shown in Figs. 8 and 9 for empty and full reservoir cases. As may be shown, the hydrodynamic pressure of reservoir fluid can increase horizontal displacements of the dam. It is observed from Figs. 8 and 9 that the top dam block undergoes a significant sliding during an earthquake, which attains the value of 9.15 cm in empty reservoir case, while it is 4.86 cm in the full reservoir case. Fig. 10, as above, presents the envelopes of maximum horizontal displacement of the dam for both empty and full reservoir cases. It is obvious from Fig. 10 that the top block tends more to separation and sliding along contact joints in the empty reservoir case.

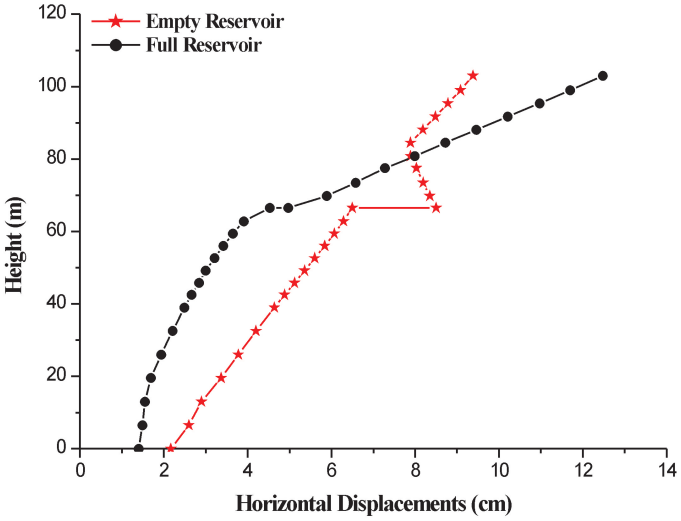


Fig. 8. Maximum horizontal displacements along dam height in upstream direction

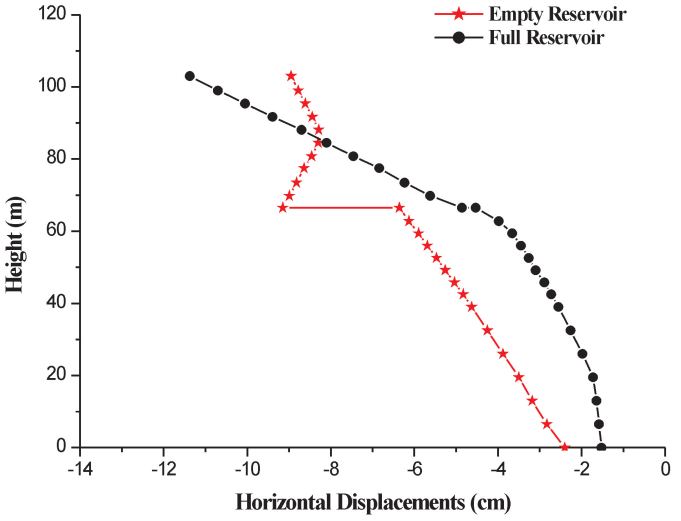


Fig. 9. Minimum horizontal displacements along dam height in upstream direction

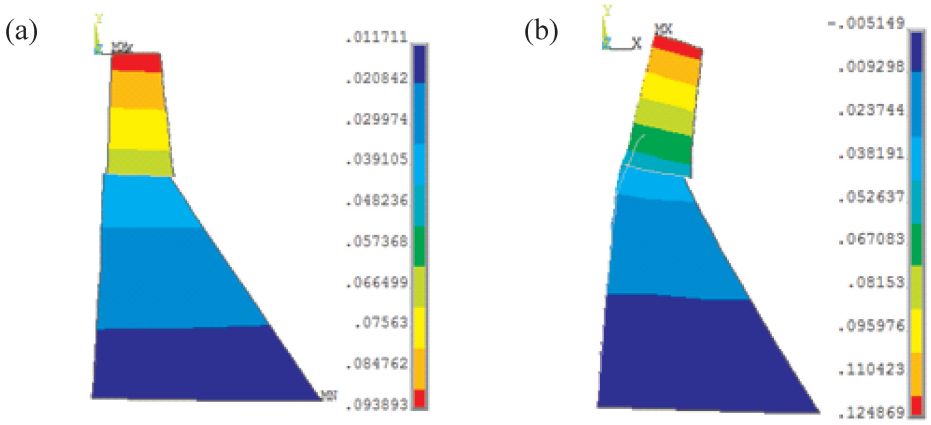


Fig. 10. Envelopes of maximum horizontal displacements for the dam: (a) empty reservoir case; and (b) full reservoir case (Unit: m)

The time history horizontal displacement at the dam crest is presented in Fig. 11, in which the maximum displacement at the crest increases from 9.39 cm in the first case to 12.48 cm in the case of hydrodynamic water pressure effect. This indicates an increase of 33% in the crest displacement amount for the second case. Fig. 12 represents the time history of the sliding displacement at point P1, in which the sliding decreases from 9.15 cm in the first case to 4.86 cm in second case. Thus, the hydrodynamic pressure of the reservoir water may reduce the sliding of the top block along the structural crack. The time history of the horizontal displacement at point P2 is illustrated in Fig. 13, in which the horizontal displacement decreases from 6.51 cm in the first case to 4.67 cm in the second case.

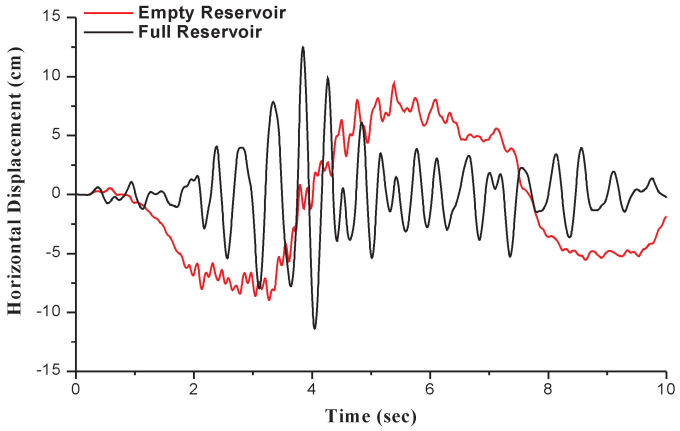


Fig. 11. Time history horizontal displacement at dam crest

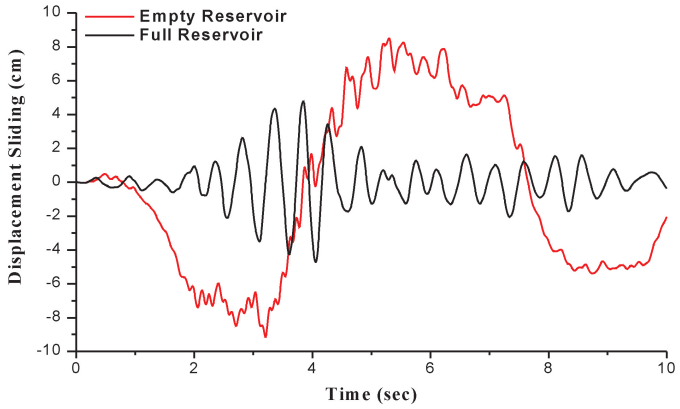


Fig. 12. Time history sliding displacement at point P_1

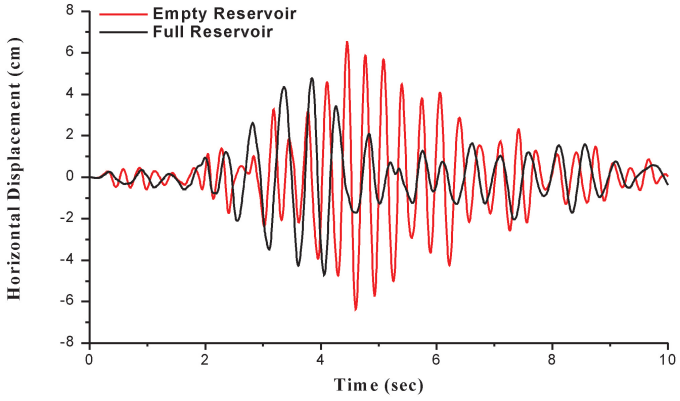


Fig. 13. Time history horizontal displacement at point P_2

4.2.2. Stresses

The distribution of maximum principal tensile and compressive stresses along dam height in the upstream direction is compared, respectively, in Figs. 14 and 15 for the empty and full reservoir cases. As may be seen, the hydrodynamic pressure of reservoir fluid can increase the principal stresses in the dam.

The time history of principal stresses at point P_1 is depicted in Fig. 16, in which the maximum principal tensile and compressive stresses increase from 5.4 MPa and

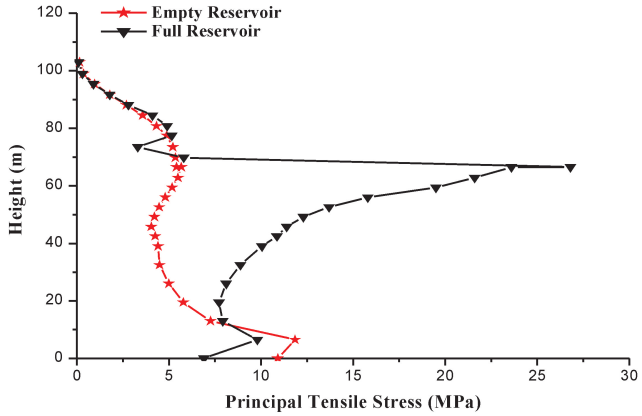


Fig. 14. Principal tensile stresses along dam height in upstream direction

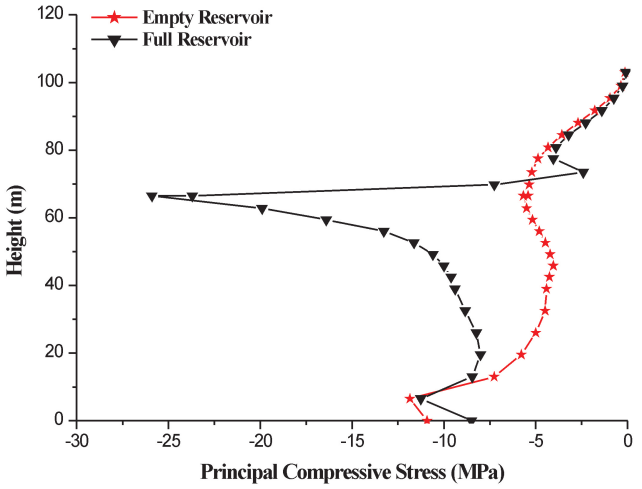


Fig. 15. Principal compressive stresses along dam height in upstream direction

−4.6 MPa in the first case to 26.8 MPa and −23.7 MPa in the second case. This suggests an increase of 396.3% and 415.2%, respectively, in the amount of the principal stresses in the second case. According to Fig. 17 representing the time history of the principal stresses at point P_2, these values of stresses are 5.7 MPa and −4.5 MPa in the first case, while these increase to 23.6 MPa and −25.9 MPa in the second case, i.e, an augmentation of 314% and 475.6%, respectively, in the amount of the principal

stresses in the full reservoir case. Thus, the crack plane is subjected to high principal stresses due the hydrodynamic pressure of water.

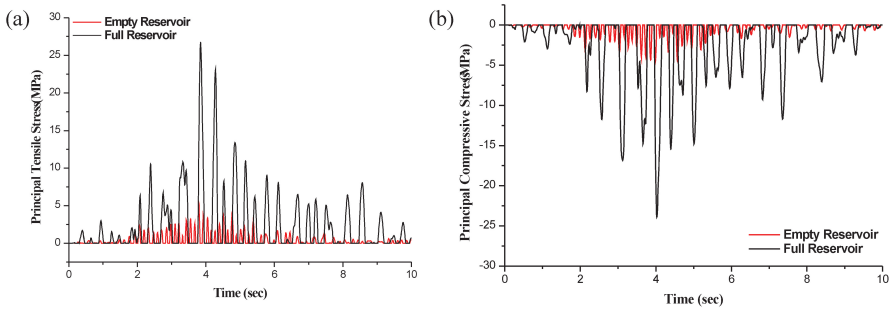


Fig. 16. Time history of principal stresses at point P_1: (a) Principal tensile stress; and (b) Principal compressive stress

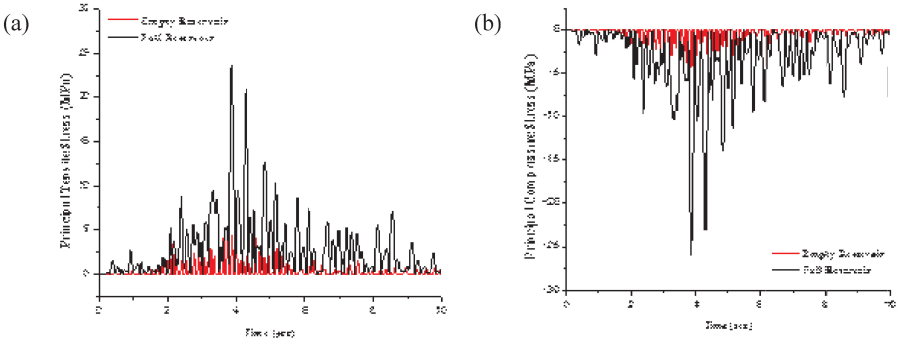


Fig. 17. Time history of principal stresses at point P_2: (a) Principal tensile stress; and (b) Principal compressive stress

Fig. 18 depicts the dam failure process under an earthquake. In the first case, the top block moves 7.41 cm in the downstream direction at time of 2.055 sec, and its primary motion is sliding along the crack before that point. Then, it slides more in the same direction up to the value of 9.15 cm at time of 3.205 sec. After this, the top block moves 8.51 cm in the upstream direction at time of 5.295 sec. At time of 8.740 sec, it slides again in the opposite direction up to 5.38 cm. The top block sliding decreases to achieve 2.03 cm at the end time (10 sec).

In the case of the hydrodynamic pressure effect, the top block sliding is generally limited compared to the,first case. Its displacement attaints 3.49 cm in the downstream direction at time of 3.105 sec. Then, the top block slides 4.86 cm in the upstream

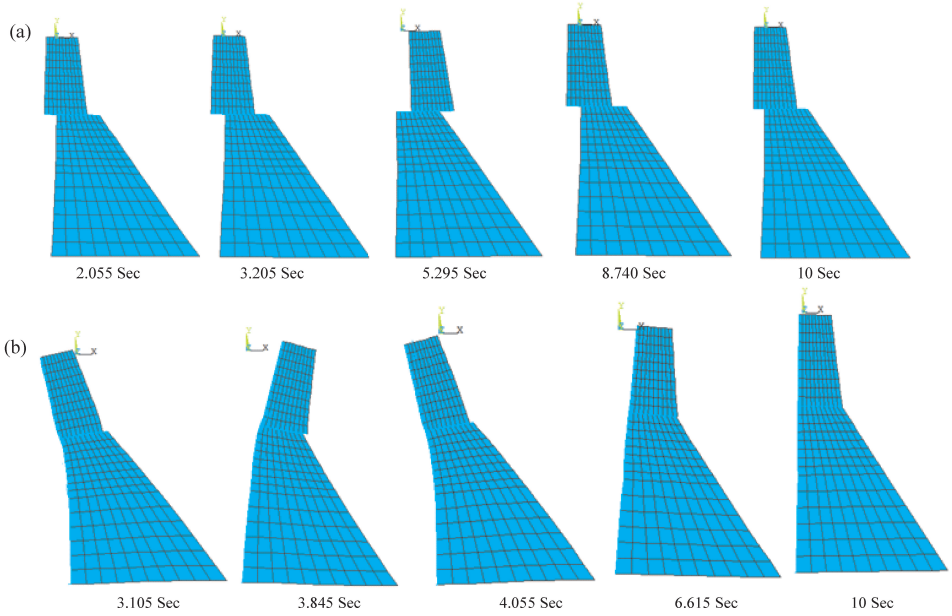


Fig. 18. Dam failure process under earthquake: (a) Empty reservoir case; and (b) Full reservoir case

direction at time of 3.845 sec. After this, it moves again in the opposite direction up to 4.79 cm at time of 4.055 sec. The displacement sliding is 1.63 cm in the upstream direction at time of 6.615 sec. At the end time (10 sec), the top block sliding decreases to arrive 0.36 cm in opposite direction.

Summarizing the above failure processes (Fig. 18), the two failure modes, separation and sliding are possible under an earthquake. However, the dam is safe in the case of the crack presence in the horizontal direction to a large extent.

5. Conclusions

The present work shows the earthquake behavior of the cracked Koyna concrete gravity dam considering the dam-reservoir-foundation rock interaction using a finite element method. The Lagrangian approach is used to model the hydrodynamic pressure influence of the reservoir water on the dam seismic behavior. Material and contact nonlinearity are considered in transient analyses. The Drucker-Prager model is utilized in materially nonlinear response for the dam concrete and foundation rock. From the numerical investigation, one can draw the following inferences:

– The reservoir water's hydrodynamic pressure decreases natural frequencies of the dam.
– Hydrodynamic water pressure increases the displacements and principal stresses in the dam.

– The seismic performance of the dam is closely related to the structural crack features present between top and bottom blocks.
– The total amount of sliding at the earthquake end time is very small under the hydrodynamic pressure effect, and the stability of the dam block above the crack has not been an issue.
– The sliding of top block increases when the hydrodynamic pressure effect is not taken into account.
– Contact joints are anticipated to separate and slide repeatedly during strong ground motions. These joints can reduce the rigidity of the crack region, and thus lead to nonlinear demands for dam-reservoir-foundation rock system.

The results obtained in this study indicate that when the crack direction is horizontal, the safety of the studied dam is guaranteed. Even with the horizontal crack present, the top block will briefly separate from the lower part, which may cause high hydrodynamic pressure of water inside the crack. Thus, to determine the cracked Koyna dam's safety, it is necessary to carefully examine the property and shape of the crack.

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