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Two Dimensional Dynamic Nonlinear Finite Element Model Based Seismic Analysis of a Concrete Gravity Dam

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Abstract: *The seismic response of spatially extended structures, such as bridges, pipelines and dams, is influenced by the differences in the ground excitations over distance. This research analyzes the effect of ground motions on the 2D response of concrete gravity dams. The modeling of concrete gravity dams involves material nonlinearities (the concrete in the body of the dam), and geometric nonlinearities (contact between the dam and the reservoir). The model is then utilized to reproduce the 2D cross section of the Koyna Dam in India, which was severely damaged during the 1967 Koyna Earthquake. The research will include the analysis of the Koyna dam example in the ABAQUS manual then the results obtained will compare with other cases for the dam when geometry of it changes also when the boundary condition also changes.*

Keywords: *ABAQUS, Cracks, nonlinear, concrete dam, seismic Analysis.*

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I. Introduction

Concrete gravity dams are critical structures that serve electricity generation, water supply, flood control, irrigation, recreation, and other purposes. They are an integral component of the society's infrastructure system. Concerns about their safety in a seismic environment have been growing over the past few decades, partly, because earthquakes may impair their proper functioning and trigger catastrophic failure causing property damage and loss of life, and, also, because the current knowledge on the behavior of dams during very strong ground shaking is inadequate. The risks posed by earthquakes on concrete gravity dams have been demonstrated by the damage of such dams throughout the world, as, e.g. the Koyna Dam in India. The Koyna Earthquake resulted in a considerable amount of damage to the Koyna Dam, including the development of cracks in the dam, water leakage on the downstream face of the dam, and spalling of concrete along the vertical joints between monoliths. Figure 1shows the Koyna dam.

The concrete in the body of the dam exhibits complicated nonlinear mechanical behavior under dynamic loadings conditions. During severe earthquake events, these unreinforced concrete masses are likely to undergo cracking due to the concrete's low tensile strength. Over the last two decades, considerable research has been invested in the development of numerical techniques for the nonlinear fracture analysis of concrete, which can be essentially grouped into two categories, i.e. the fracture mechanics based approach and the continuum damage mechanics based approach. Extensive reviews of these numerical techniques are provided in the work [1-5].

A brief summary of these available techniques is given in the following:

Continuum damage mechanics has provided an elegant way of simulating crack formation and propagation by way of stiffness degradation and recovery. The applications of the continuum damage mechanics based approach to analyze the earthquake response of dams [6-8]. In the fracture mechanics approach, a typical concrete cracking model is generally composed of three components, i.e. a condition for determining the onset of crack initiation, a method for crack representation, and a criterion for crack propagation. The crack initiation and propagation criteria can be based either on strength of material or on theory of fracture mechanics [9]. Typical strength-of-material-based crack initiation and propagation criteria include the maximum principal stress criteria and the maximum principal strain criteria, which assumes that a crack will be initiated when the computed maximum principal stress or strain at the crack-tip exceeds the strength of the material. Once the material at the crack-tip reaches its strength limit, the stresses on the fracture surface are assumed to be suddenly released [9].

On the other hand, fracture-mechanics-based crack initiation and propagation criteria can be generally divided into two groups, i.e. linear elastic fracture mechanics criteria (e.g. stress intensity factor approach) and nonlinear fracture mechanics criteria (e.g. energy principle). For example, according to linear elastic fracture mechanics criteria, once the stress intensity factors and the material fracture toughness (also called critical stress intensity factor) have been determined, a functional relationship between them can be formed and applied for crack propagation [9]. Linear elastic fracture mechanics allows the stress to approach infinity at the crack tip. However, since infinite stress cannot exist in real materials, a certain range of plastic zone should develop at the crack tip.

In concrete, this plastic zone is termed as fracture process zone and dominated by complex mechanisms [9-11]. The fracture behavior of concrete is greatly influenced by this fracture process zone and should be described by nonlinear fracture mechanics criteria. The most referenced model that has been proposed to characterize the Mode I nonlinear fracture propagation in the fracture process zone of concrete is the fictitious crack model developed by [12]. According to their model, the fracture process zone is represented by a fictitious crack lying ahead of the real crack tip. The behavior of concrete in the fracture is described by a diminishing stress versus crack opening displacement. As a result, the energy dissipation for crack propagation can be completely characterized by the stress-displacement relationship. The area under stress-displacement curve is commonly referred to as the fracture energy. Crack representation deals with spatially representing the cracks in the finite element model.

Commonly, representation of the cracks in numerical models is achieved by the smeared crack approach [13] and the discrete crack approach [14]. The discrete crack method has the potential of determining accurately the geometry of each crack, but its principal disadvantage is the difficulty and high computational cost due to the continuous change of the finite element topology during the analysis. On the other hand, for the smeared crack approach, only the constitutive relationship is updated with the propagation of cracks, and the finite element mesh is kept unchanged; a disadvantage of the approach, however, is that it can be mesh-dependent.

II. Finite Element

Based on the finite element (FE) software ABAQUS, the dynamic time history of the concrete gravity dam has been analyzed [15]. Considering the gravity dam's action of dynamic water pressure effect under the earthquake. The following input data are for the all the three cases (case 1 without dam–reservoir hydrodynamic interactions, case 2 with dam–reservoir hydrodynamic interactions and case 3 with on slope geometry for the Koyna dam), which is the given in example in the ABAQUS manual. The geometry of the ABAQUS dam is showing in figure 1.

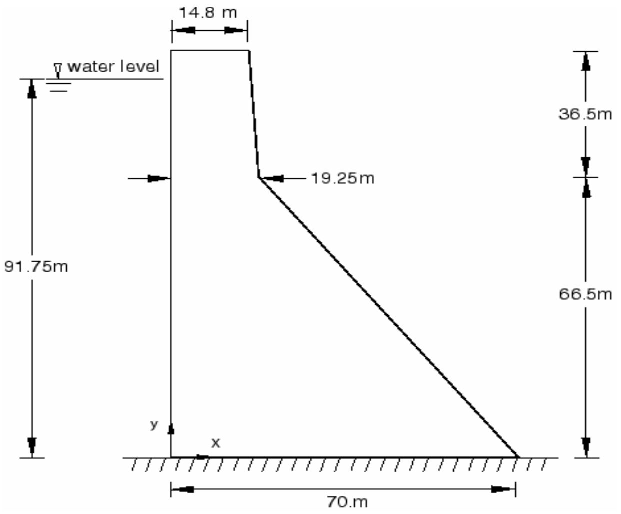


Figure 1. Geometry of Koyna dam

2.1 Element type

The 2-D finite element model of system is shown in Figure 2. The dam and foundation are modeled by CPE4R elements (4-node bilinear plane strain quadrilateral with reduced integration and hourglass control).

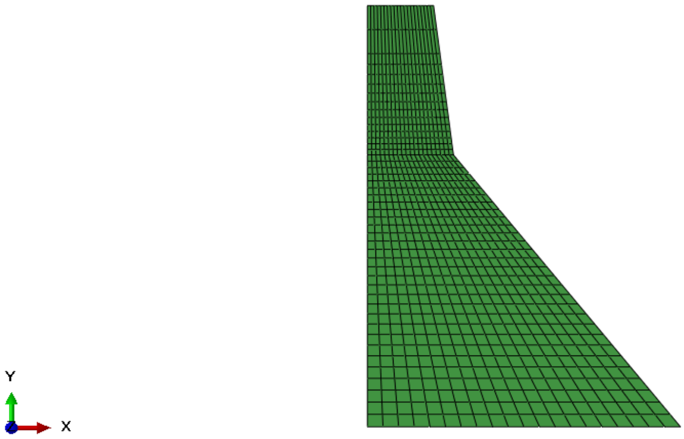


Figure 2. Finite element model for the Koyna dam

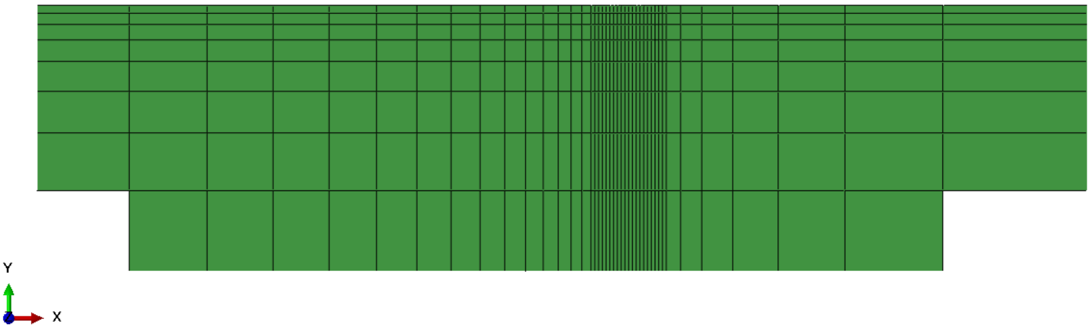


Figure 3. Finite element model for the Koyna Foundation

The reservoir is modeled by AC2D4 elements (4-node linear 2-D acoustic quadrilateral)

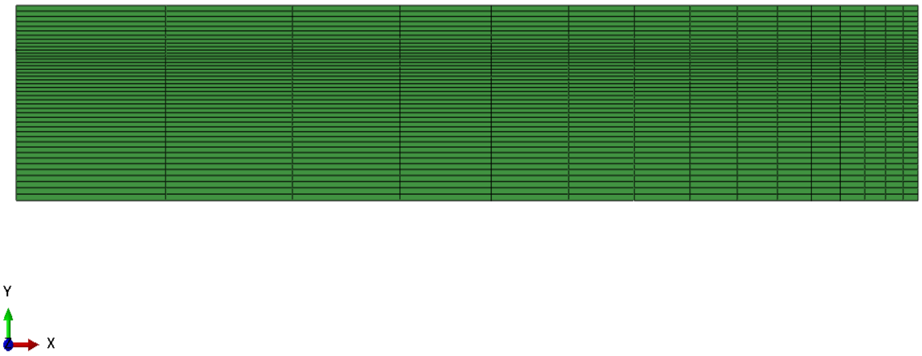


Figure 4. Finite element model for the Reservoir

2.2 Material properties (models)

The material properties will be summarized in the following table for the concrete, rock and water materials.

Table 1. Material properties

Property		Concrete (dam)	Rock (foundation)	Water (reservoir)
Young’s modulus E		31027 MPa	27580000000 MPa	_
Poisson’s ratio v		0.2	0.333	_
Density		2643kg/m3	2643kg/m3	2643kg/m3
Dilation angle		36.31	_	_
Damping	Alpha	_	1.64	_
	Beta	0.00323	0.0012	_
Bulk modulus		_	_	2070000000

2.3Boundary conditions

The boundary conditions shown in the following figures

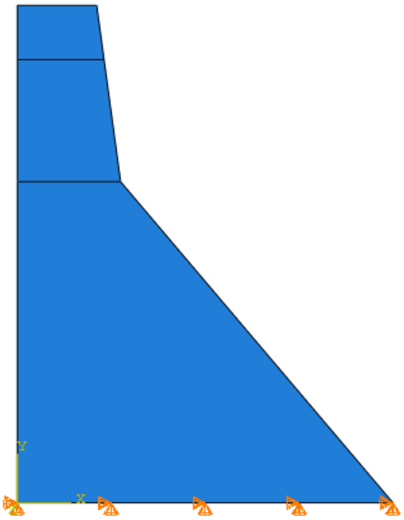


Figure 5. Foundation boundary condition

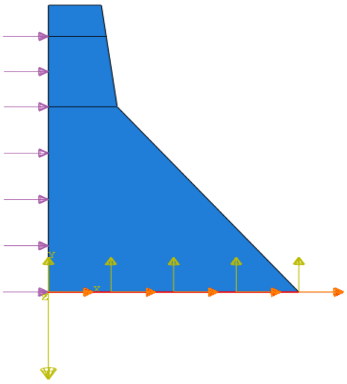


Figure6.Acceleration/angular acceleration boundary condition in x-direction

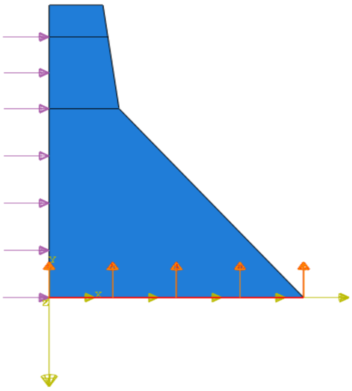
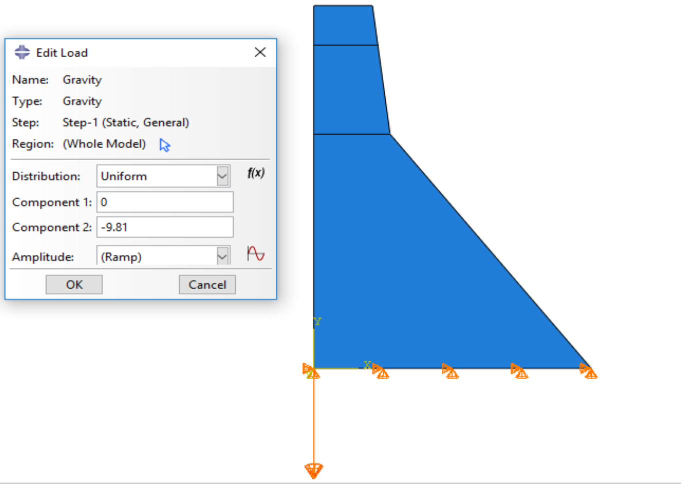


Figure 7. Acceleration/angular acceleration boundary condition in y-direction

2.4Loading

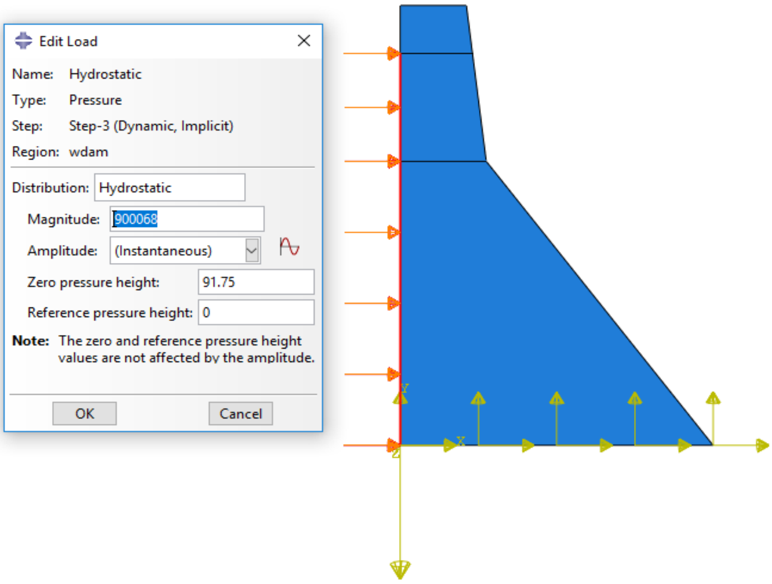
There is three load cases effect on the dam the gravity load its region in the whole model, the hydrostatic load at the left side of the dam and the earthquake excitation at the base of the dam.



Edit Load

Name: Gravity
Type: Gravity
Step: Step-1 (Static, General)
Region: (Whole Model)
Distribution: Uniform
Component 1: 0
Component 2: -9.81
Amplitude: (Ramp)

Figure 8. Gravity load



Edit Load

Name: Hydrostatic
Type: Pressure
Step: Step-3 (Dynamic, Implicit)
Region: wdam
Distribution: Hydrostatic
Magnitude: 900068
Amplitude: (Instantaneous)
Zero pressure height: 91.75
Reference pressure height: 0

Note: The zero and reference pressure height values are not affected by the amplitude.

Figure 9. Hydrostatic load

2.5.Interaction

In the second case will be interaction between the reservoir and the dam in order to know how this interaction will effect on the response of the dam (tensile damage).

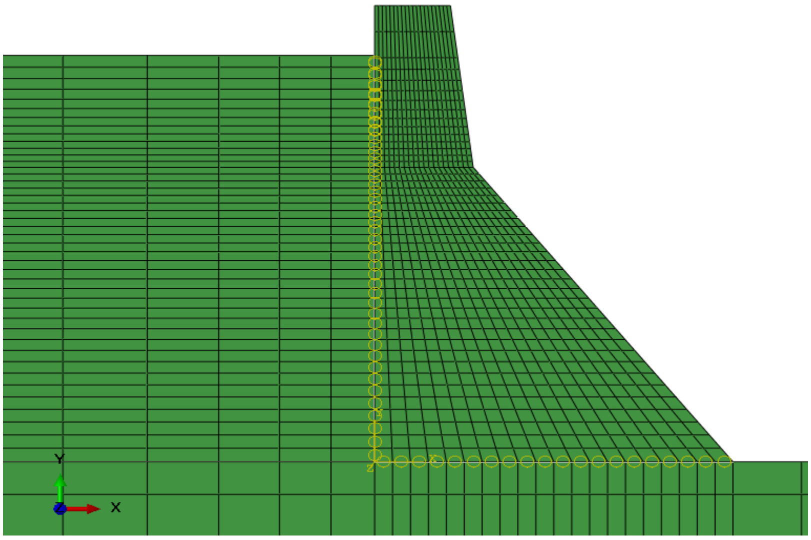


Figure 10. Surfaces interaction between dam and reservoir and foundation

III. Result And Discutions

For the first case that without dam–reservoir hydrodynamic interactions figure 11 shows

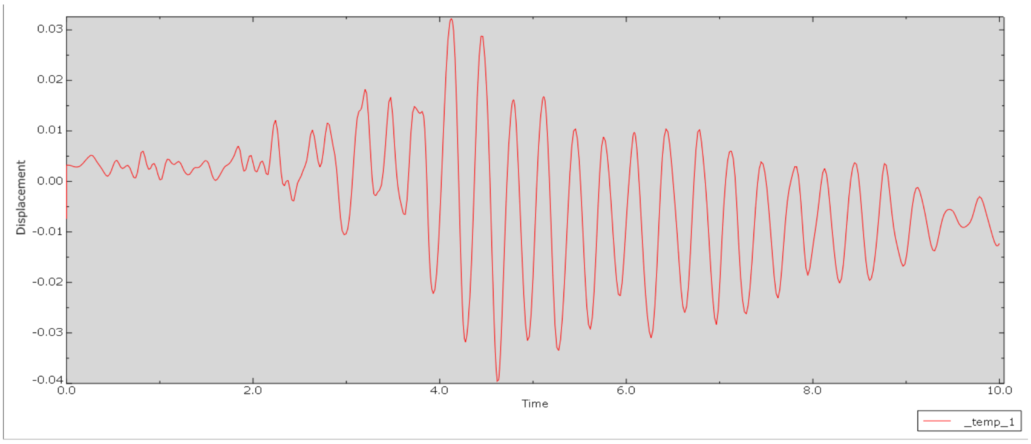


Figure 11. Horizontal crest displacement (relative to ground displacement) case 1

the horizontal displacement at the left corner of the crest of the dam relative to the ground motion. In this figure positive values represent displacement in the downstream direction. The crest displacement remains less than 30 mm during the first 4 seconds of the earthquake. After 4 seconds, the amplitude of the oscillations of the crest increases substantially. As discussed below, severe damage to the structure develops during these oscillations.

The concrete material remains elastic with no damage at the end of the second step, after the dam has been subjected to the gravity and hydrostatic pressure loads. Damage to the dam initiates during the seismic analysis in the third step. The evolution of damage in the concrete dam at six different times during the earthquake. Times t_1 = 3.96 sec, t_3 = 4.315 sec, and t_5 = 4.687 sec correspond to the first three large excursions of the crest in the upstream direction. Times t_2 = 4.163 sec and t_4 = 4.526 sec correspond to the first two large excursions of the crest in the downstream direction. Time t_6 = 10 sec corresponds to the end of the earthquake.

At time t1, damage has initiated at two locations: at the base of the dam on the upstream face and in the region near the stress concentration where the slope on the downstream face changes.

When the dam displaces toward the downstream direction at time t_2, the damage at the base leads to the formation of a localized crack-like band of damaged elements. This crack propagates into the dam along the dam–foundation boundary. The nucleation of this crack is induced by the stress concentration in this area due to the infinitely rigid foundation. At this time, some partial tensile damage is also observed on several elements along the upstream face.

During the next large excursion in the upstream direction, at time t_3, a localized band of damaged elements forms near the downstream change of slope. As this downstream crack propagates toward the upstream direction, it curves down due to the rocking motion of the top block of the dam. The crack at the base of the dam is closed at time t_3 by the compressive stresses in this region. This is easily verified by looking at the contour plot of SDEG at time t_3, which clearly shows that the stiffness is recovered on this region, indicating that the crack is closed.

When the load is reversed, corresponding to the next excursion in the downstream direction at time t_4, the downstream crack closes and the stiffness is recovered on that region. At this time tensile damage localizes on several elements along the upstream face, leading to the formation of a horizontal crack that propagates toward the downstream crack.

As the upper block of the dam oscillates back and forth during the remainder of the earthquake, the upstream and downstream cracks close and open in an alternate fashion. The dam retains its overall structural stability since both cracks are never under tensile stress during the earthquake. At time t_6. The contour plot of the stiffness degradation variable indicates that, except at the vicinity of the crack tips, all cracks are closed under compressive stresses and most of the stiffness is recovered. No compressive failure is observed during the simulation. The damage patterns predicted by ABAQUS.

Figure 12 shows the distribution of tensile damage at the end of the simulation. Two major cracks develop during the earthquake, one at the base of the dam and the other at the downstream change of slope

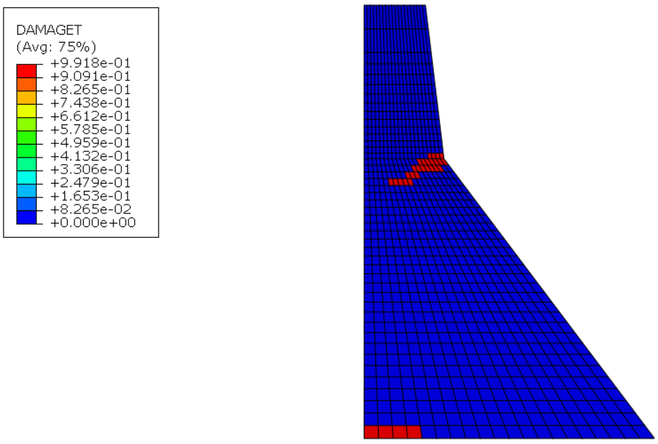


Figure 12. Tensile damage at the end of the simulation with dam–reservoir hydrodynamic interactions case 1.

For the Second case that with dam–reservoir hydrodynamic interactions figure 13 shows the

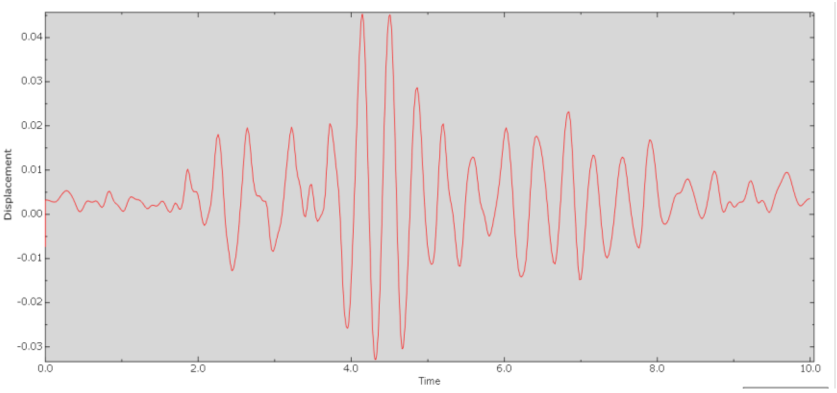


Figure 13. Horizontal crest displacement (relative to ground displacement) case2

horizontal displacement at the left corner of the crest of the dam relative to the ground motion it has the same of crack propagate time but in this case the crack propagation is in wide range because the effect of the reservoir interaction to the dam crest figure 14 shows the crack on its final stage in this case.

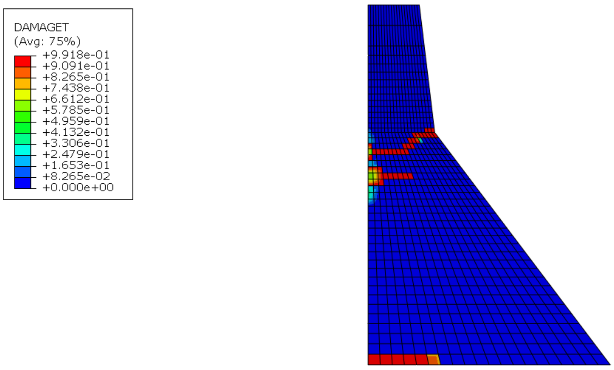


Figure 14. Tensile damage at the end of the simulation with dam–reservoir hydrodynamic interactions case 2.

For the third case that dam has one slope figure 15 shows the horizontal displacement at the left corner of the crest of the dam relative to the ground motion and it’s different from the two other cases that because the of not complicated geometry. And figure 16 shows the tensile damage for this case which contain only single crack at the heel of the dam.

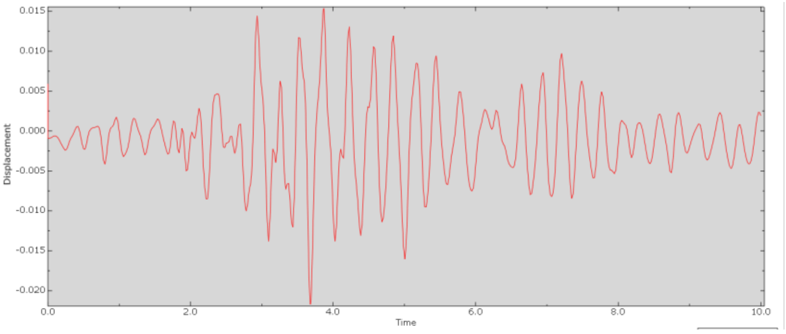


Figure 15. Horizontal crest displacement (relative to ground displacement) case 3

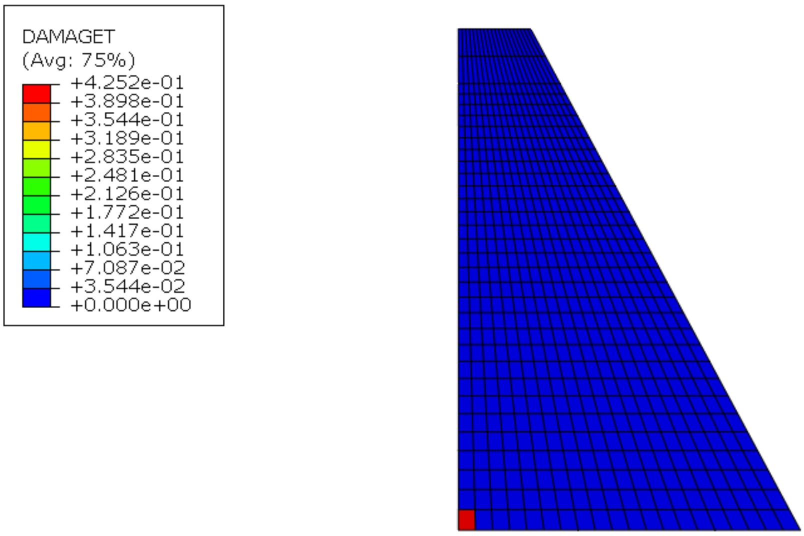


Figure 16. Tensile damage at the end of the simulation with dam–reservoir hydrodynamic interactions case 3.

Figure 17 summarize the displacement for the different cases, where the largest displacement is for the dam with interaction with reservoir.

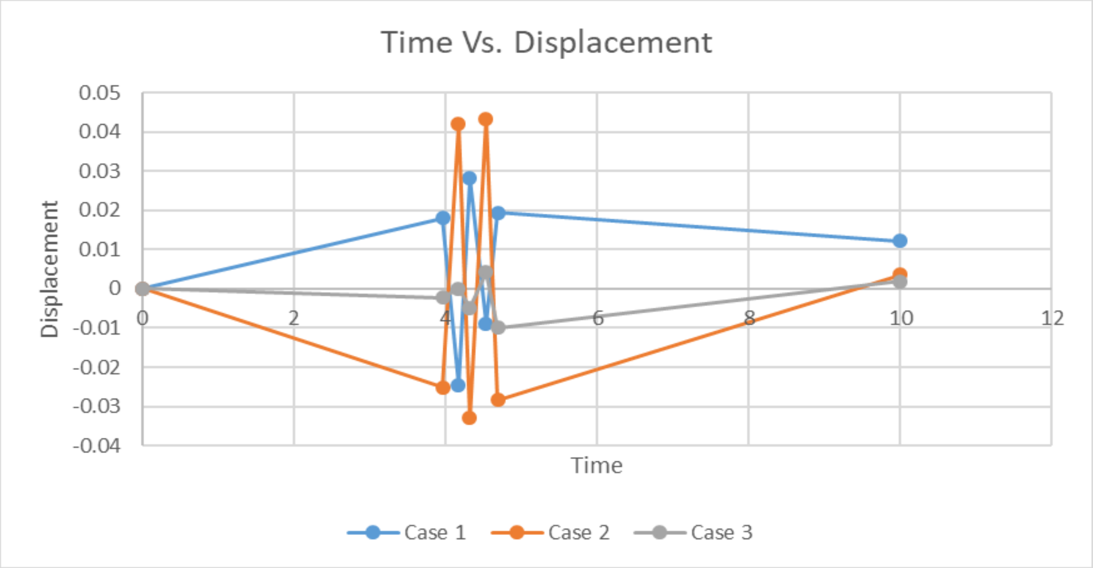


Figure 17. Horizontal crest displacement (relative to ground displacement)

IV. Conclusion

For the Koyna concrete gravity dam presented based on the two dimensional dynamic nonlinear finite element model. All of the following important factors are taken into account: the interaction of dam-reservoir-foundation, and the opening/closing cracking. Comparisons are made between the results from different cases model. The effectiveness of the numerical framework which not considers the dam-reservoir-foundation interaction is first validated. Then numerical framework which considers the dam-reservoir-foundation interaction is conducted in order to characterize the effects of the interaction on the seismic performance of the Koyna concrete gravity dam.

In particular, earthquake ground motions induce more severe cracking at the neck of the dam, larger opening at the heel of the dam, and more severe slipping at the toe of the dam, which can have a significant influence on the response of the dam and impact the dam’s global stability in the earthquake.

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