NONLINEAR ANALYSIS OF A DAM-RESERVOIR-FOUNDATION SYSTEM UNDER SPATIALLY VARIABLE SEISMIC EXCITATIONS

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ABSTRACT :

The safety and stability of concrete gravity dams under strong earthquake shaking has long been an issue of great practical importance, and has attracted and continues to attract considerable research interest. The evaluation of their response to earthquakes requires special attention due to their unique characteristics: (i) Nonlinear behavior of the concrete and foundation rock; (ii) Interaction between the dam, the reservoir, and the foundation; (iii) Unbounded feature of the reservoir and foundation domain; and (iv) Spatial variation of seismic ground motions over distances comparable to the base dimensions of the dam. This paper addresses these issues by developing a computational procedure for studying the effects of the spatial variability of the earthquake motions on the response of concrete gravity dams using the finite element method. The proposed scheme is illustrated with the Koyna Dam in India. The primary results of the evaluation show that diverse response patterns occur when the excitation is uniform or nonuniform. The major differences in the patterns are caused by the pseudo-static response that is induced only by the nonuniform excitations.

KEYWORDS: dam-reservoir-foundation interaction, finite element method, infinite elements, spatially variable ground motion, nonlinear dam response

1. INTRODUCTION

Concrete gravity dams are vital infrastructures that serve water supply, electricity generation, flood control, and other purposes. Many of them were built in highly seismic areas and have been operating for a long period of time. Earthquakes may impair their proper functioning and trigger catastrophic failure causing property damage and loss of life. To this end, the seismic response of concrete gravity dams has been extensively studied over the past decades. Significant progress has been made to comprehend their dynamic characteristics and seismic behavior. However, in spite of the advancements achieved so far, a number of important aspects with respect to these massive structures are yet to be fully understood and still require particular attention: (i) They are long structures located at complex sites, and hence the spatial variability of seismic ground motions may play a significant role; (ii) The dam-reservoir-foundation interaction is an important component of the structural response and should be incorporated into the complete system; (iii) The concrete in the dam and the rock in the foundation exhibit complicated nonlinear mechanical behavior under dynamic loadings and need to be represented in an appropriate way; and (iv) The reservoir and foundation are semi-infinite unbounded domains and require special techniques for simulating the radiation of the out-going waves from the finite computational domain. This paper addresses these issues by developing a numerical procedure for studying the effects of the spatial variability of the earthquake motions on the response of concrete gravity dams using the finite element method. The proposed methodology is exemplified with the Koyna Dam in India. The commercial finite element software package Abaqus is employed to carry out the analysis. The simulation sequence is accomplished in two consecutive stages. A static analysis of the dam-reservoir-foundation system is first conducted to model its state prior to the earthquake loading. A dynamic analysis is then performed by applying the earthquake motions as excitations to the model. Both spatially uniform and nonuniform seismic excitations are utilized so that the effects of the spatial variability of the earthquake motions on the dam response are explored.

2. MATHEMATICAL MODEL

The system considered is a gravity dam with a vertical upstream face, which impounds a reservoir extending to infinity in the upstream direction and rests on a semi-infinite foundation. A sketch of the dam-reservoir-foundation system is shown in Figure 1.

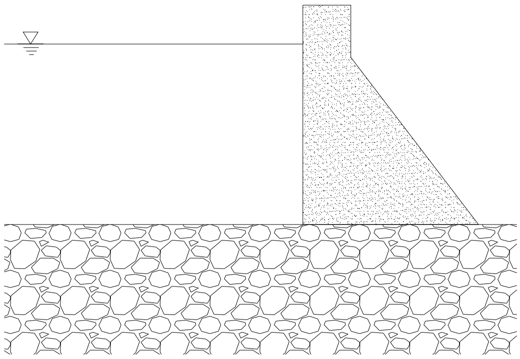


Figure 1 Schematic diagram of the dam-reservoir-foundation system

2.1. Modeling of the Dam, the Foundation, and the Reservoir

The concrete in the body of the dam exhibits a complicated nolinear stress-strain relationship that depends on the loading rate and history. In this paper, its constitutive relationship is emulated by the concrete damaged plasticity model in Abaqus (2007), which is based on the models proposed by Lubliner et al. (1989) and by Lee and Fenves (1998). The foundation rock is idealized as a Mohr-Coulomb material. Although this yield criterion is incapable of simulating yielding and cracking leading to softening and fracturing, it is comparatively easy to apply. In addition to its nonlinear behavior, to appropriately represent the unbounded foundation rock, we divide it into two sub-domains, i.e., the near-field region of interest and the far-field unbounded medium. A finite element model is adopted for the near-field region, while the far-field response is approximated by infinite elements. Assuming that the water in the reservoir is inviscid and compressible, the fluid model for representing the dynamic dam-reservoir interaction follows the one developed by Darbre (1998), in which a group of incompressible fluid masses are attached to a series of dampers. As this two-parameter model is discrete and frequency-independent, it can be built into a finite element model for nonlinear seismic analyses.

2.2. Coupling of the Dam-Reservoir-Foundation System

The amalgamation of the dam, the reservoir, and the foundation into a unified system is accomplished in a series of steps. The dam and the foundation are first integrated to form a dam-foundation system by imposing contact conditions at the dam-foundation contact interface using the Lagrange multiplier method. The reservoir is then coupled to the dam-foundation system through the pressure-motion relation for the two parameter model (Darbre, 1998). The coupling of the dam-reservoir-foundation system leads to the following discrete equation of motion:

$$\begin{bmatrix} [M] & [0] \\ [m] & [0] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}(t)\} \\ \{\ddot{p}(t)\} \end{Bmatrix} + \begin{bmatrix} [C] & [0] \\ [0] & [m/c] \end{bmatrix} \begin{Bmatrix} \{\dot{u}(t)\} \\ \{\dot{p}(t)\} \end{Bmatrix} + \begin{bmatrix} [K] & -[H] \\ [0] & [I] \end{bmatrix} \begin{Bmatrix} \{u(t)\} \\ \{p(t)\} \end{Bmatrix} = \begin{Bmatrix} \{F(t)\} \\ 0 \end{Bmatrix} \tag{2.1}$$

in which [M] is the dam-foundation mass matrix, [C] is the dam-foundation damping matrix associated with the energy dissipation and radiation in the system, [K] is the dam-foundation structural stiffness matrix, [H] is the fluid-structure coupling matrix, [m] is the mass matrix for the added fluid masses, c is the damping constant of the dampers, [I] is a unit matrix, {u(t)} is the displacement and Lagrange multiplier vector, {p(t)} is the hydrodynamic pressure applied on the dam, {F(t)} is the vector related to forces excluding hydrodynamic load and penetration, and over-dot denotes differentiation with respect to time.

An automatic incrementation scheme (Abaqus, 2007) is utilized to solve Equation 2.1. The scheme iterates until the equilibrium convergence criteria are reached.

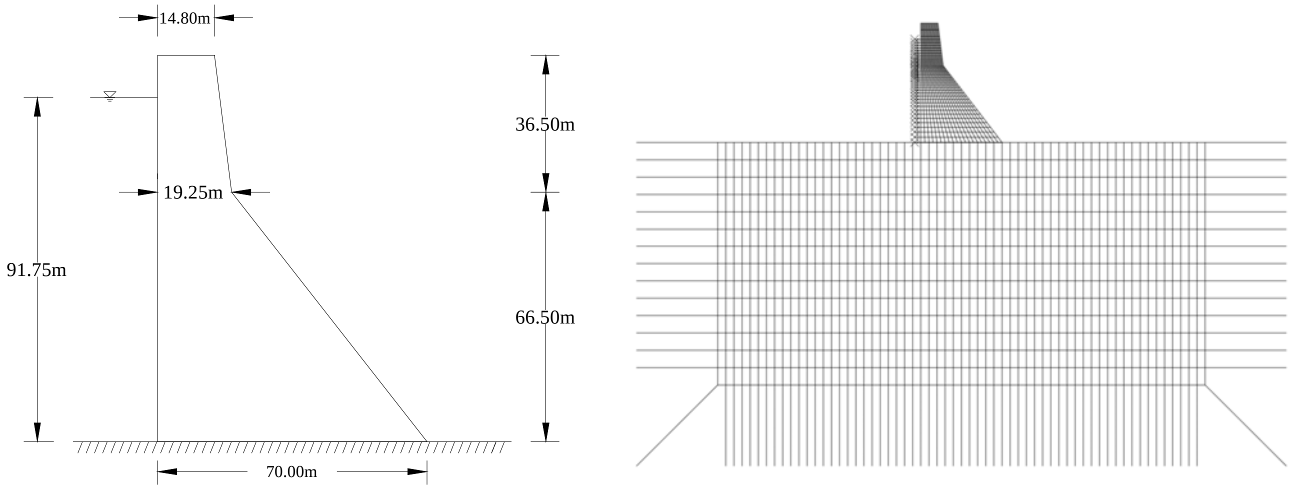
3. EARTHQUAKE INPUT MECHANISM

In the evaluation of the seismic response of concrete dams, the manner in which the earthquake ground motions are applied to the numerical model can influence the numerical results significantly. The present study applies the recorded free-field earthquake acceleration directly at the foundation ground surface. Although this approach assumes that the motions at the level of the ground surface, where the free-field accelerations are exerted, are not affected by the dam, it has the advantages that it avoids deconvolution analyses, the results of which are highly contingent on the accuracy of the deconvolution process, and, theoretically, it is possible to specify any spatially varying ground motions as input excitations to the problem. It is also worth mentioning that, according to the findings reported by Leger et al. (1989), the current approach and the deconvolution approach for inputting the seismic excitation for uniform seismic motions and vertical wave propagation gave very similar results for linear models of the dam and the foundation. Overall, this approach offers a reasonable tool for studying the effect of the spatial variability of ground motions on the seismic response of dam-reservoir-foundation systems.

4. NUMERICAL EXAMPLE

4.1. Numerical Model

The proposed numerical procedure is illustrated with the analysis of a concrete gravity dam, which closely resembles the Koyna Dam in India. Figure 2a shows the geometry of a typical non-overflow monolith of the Koyna dam in which the upstream wall of the monolith is assumed to be straight and vertical, which is slightly different from its real configuration (Abaqus, 2007). Figure 2b presents the finite element mesh for the dam-reservoir-foundation system.



(a) Non-overflow monolith geometry (b) Finite element mesh

Figure 2 The numerical model of the Koyna dam

The computational evaluation is performed with the commercial finite element software package Abaqus. The dam and the near-field foundation are modeled using 4-node bilinear finite elements, and the far-field foundation is represented by 4-node linear infinite elements. The fluid-structure interaction is modeled via the damper and added mass elements. The dam-foundation interface is simulated by a contact surface with a “hard” contact and a Coulomb friction model for the interaction normal and tangential to the surface, respectively (Abaqus, 2007). The major material properties used in this study for the dam-reservoir-foundation system, which are mostly based on Abaqus (2007) and Dhawan et al. (2004) are: i) for the concrete: Young’s modulus 31027 MPa, Poisson’s ratio 0.15, density 2643 kg/m^3, dilation angle 36.31^o, compressive initial yield stress 13.0 MPa, compressive ultimate stress 24.1 MPa, tensile failure stress 2.9 MPa; ii) for the rock: Young’s modulus 16860 MPa, Poisson’s ratio 0.18, density 2701 kg/m^3, cohesion 0.6 MPa, angle of friction 41^o; and iii) for the water: density 1000 kg/m^3, pressure wave velocity 1439 m/sec.

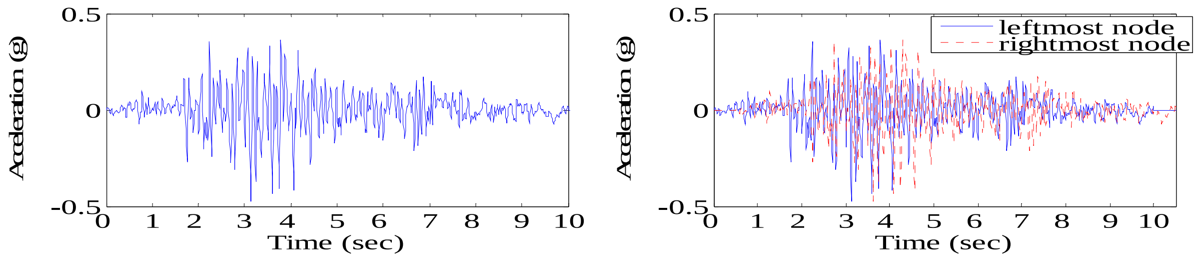
4.2. Seismic Analysis of the Koyna Dam-Reservoir-Foundation System

4.3.1 Free-vibration analysis

The largest four vibration periods of the dam on a rigid foundation are 0.327 sec, 0.124 sec, 0.090 sec, and 0.063 sec. The largest four vibration periods of the dam-foundation system are 0.442 sec, 0.321 sec, 0.285 sec, and 0.233 sec. The results for the rigid foundation case are in good agreement with those obtained by Chopra and Chakrabarti (1973). The results also indicate that the vibration periods lengthen with increasing foundation flexibility, which coincides with the investigation by Leger et al. (1989). Five percent of critical damping is utilized for the dam-foundation system.

4.3.2 Seismic analysis

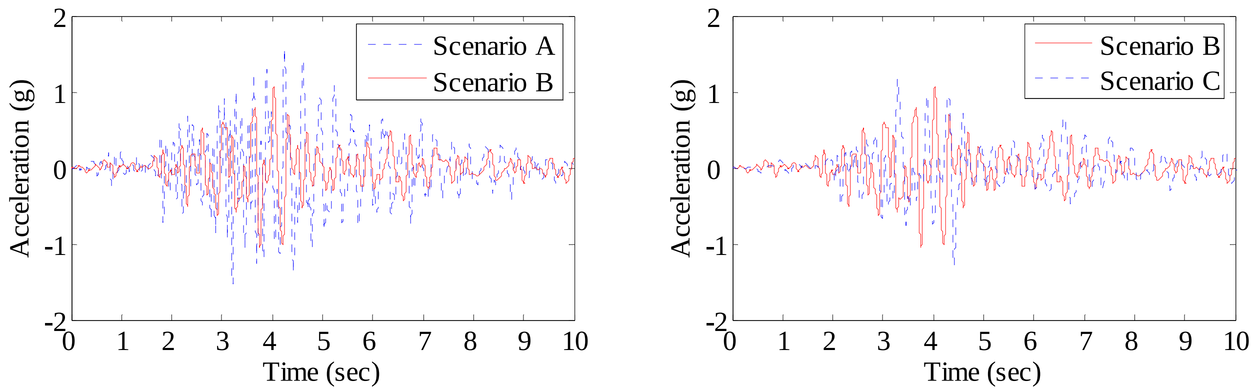
A static analysis of the dam-reservoir-foundation system is performed first to assess its pre-seismic state. The results of the static analysis are then utilized as the initial conditions for the subsequent seismic analyses. In order to evaluate the effects of the dam-foundation interaction and the spatial variation of ground motion on the response of the coupled system, three earthquake loading scenarios are compared: Scenario A considers the dam fixed on a rigid foundation under uniform seismic excitations; Scenario B the dam on a deformable foundation with contact interaction under uniform seismic excitations; and Scenario C the dam on a deformable foundation with contact interaction under spatially variable seismic excitations. To be consistent with Darbre’s two-parameter model described earlier, only the horizontal component of the Koyna earthquake is considered. Figure 3a shows the acceleration time history of the input ground motion for Scenarios A and B. For Scenario C, the input earthquake motion of the left-most node and the right-most node of the foundation surface is shown in Figure 3b. In this scenario, the spatial variability of the earthquake ground motions is simulated by permitting the seismic wave to travel horizontally from the left (upstream) to the right (downstream) with a propagation velocity of 840 m/s. The wave propagation effect can be clearly observed in Figure 3b from the time delay between the two acceleration time histories. It is noted that, for Scenario C, the duration of the original acceleration time history has been extended from 10 sec to 10.50 sec to account for the wave propagation effects.



(a) Scenarios A and B (b) Scenario C

Figure 3 Earthquake input motions

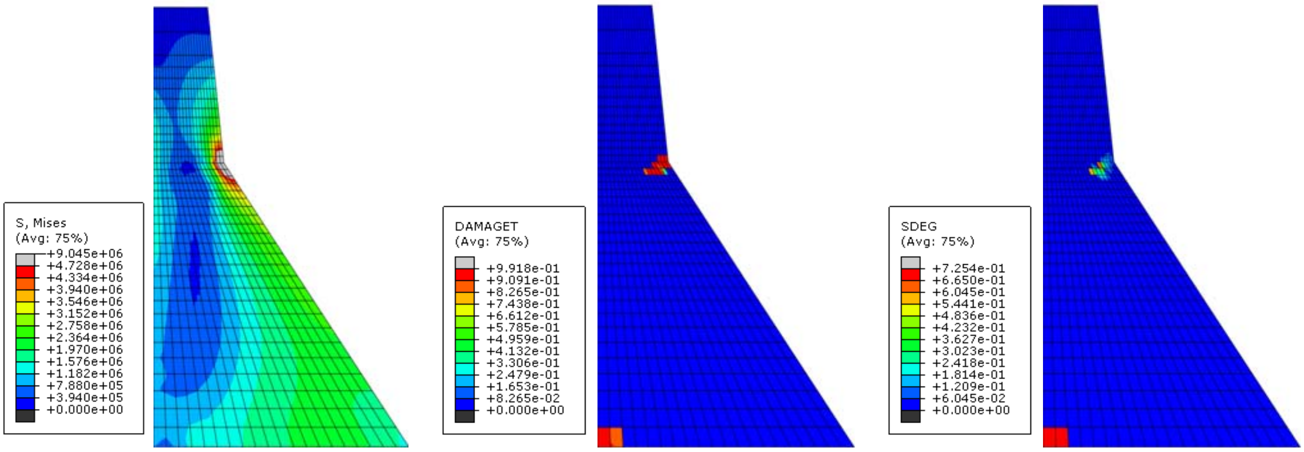
The results of the evaluation show that the Koyna dam undergoes strong shaking under both uniform and nonuniform seismic excitations leading to damage. The horizontal crest acceleration response for Scenarios A and B is plotted in Figure 4a, and for Scenarios B and C in Figure 4b. It follows from Figure 4a that the dynamic dam-foundation interaction effect tends to lessen the dam response, which is corroborated by Lin and Hu (2005). On the other hand, Figure 4b indicates that the effect of the spatial variation of earthquake ground motions tends to magnify the dam response. These observations are consistent with those from the peak stress contours in the dam and the damage at the neck and the base of the dam, which are discussed below.



(a) Scenarios A and B (b) Scenario B and C

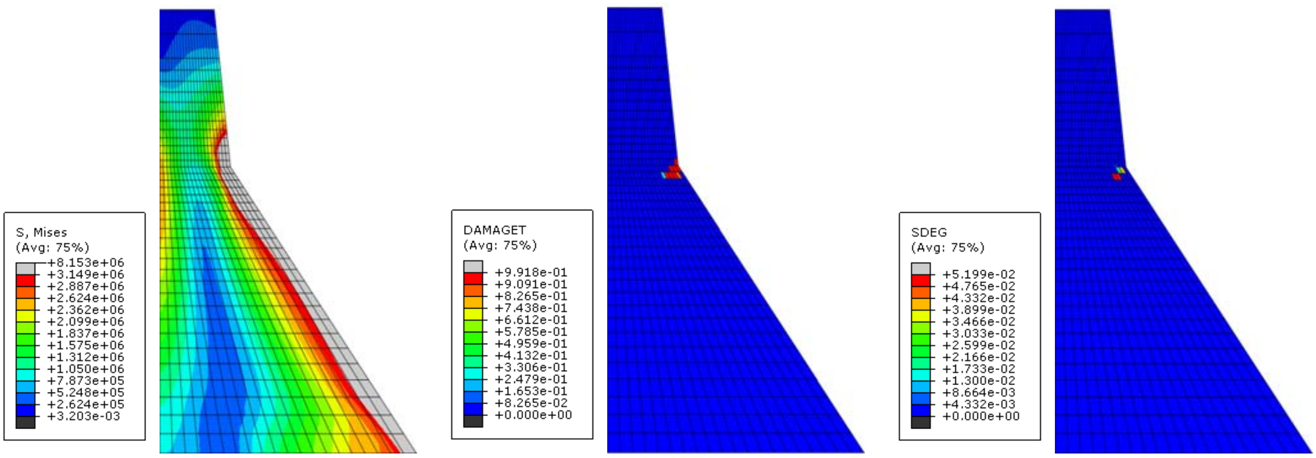
Figure 4 Comparison of horizontal crest acceleration responses

Figures 5a-7a display the peak von Mises equivalent stress contours occurring in the body of the dam during the earthquake excitation for each loading scenario. The examination of the evolution of the stress distribution in the dam reveals that the dam-foundation interaction and the nonuniform seismic excitation reduce and augment the dam response, respectively. It can also be seen from all three loading cases that high stress concentration builds up in the slope transition region on the downstream dam face, which indicates that cracks may be forming in this vulnerable region. The concrete cracking patterns in the dam can better be visualized by means of the tensile damage variable DAMAGET and the stiffness degradation variable SDEG (Abaqus, 2007). In case of no compressive damage, DAMAGET > 0 and SDEG > 0 represent an open crack, whereas DAMAGET > 0 and SDEG = 0 stand for a closed crack (Abaqus, 2007). Figures 5b-7b and 5c-7c present the DAMAGET and SDEG contours, respectively, for each scenario. The figures indicate that cracks form at the neck of the Koyna dam, as also noted earlier by other numerical and experimental studies (e.g., Ghrib, 1995; Niwa and Clough, 1980). It is further observed from Figures 5b and 5c that a localized crack develops at the heel of the dam. The formation of this crack is caused by the energy trapped in this region due to presence of the infinitely rigid foundation. The cracking and sliding at the dam-foundation interface become more apparent with the introduction of the contact surface. Figure 8 shows the cracking of at the heel of the dam for Scenarios B and C. Figures 9 and 10 present the sliding at the base of the dam for Scenarios B and C, respectively. It is noted that nodes 1 to 3 are located at the heel of the dam (upstream), and nodes 19-21 at the toe of the dam (downstream). Figures 8a, 9a, and 9b (response due to uniform input motions) and Figures 8b, 10a, and 10b (response due to spatially variable ground motions) indicate that intermittent crack openings and closures develop at the heel of the dam for both earthquake loading scenarios. The cracking for spatially variable ground motions is more severe than that induced by uniform seismic excitations, and more crack openings are observed throughout the duration of the spatially variable seismic excitation as compared to the concentrated peaks within a short time range for the uniform motion case. For both the uniform and nonuniform excitation cases, sliding occurs along the entire dam base in the downstream direction, with a slightly more pronounced sliding response at the heel of the dam, but the sliding displacements are larger for the nonuniform excitation case.



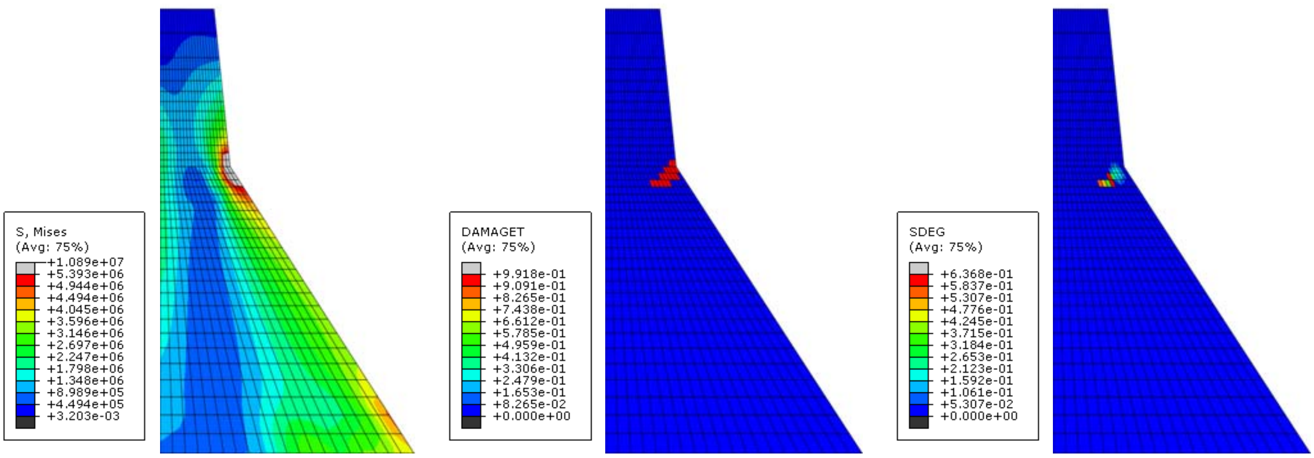
(a) von Mises equivalent stress (Pa) (b) DAMAGET (c) SDEG

Figure 5 Contours of peak stress distribution and damage of the Koyna dam for Scenario A at 4.790 sec



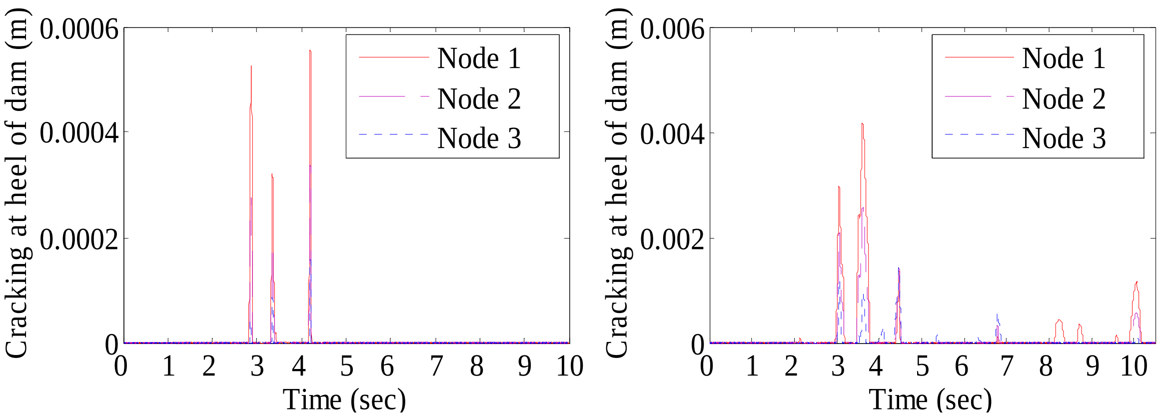
(a) von Mises equivalent stress (Pa) (b) DAMAGET (c) SDEG

Figure 6 Contours of peak stress distribution and damage of the Koyna dam for Scenario B at 4.208 sec



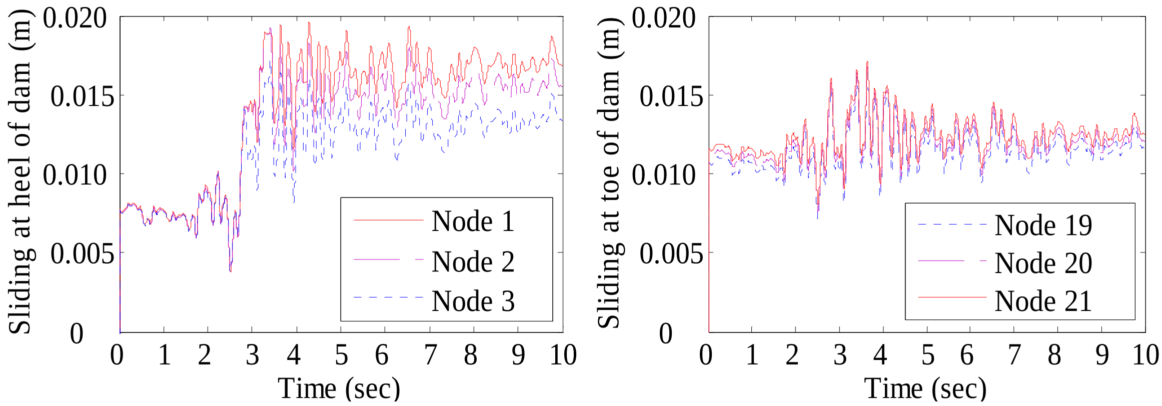
(a) von Mises equivalent stress (Pa) (b) DAMAGET (c) SDEG

Figure 7 Contours of peak stress distribution and damage of the Koyna dam for Scenario C at 4.427 sec



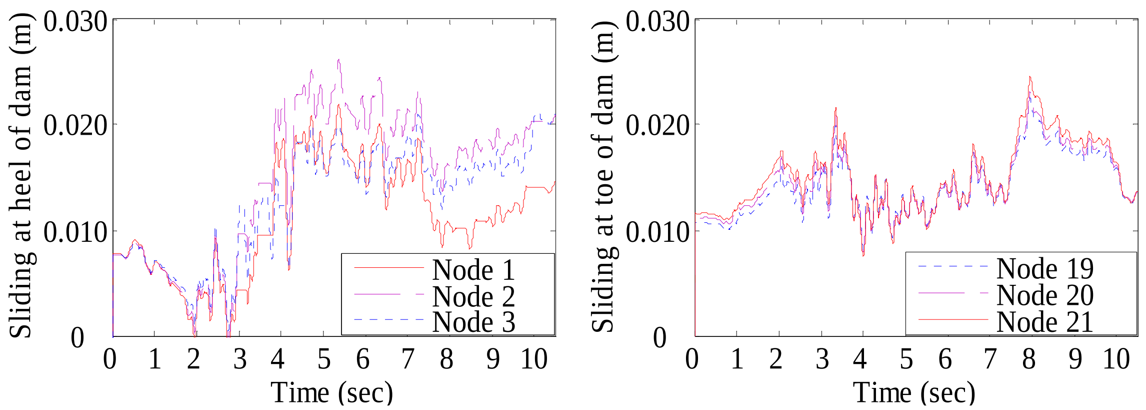
(a) Scenario B (b) Scenario C

Figure 8 Cracking at the heel of the dam



(a) Sliding at the heel of the dam (b) Sliding at the toe of the dam

Figure 9 Sliding at the base of the dam for Scenario B



(a) Sliding at the heel of the dam (b) Sliding at the toe of the dam

Figure 10 Sliding at the base of the dam for Scenario C

5. CONCLUSIONS

The following conclusions can be drawn from this nonlinear seismic response analysis of the Koyna dam-reservoir-foundation system: (i) The assumption of an infinitely rigid foundation appears to overestimate the structural response. The contact interaction at the dam-foundation interface can have a considerable impact on the dam response and should be considered in the evaluation. (ii) The numerical results presented herein show that the Koyna dam undergoes strong shaking under uniform and nonuniform seismic excitations. Cracks form at the neck and the heel of the dam for both excitation cases. Sliding occurs along the entire dam base with a slightly more pronounced sliding response at the heel of the dam. However, the spatially variable seismic excitation tends to magnify the dam response and may pose a threat to the dam safety. (iii) The analysis conducted in this work further indicates that diverse response patterns occur when the excitation is uniform or nonuniform. The major differences in the patterns are caused by the pseudo-static response, which is induced only by the nonuniform excitations.

ACKOWLEDGEMENTS

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