EFFECT OF DAM-FOUNDATION INTERFACE ON NONLINEAR SEISMIC RESPONSE OF CONCRETE GRAVITY DAMS

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ABSTRACT

Strong earthquakes cause concrete structures to crack. For the case of concrete dams, this problem is more severe since there are no reinforcements installed in the body of the dam. For these cases linear analysis ceases to represent reliable results and performing sophisticated nonlinear simulation becomes mandatory. However, traditional method of modelling interface of dam and foundation is assumed to be perfect, which continuity is maintained throughout the analysis regardless of magnitude of the stress on interface. This condition becomes more problematic in nonlinear analysis as excessive unreal energy is injected into the system and false crack patterns develop. To solve this issue, a realistic model of the interface needs to be considered. In this study, a comparative analysis between continuous model of interface and discontinuous model is performed. Due to magnification of stress in sharp corners, high magnitude of stress is developed. This leads to initiation of damage from those regions. Releasing stress by introducing a discontinuous interface model would help with stress redistribution and hence alleviate stress concentration in sharp corners. This could help yield more realistic nonlinear responses. To this end, a case study of Koyna concrete gravity dam is analyzed under both continuous and discontinuous dam-foundation interface model and responses and crack profiles are compared to each other. Results indicate the importance of considering a discontinuous interface model on producing reasonable crack profiles.

***Keywords** : concrete gravity dam, nonlinear seismic analysis, interface model, contact mechanics.*

1. INTRODUCTION

One of the dangers which always threatens the safety of structures, more specifically concrete structures, is the probability of cracking under various loading conditions. The situation gets more critical when concrete structures are built without any types of reinforcements. For plain concrete structures, concrete cracking is always a concern and should precisely cared for. The most important structures in the category of plain concrete structures are concrete dams. Due to development of huge forces in body of the dam as well as erosion of steel due to exposure to moist, use of rebar or any other means of steel reinforcement is not logical for concrete dams. Therefore, as concrete is very weak in tension and would easily crack, the designer should take special care in the process of analyzing the dam. Whether it is in the designing period or it is after the dam is built, one of the main loadings that should always be accounted for in analysis of concrete dams is earthquake loading. Apart from seismological concepts of the subject, the basic idea in seismic analysis of concrete dams is based on the fact that the stress level in no region of the dam body should exceed the apparent strength of the concrete. For this purpose, initially a linear dynamic analysis is performed. Whether the stress levels are within a reasonable range or not, the need to perform a nonlinear analysis is determined. Nonlinear dynamic analysis defines the safety and stability of dams under severe loadings. The results of nonlinear analysis are usually presented in the form of crack profiles and damaged elements. Many factors affect the crack pattern under a specific loading. One characteristic which affects the crack pattern under seismic loading is the interaction between dam body and foundation as well as between dam and reservoir.

Many studies have been devoted to study of seismic analysis of dams with respect to all kinds of interactions involved in the problem. Chopra and Perumalswami (1969) studied the effects of foundation stiffness on seismic behavior of concrete dams. Their study showed foundation stiffness could affect modal frequencies of the dam which can directly affect dynamic behavior of the dam. They also investigated the effects of dynamic characteristics of materials, geometry and dam-foundation interaction on modal frequencies and shapes of the dam in Chopra and Perumalswami (1971). Tan and Chopra (1995 and 1996) considered dam-foundation and dam-reservoir interaction in seismic simulation of Morrow Point Dam under Taft earthquake. Considering dam-foundation and dam-reservoir interactions, Chopra and Chakrabarti (1981) performed a seismic analysis of a system of gravity dam-foundation-reservoir. Fok and Chopra (1986) utilized sub-structure method for including elastic behavior of foundation in dynamic analysis of an arch dam. By comparing cases with different assumptions for interaction, Pelecanos et al. (2018) indicated that including realistic interaction between dam and foundation affects the nonlinear responses of embankment dams and could reduce stress levels in dam body.

As a common practice, the dam and foundation are generally tied together at their contact interface. Assuming a perfect bond in the contact interface of dam and foundation has been proven to be far from realistic conditions. In this paper, by utilizing novel method of Daneshyar and Ghaemian (2017), a nonlinear seismic analysis of Koyna concrete gravity dam is performed under two separate cases. One case involves introducing continuous bond (tie) at the interface of dam and foundation and the other case includes the same problem but with discontinuous bond between dam and foundation. Results are extracted in the form of crack patterns, developed in the dam body, and compared together.

2. MATHEMATICAL PRELIMINARY

2.1 Coupled adhesion-friction, and unilateral contact model

Damage mechanics, which employs density of micro-cracks and micro-voids as an indicator for integrity of materials, provides a framework for including nonlinearities due to degeneration of structure within models. Capturing realistic responses for grouted contraction and peripheral joints can also be provided by the aforementioned theory. In order to include the effect of grouted joints, the model of Raous et al. (1999) is employed. The model considers adhesion, unilateral contact, and Coulomb friction law in a coupled and rate-dependent fashion. Joints are considered as material boundaries, and nonlinearities caused by degeneration of grouting material are included in the zero-width constitutive relations of interface. In addition, the adhesion of joints, which is characterized by integrity variable ω, is strongly coupled with Coulomb friction, leading to smooth transition from pure adhesion to pure friction.

Kuhn-Tucker conditions constraint normal contact as follows,

$$-r^n + C^n u^n \omega^2 \geq 0, \quad u^n \geq 0, \quad (-r^n + C^n u^n \omega^2) u^n = 0 \tag{1}$$

where r^n is the normal force of interface, C^n is the normal stiffness of interface, u^n is the opening, and ω is the integrity of grouting material, which can be defined as:

$$\dot{\omega} = \zeta^{-1/p} \left(U \frac{\partial f(\omega)}{\partial \omega} - \omega \left(u^n C^n u^n + u^t_\alpha C^t_{\alpha\beta} u^t_\beta \right) \right)^{1/p} \qquad \alpha, \beta = 1{,}2 \tag{2}$$

In the above equation, ζ is the viscosity parameter, U is the limit of decohesion, $f(\omega)$ is a function of ω, and p is a material constant.

Coulomb friction law can be written as:

$$S = \left\| r^t_\alpha - C^t_{\alpha\beta} u^t_\beta \omega^2 \right\| - \mu (r^n - C^n u^n \omega^2) \leq 0 \tag{3}$$

where r^t_α is the tangential force, $C^t_{\alpha\beta}$ is the initial stiffness matrix, u^t_β is the relative tangential displacement, and μ is the friction coefficient.

Relative tangential displacement u^t_α can be decomposed as follows:

$$u^t_\alpha = u^e_\alpha + u^s_\alpha \tag{4}$$

where u^e_α and u^s_α are the stick and slip parts, respectively.

Evolution of irreversible relative displacement is defined by the following slip flow rule:

$$\dot{u}^s_\alpha = \dot{\gamma}_s \frac{\partial S}{\partial r^t_\alpha} \tag{5}$$

where $\dot{\gamma}_s$ is the slip consistency parameter.

Kuhn-Tucker conditions for stick/slip response of interface can be written as:

$$S \leq 0, \; \dot{\gamma}_s \geq 0, \; S\dot{\gamma}_s = 0 \tag{6}$$

It should be mentioned that $f(\omega) = \omega$ and $p = 1$ are assumed.

2.2 Joints Behavior

Three different scenarios are employed here to assess the formulation in different conditions. In the first scenario, a hysteresis loop resulted by cyclic loading is produced. For this purpose, an initial normal pressure is assumed on a joint, and then tangential displacement is imposed. Resulted stress-displacement response, which is reported in Fig. 1, indicates strong coupling between adhesion and friction.

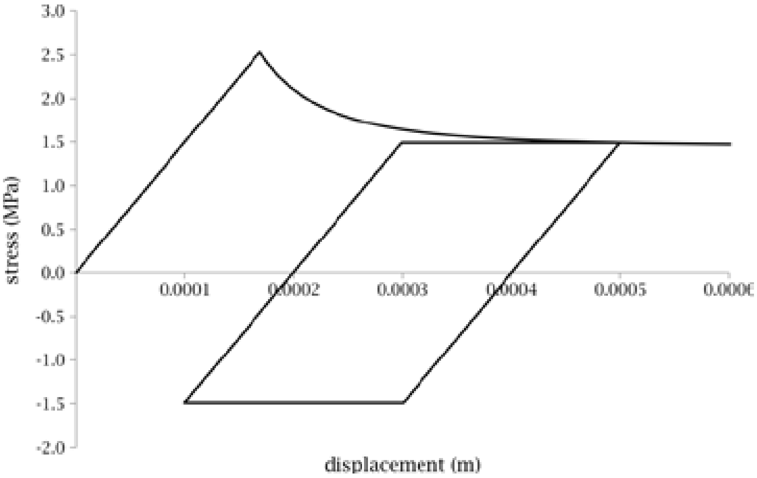

Figure 1 : Hysteresis response of joints.

In the second scenario, which the result is presented in Fig. 2, an initially opened joint undergoes tangential displacement, then the gap is closed and further tangential displacement is imposed.

The final scenario consists of a closed gap which undergoes relative tangential displacement, then the gap is opened and tangential displacement continues. Stress-displacement response of this case is also reported in Fig. 3.

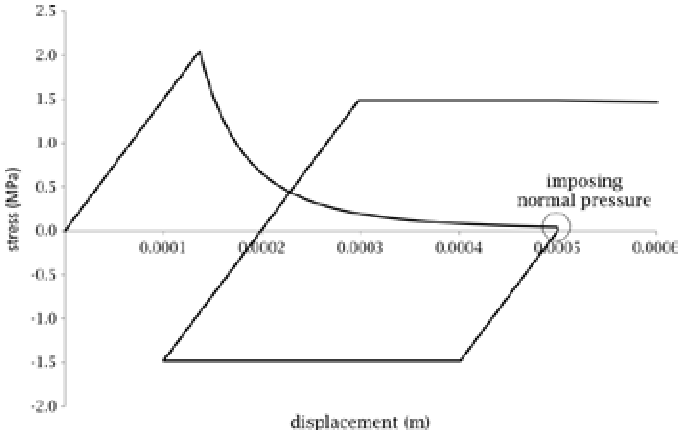

Figure 2 : Stress-displacement response of the second scenario.

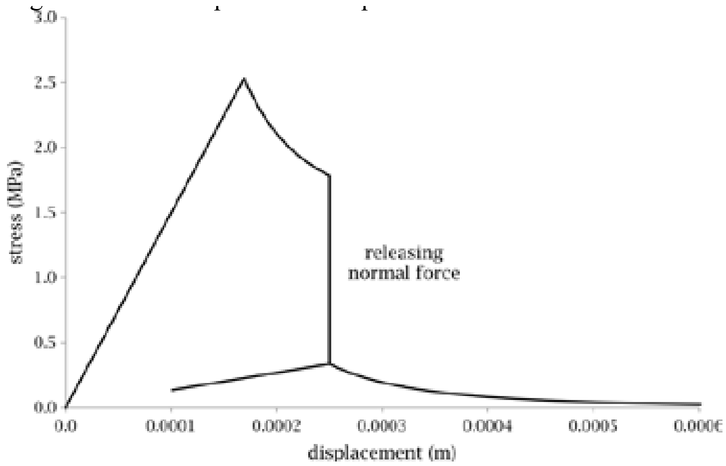

Figure 3 : Third scenario response.

2.3 Joints properties

Material properties of contraction and peripheral joints are selected as: initial normal stiffness C =32 GN/m, initial tangential stiffness $C^t_{\alpha\beta}$ = 15 GN/m for $\alpha=\beta$ and zero for the rest, tensile strength f_t = 2MPa, friction coefficient μ=0.9, and viscosity of adhesion evolution ζ=400 ms.

3. NUMERICAL SIMULATION

3.1 Earthquake record

For the purpose of seismic analysis of the system horizontal component of Koyna earthquake is employed in the analysis. Since strong motion occurs within first ten seconds of the earthquake and for reducing computation time, first ten seconds of the earthquake is employed and shown in Fig. 4.

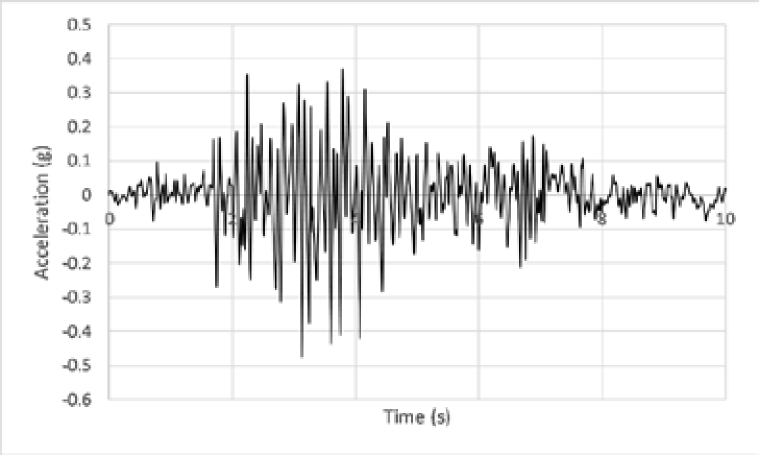

Figure 4 : Acceleration time history of Koyna earthquake

3.2 Finite element model

A numerical model for nonlinear seismic analysis of Koyna concrete dam was generated, which is shown in Fig. 6. Material properties of the model are selected according to Table 1.

Table 1 : Material properties

Region	Elastic modulus (MPa)	Density (Kg/m^3)	Poison's Ratio	Tensile strength (MPa)	Fracture energy (N/mm)	Bulk modulus (MPa)
Dam	3.00	2630	0.20	2.41	0.025	-
Foundation	2.24	-	0.33	-	-	-
Reservoir	-	-	-	-	-	2.07

To solely focus on the effects of correct interface modelling between dam and foundation, a simple earthquake input method namely, massless foundation model, is utilized. Massless foundation model assumes zero density for foundation region and hence, only flexibility of the foundation is accounted for in the analysis. To mesh the system, 4-node linear elements are used. For meshing the reservoir, acoustic elements, which have pressure as their degree of freedom at

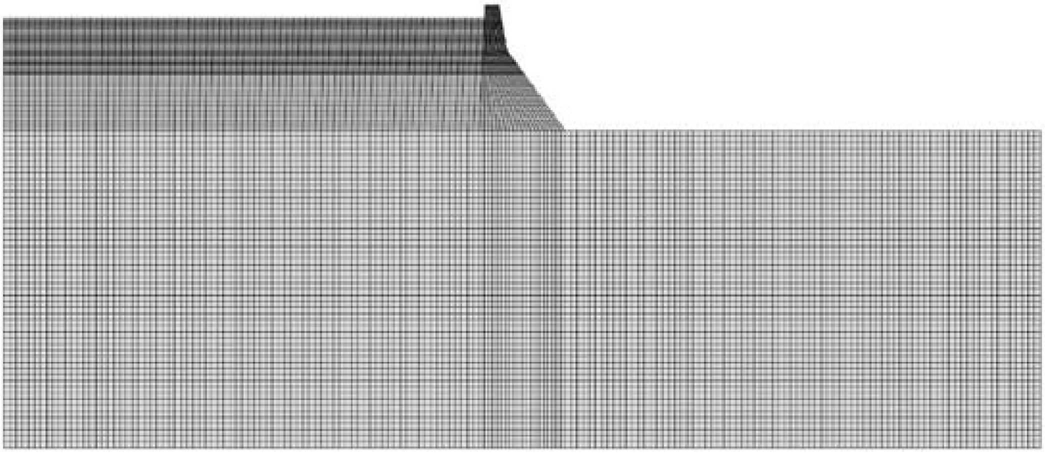

Figure 5 : Finite element model of Koyna concrete gravity dam

each node, are employed. To consider the earthquake loading, the free-field record of Koyna earthquake is applied at the foundation far-end boundary. A non-reflective boundary condition is introduced at the end of reservoir to absorb plane seismic waves reaching the end of the reservoir. Zero-pressure boundary condition is also applied at the surface of the reservoir. Accounting for hydrodynamic pressure, the reservoir and dam nodes are tied together at their respective common interface. Same analogy exists for reservoir and foundation common interface.

For the purpose of study, two separate models, namely continuous and discontinuous models, which only differ in the nature of bonding between dam and foundation, are developed. Continuous model assumes continuous bond (tie) between dam and foundation and discontinuous model assumes a more realistic discontinuous bond between dam and foundation, which is already explained in previous sections.

3.3 Numerical results

Damage contours for continuous and discontinuous models are followed as well as a comparison between relative crest displacements for two different models.

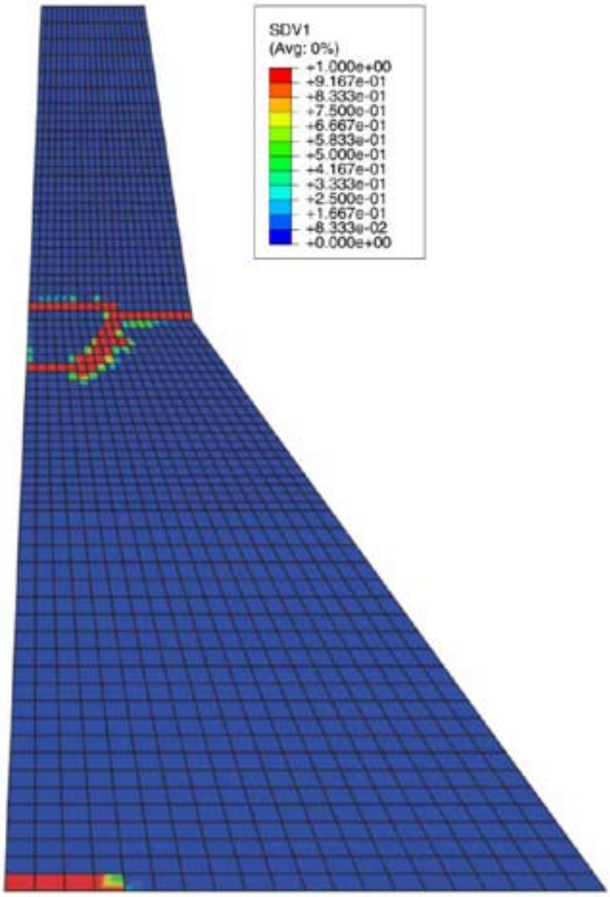

Figure 6 : Damage contour for continuous model.

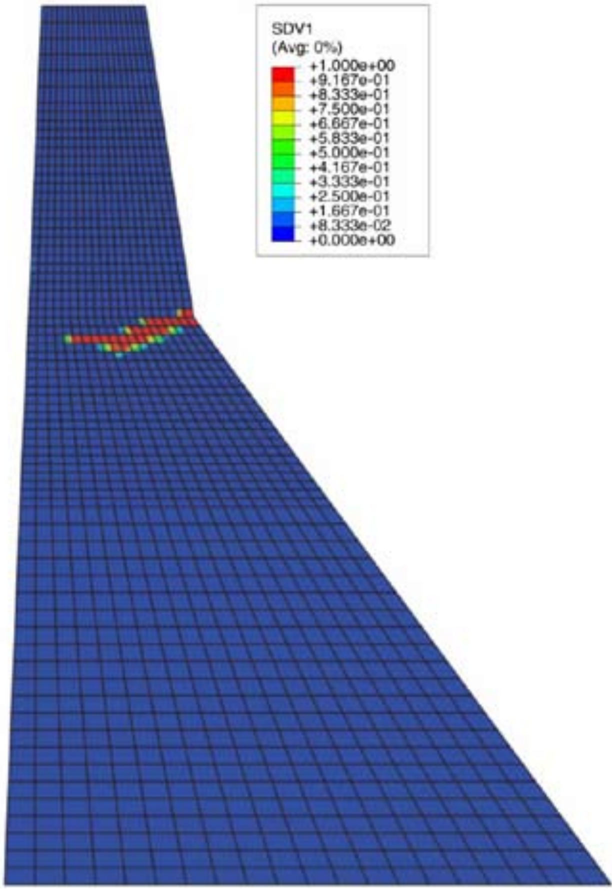

Figure 7 : Damage contour for discontinuous model.

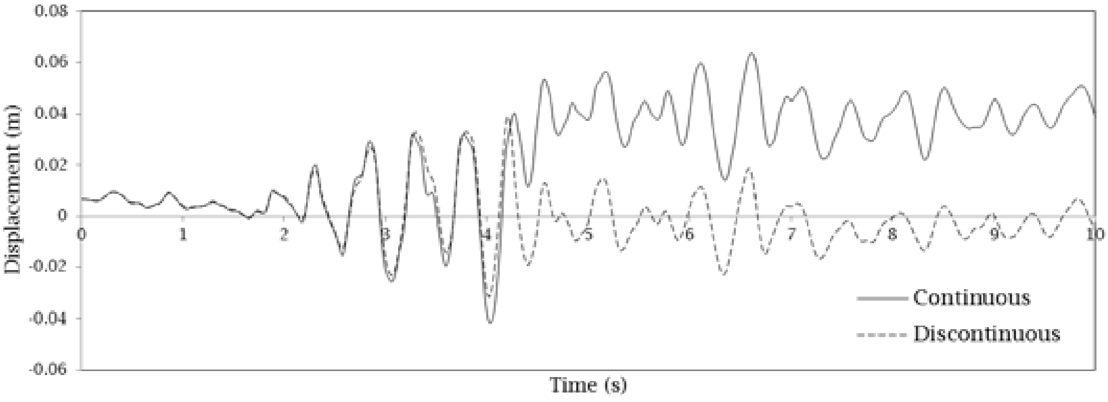

Figure 8 : Relative displacement of crest with respect to heel for two models.

As can be seen from Fig. 6, for continuous model, two cracked regions are developed in the dam body. The number of damaged elements at the top of the dam is so high that complete debonding of the top of the dam happens which means that the dam is unsafe for this model. Fig. 7 shows the crack pattern for discontinuous model in which a realistic discontinuous bond is introduced at the dam-foundation interface. As it is clear, there is no crack region present at the base of the dam (contrary to continuous model). What is more important is that, the severity of damaged elements at the top of the dam is not as much as continuous model and although cracks has developed, no debonding of the top region of the dam is observed which ensures safe performance of the dam in this model.

This result clearly shows the importance of precise numerical simulation of the system of dam-foundation-reservoir as it can be instrumental in correct judgment of safety performance of the dam.

4. CONCLUSION

In this study, the effects of introducing a realistic discontinous bond at the dam foundation interface was investigated. For this purpose two separate models were developed which are identical except for the bonding between dam and foundation. In the first model, continuous bond (tie) between dam and foundation is assumed and in the second model a more realistic discontinuous bond at the common interface of dam and foundation was defined. Since the aim of the study was focused on influence of dam-foundation interface on nonlinear seismic response of Koyna concrete gravity dam, a simple earthquake input mechanism namely, massless foundation model, was employed.

As results show, when a more realistic bond is introduced into the system for dam-foundation interface (discontinuous model), the nonlinear behavior overhauls and a dam which was unsafe under continuous bond assumption (continuous mode), can withstand the earthquake in a more realistic modelling of the system (discontinuous model). Besides, discontinuous model shows no sign of cracking at the base of the dam while continuous model indicate a noticeable cracked region starting from heel of the dam along the base. These results show that precise and realistic consideration of interactions between different regions of a system of dam-foundation-reservoir could be crucial in evaluating safety performance of the dam under severe earthquakes. They also indicate that simplifying the model sometimes results in costly estimations of the behavior of the dam.

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