NONLINEAR SEISMIC ANALYSIS OF A SYSTEM OF RCC DAM-MASSED FOUNDATION-RESERVOIR SYSTEM CONSIDERING REALISTIC BONDING CONDITIONS BETWEEN RCC LAYERS

ALI NOORZAD
Vice President, ICOLD and President, Iranian Committee on Large Dams (IRCOLD)
Dean, Faculty of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

ALIREZA DANESHYAR, PAYAM SOTOUDEH AND MOHSEN GHAEMIAN
Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

ABSTRACT

Roller Compacted Concrete dams or RCC dams are common practice in dam engineering. Due to different methods of construction for placement of RCC layers, different behaviors are assumed for this type of dams. This difference in method of placement, could yield to weaker bonding between layers of RCC. In order to take this condition into account and be able to obtain more realistic behavior from RCC dams, continuous assumption for body of dam is insufficient and a more sophisticated model is required. Thus, a model capable of considering these weak layers in numerical simulation of the dam is presented in this paper. Using nonlinear behavior of lift joints, weak planes within body of the dam are assumed and seismic responses are compared to simple homogeneous model. Results show that considering the effects of these weak layers has considerable effect on stress distribution of the body of the dam.

Keywords *: concrete gravity dam, nonlinear seismic analysis, RCC dams, lift joints.*

1. INTRODUCTION

Sensitivity of design and analysis of structures is directly influenced by the level of importance and expected services from the structure. Accordingly, complex structures such as concrete dams, which serve a variety of purposes from irrigation to electricity production and flood control, should be carefully designed and analyzed. Concrete dams, whether they are of arch type or gravity type, are built from plain concrete and no reinforcements are included in the dam body. Therefore, careful analysis of these structures is even more important because of cracking concerns in concrete due to low tensile strength.

One of the main loadings experienced during the lifetime of concrete dam, more specifically concrete gravity dams, is earthquake loading. Generally, largest levels are stress in dam body are produced due to severe level earthquakes. Therefore, a comprehensive seismic analysis, as close to reality as possible, is of paramount importance.

When dealing with the problem of seismic analysis of concrete gravity dams, a coupled system of solid and fluid is imagined. There are still aspects of seismic analysis of concrete gravity dams that are currently based on over-simplified assumptions. One of these over-simplified assumptions is related to the state of concrete dam body in nature. One widely used and practical assumption in numerical simulation of concrete gravity dams is that the dam body is made of homogeneous plain concrete. Although this is almost a good assumption for conventional gravity dams, it loses its viability when dealing with Roller-Compacted Concrete dams or RCC dams. Because of special method of construction in RCC dams, which involves fast placement of thin layers of concrete over one another in short intervals, the homogenous assumption would cause inaccurate behaviors for dam body. Therefore the need to account for such condition is sensible.

On the subject of seismic analysis of RCC dams with consideration of influential parameters few number of studies have been presented. Seismic simulation of an RCC dam has been carried out by Liapichev (2003) for MDE and MCE level earthquakes. The study concludes that for MCE level earthquake, nonlinear behavior of dam body as well as opening of RCC joints in bottom half of the dam is expected. Considering hydrodynamic pressure, Bayraktar et al. (2009) investigated the effects of considering near and far-fault ground motions on seismic performance of an RCC dam. Huang (2010) performed a dynamic analysis on Jin'anqiao RCC gravity dam.

In this paper, a nonlinear seismic analysis of an existing RCC concrete dam is performed. The task is done under two conditions which include homogenous behavior for dam body versus consideration of non-perfect bonding between layers of RCC in dam body. To solely focus on the effects of lift joints on response, material is assumed to be linear for dam and foundation. Response of dam in two cases are closely compared. Using a correct earthquake input mechanism, domain reduction method or DRM (Bielak et al. (2003) and Yoshimura et al. (2003)) is utilized to account for wave propagation effects in the system.

2. MATHEMATICAL PERLIMINERY

2.1 Domain Reduction Method

DRM is a two-step formulation to obtain the seismic response of any structure with any condition. This method is capable of accounting for wave propagation effects in any environment. Since seismic waves need a massed medium to propagate, therefore this method can account for foundation mass as well. In the first step, free-field response of the foundation is calculated. These forces are applied to a single layer of elements in the second step to perform the full analysis.

An unbounded foundation with superstructure can be shown as Fig. 1.

In DRM, source of excitation is inside the model and therefore a simple boundary condition on the sides of the foundation could effectively absorb the scattering waves emanating toward these boundaries. Because of simplicity and easy implementation, Lysmer's boundary condition is employed in this paper as the absorbing boundary

The problem at hand is represented as Figure 4. Γ+ is the foundation boundary and Γ is a desired virtual boundary that effective seismic forces are applied on. Introducing these boundaries results in two domains namely, Ω and Ω+ and 3 sets of nodal displacement by the names of u_e, u_b and u_i. Subscripts e, b and i refer to external, boundary and internal displacements.

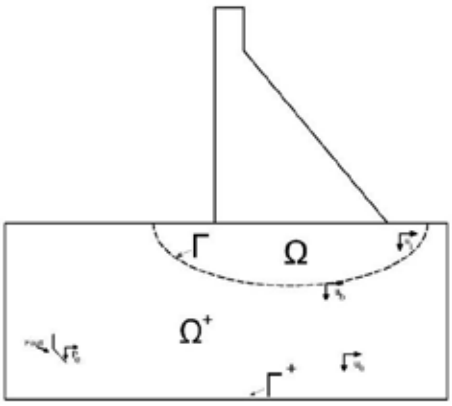


Figure 1 : Truncated region

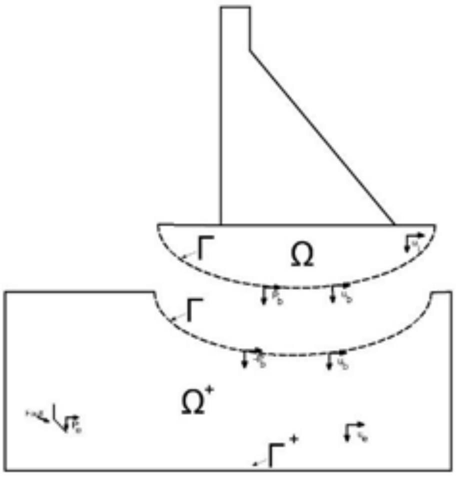


Figure 2 : Domains of the problem

The domain is governed by Navier's equation of motion. Partitioned finite element equations of motion for each domain is represented as:

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} \end{bmatrix} \begin{bmatrix} \ddot{u}_i \\ \ddot{u}_b \end{bmatrix} + \begin{bmatrix} C_{ii}^{\Omega} & C_{ib}^{\Omega} \\ C_{bi}^{\Omega} & C_{bb}^{\Omega} \end{bmatrix} \begin{bmatrix} \dot{u}_i \\ \dot{u}_b \end{bmatrix} + \begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} \end{bmatrix} \begin{bmatrix} u_i \\ u_b \end{bmatrix} = \begin{bmatrix} 0 \\ P_b \end{bmatrix} \quad in\ \Omega \tag{1}$$

$$\begin{bmatrix} M_{bb}^{\Omega^+} & M_{be}^{\Omega^+} \\ M_{eb}^{\Omega^+} & M_{ee}^{\Omega^+} \end{bmatrix} \begin{bmatrix} \ddot{u}_b \\ \ddot{u}_e \end{bmatrix} + \begin{bmatrix} C_{bb}^{\Omega^+} & C_{be}^{\Omega^+} \\ C_{eb}^{\Omega^+} & C_{ee}^{\Omega^+} \end{bmatrix} \begin{bmatrix} \dot{u}_b \\ \dot{u}_e \end{bmatrix} + \begin{bmatrix} K_{bb}^{\Omega^+} & K_{be}^{\Omega^+} \\ K_{eb}^{\Omega^+} & K_{ee}^{\Omega^+} \end{bmatrix} \begin{bmatrix} u_b \\ u_e \end{bmatrix} = \begin{bmatrix} -P_b \\ P_e \end{bmatrix} \quad in\ \Omega^+ \tag{2}$$

In Which M, C and K are mass, damping and stiffness matrices respectively.

By adding Eq. 1 and Eq. 2, the equation for the whole domain is obtained. To calculate effective seismic forces on Γ, an auxiliary problem is solved in which the interior domain (Ω) is replaced with Ω0 which has the same properties as Ω+ (Fig. 3-a).

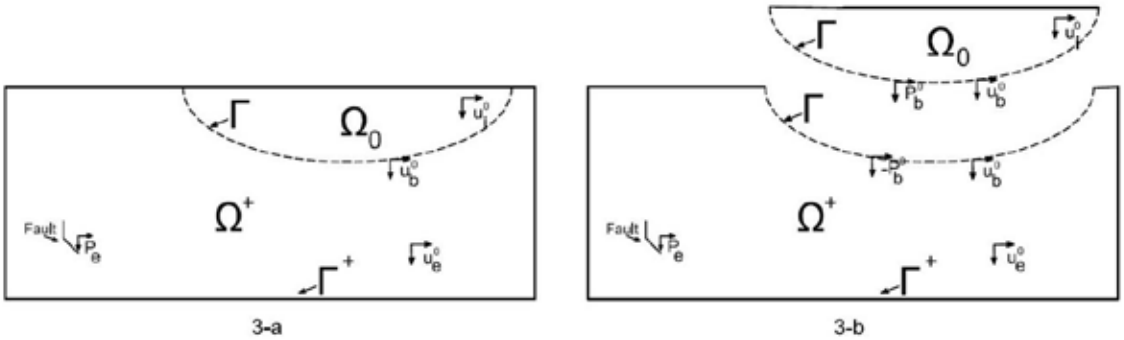


Figure 3 : (a) Auxiliray problem (b) two sub domains

The equation of motion in Ω+ is represented as:

$$\begin{bmatrix} M_{bb}^{\Omega^+} & M_{be}^{\Omega^+} \\ M_{eb}^{\Omega^+} & M_{ee}^{\Omega^+} \end{bmatrix}\begin{bmatrix} \ddot{u}_b^0 \\ \ddot{u}_e^0 \end{bmatrix} + \begin{bmatrix} C_{bb}^{\Omega^+} & C_{be}^{\Omega^+} \\ C_{eb}^{\Omega^+} & C_{ee}^{\Omega^+} \end{bmatrix}\begin{bmatrix} \dot{u}_b^0 \\ \dot{u}_e^0 \end{bmatrix} + \begin{bmatrix} K_{bb}^{\Omega^+} & K_{be}^{\Omega^+} \\ K_{eb}^{\Omega^+} & K_{ee}^{\Omega^+} \end{bmatrix}\begin{bmatrix} u_b^0 \\ u_e^0 \end{bmatrix} = \begin{bmatrix} -P_b^0 \\ P_e \end{bmatrix} \quad in\ \Omega^+ \tag{3}$$

Where superscript "0" refers to free-field value of the parameter obtained from auxiliary problem (Fig. 3-b).

Extracting P_e from Eq. 3, we have:

$$P_e = M_{eb}^{\Omega^+}\ddot{u}_b^0 + M_{ee}^{\Omega^+}\ddot{u}_e^0 + C_{eb}^{\Omega^+}\dot{u}_b^0 + C_{ee}^{\Omega^+}\dot{u}_e^0 + K_{eb}^{\Omega^+}u_b^0 + K_{ee}^{\Omega^+}u_e^0 \tag{4}$$

Consider following decomposition:

$$u_e = u_e^0 + w_e \tag{5}$$

In which w_e is the relative displacement with respect to free-filed motion.

By substituting Eq. 5 into summation of Eq. 1 and Eq. 2, new main equation of the system is obtained as follow:

$$\begin{bmatrix} M_{ii}^{\Omega} & M_{ib}^{\Omega} & 0 \\ M_{bi}^{\Omega} & M_{bb}^{\Omega} + M_{bb}^{\Omega^+} & M_{be}^{\Omega^+} \\ 0 & M_{eb}^{\Omega^+} & M_{ee}^{\Omega^+} \end{bmatrix}\begin{Bmatrix} \ddot{u}_i \\ \ddot{u}_b \\ \ddot{w}_e \end{Bmatrix} + \begin{bmatrix} C_{ii}^{\Omega} & C_{ib}^{\Omega} & 0 \\ C_{bi}^{\Omega} & C_{bb}^{\Omega} + C_{bb}^{\Omega^+} & C_{be}^{\Omega^+} \\ 0 & C_{eb}^{\Omega^+} & C_{ee}^{\Omega^+} \end{bmatrix}\begin{Bmatrix} \dot{u}_i \\ \dot{u}_b \\ \dot{w}_e \end{Bmatrix}$$
$$+ \begin{bmatrix} K_{ii}^{\Omega} & K_{ib}^{\Omega} & 0 \\ K_{bi}^{\Omega} & K_{bb}^{\Omega} + K_{bb}^{\Omega^+} & K_{be}^{\Omega^+} \\ 0 & K_{eb}^{\Omega^+} & K_{ee}^{\Omega^+} \end{bmatrix}\begin{Bmatrix} u_i \\ u_b \\ w_e \end{Bmatrix} = \begin{Bmatrix} 0 \\ -M_{be}^{\Omega^+}\ddot{u}_e^0 - C_{be}^{\Omega^+}\dot{u}_e^0 - K_{be}^{\Omega^+}u_e^0 \\ P_e - M_{ee}^{\Omega^+}\ddot{u}_e^0 - C_{ee}^{\Omega^+}\dot{u}_e^0 - K_{ee}^{\Omega^+}u_e^0 \end{Bmatrix} \tag{6}$$

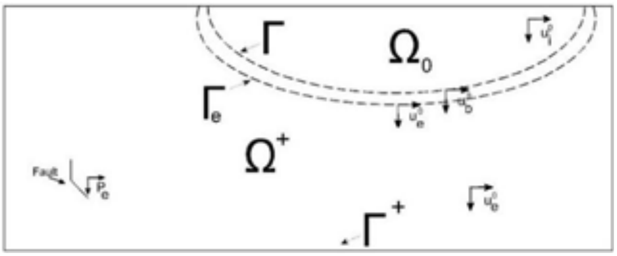
Substitute Eq. 4 into Eq. 6 and the final form of effective seismic forces which should be applied in the second step is obtained:

$$P^{eff} = \begin{Bmatrix} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{Bmatrix} = \begin{Bmatrix} 0 \\ -M_{be}^{\Omega^+}\ddot{u}_e^0 - C_{be}^{\Omega^+}\dot{u}_e^0 - K_{be}^{\Omega^+}u_e^0 \\ M_{eb}^{\Omega^+}\ddot{u}_b^0 + C_{eb}^{\Omega^+}\dot{u}_b^0 + K_{eb}^{\Omega^+}u_b^0 \end{Bmatrix} \tag{7}$$

As it can be observed from Eq. 7, subscript indices are either be or eb which causes the matrices to have zero values except on one single layer of elements bounded by b and e nodes.

To summarize, for the first step the auxiliary problem needs to be solved to obtain the effective seismic forces on all nodes of elements bounded by Γ and Γe boundaries (Fig. 4).

For the second step, effective forces of first step are applied at their respective nodes. (Fig. 5).



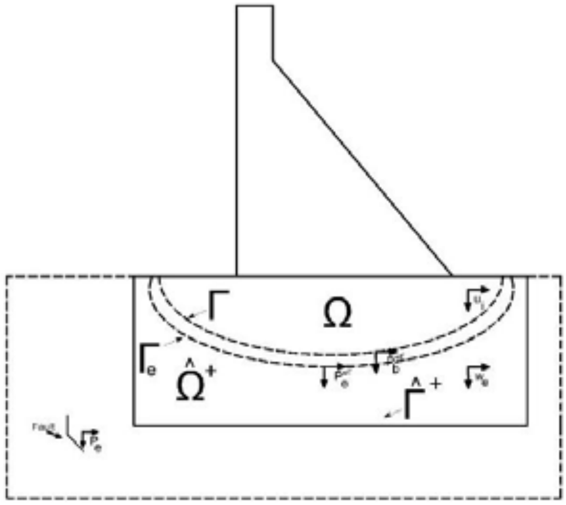


Figure 4 : First step of the DRM model

Figure 5 : Second step of the DRM model

2.2 Joint description

Degradation of lift joint materials is quantified using the model of Raous et al. (1999). According to the model, yield surface for interface material is defined by:

$$S = \left\| r_\alpha^t - C_{\alpha\beta}^t u_\beta^t \omega^2 \right\| - \mu\left(r^n - C^n u^n \omega^2\right) \leq 0 \quad (8)$$

where r_α^t is the tangential force, $C^t_{\alpha\beta}$ is the initial stiffness matrix, u^t_β is the relative tangential displacement, μ is the friction coefficient, 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:

$$\dot{\omega} = (1/\zeta)\left(U - \omega\left(u^n C^n u^n + u_\alpha^t C_{\alpha\beta}^t u_\beta^t\right)\right) \qquad \alpha, \beta = 1,2 \quad (9)$$

In the above equation, ζ is the viscosity parameter and U is the limit of decohesion. For further detail on the subject refer to Daneshyar and Ghaemian (2019).

3. FINITE ELEMENT ANALYSIS OF THE SYSTEM OF DAM-FOUNDATION-RESERVOIR

3.1 Earthquake record and dam description

As the case study, an existing RCC dam in Iran is selected which is schematically shown in Fig. 6.

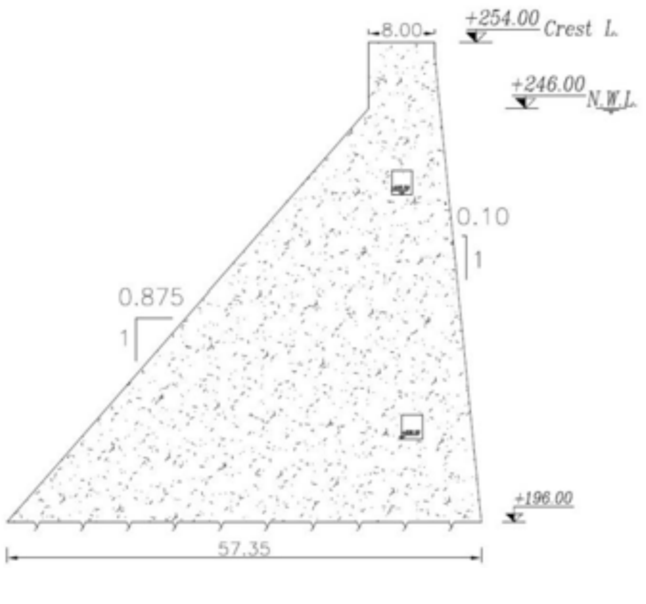


Figure 6 : Schematics of RCC dam

For dynamic analysis of the system, first ten seconds of Koyna earthquake record is utilized. The acceleration time history of Koyna earthquake is shown in Fig. 7.

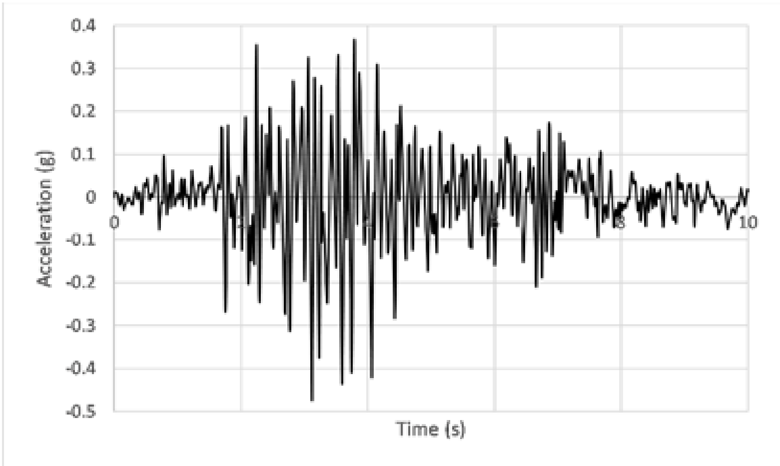


Figure 7 : Koyna earthquake record

3.2 Finite element model of the system

For numerical analysis, a finite element model of the RCC dam-reservoir-massed foundation is developed which is shown in Fig. 8. Material properties of the model are shown in Table 1. 4-node linear elements are employed in meshing the system. Solid elements are used for dam and foundation while acoustic elements are utilized for meshing the reservoir. Earthquake input is applied as effective forces (according to DRM procedure) on a single layer of elements in the foundation. Since DRM nature implies that outgoing waves are of small amplitudes, a simple absorbing boundary condition can be used to absorb scattering waves reaching foundation boundary. For this aim, Lysmer's dashpots are used. A non-reflective planar absorbing boundary condition is also introduced at the far end of reservoir. Dam, reservoir and foundation are tied together at their respective shared interfaces.

For the purpose of this study, two cases are considered. Both cases are based on the general numerical model which is shown in Fig. 8. The difference is related to the behavior of the dam. For case 1, the dam is assumed to be homogeneous and no RCC lift joint is present in the dam body. In Case 2, this assumption is dropped and RCC lift joints are introduced along dam height. For relatively lower computational costs, a total of 25 lifts are considered along dam height. Between each two lift, a non-perfect bond (as explained earlier) is introduced to model the heterogeneous behavior of the dam.

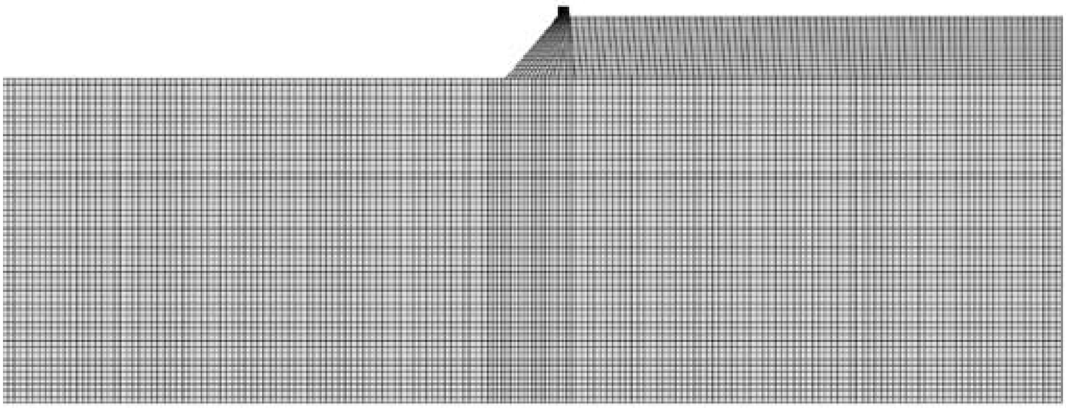


Figure 8 : Finite element model of RCC dam-reservoir-foundation

Table 1 : Material properties

Region	Elastic modulus (MPa)	Density (Kg/m^3)	Poison's Ratio	Bulk modulus (MPa)
Dam	3.00	2630	0.20	-
Foundation	2.24	2643	0.33	-
Reservoir	-	-	-	2.07

4. RESULTS AND DISCUSSION

Results of case 1 and 2 are presented as follows.

As Figs. 9 & 10 show, introducing lift joints in the model changes the contours for maximum principal tensile stress, while compressive stress almost remains unaffected. It is concluded from the figures that tensile stresses of jointed model are dropped significantly, and tensile stress of upstream face of the dam is almost zero. Close agreement between relative crest displacements of two cases is obtained (see Fig. 11).

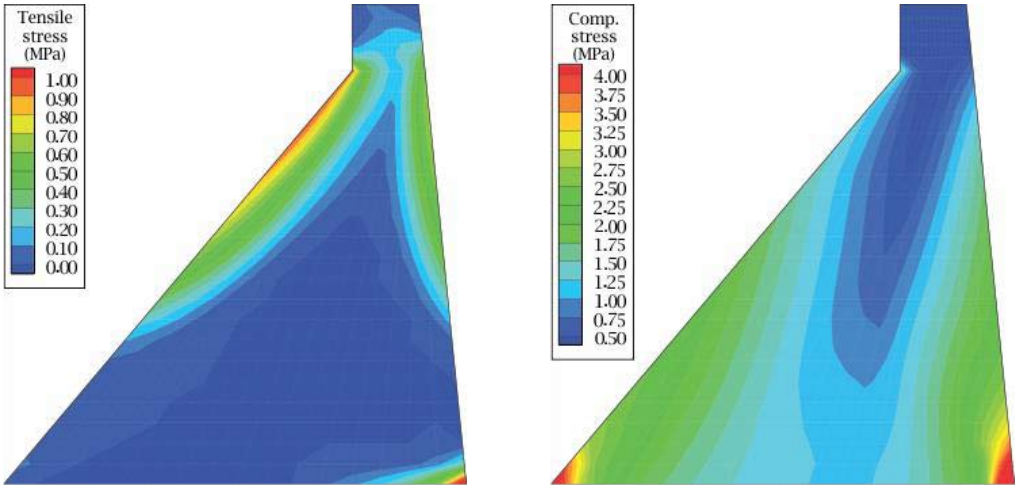


Figure 9 : Tensile (left) and compressive (right) Contours of principal stress for Case 1.

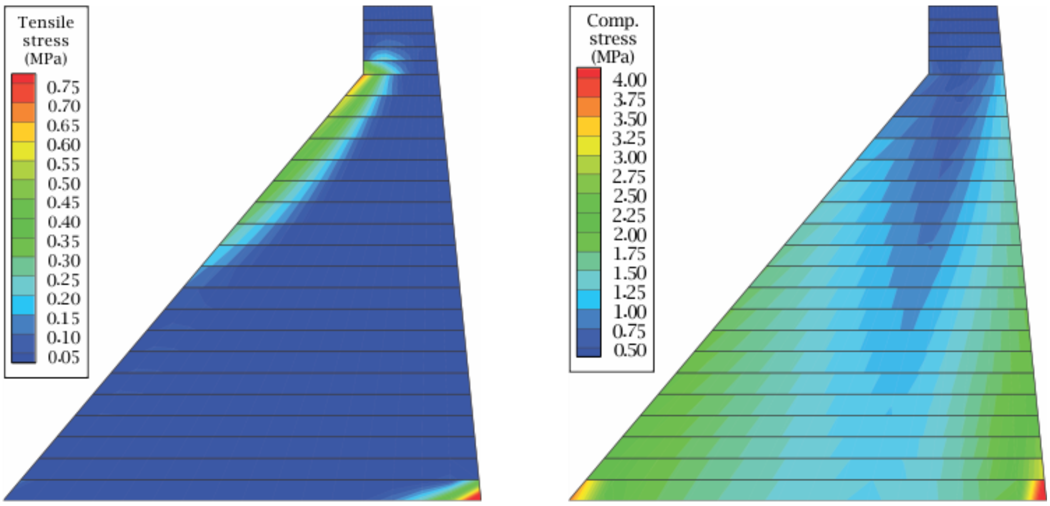


Figure 10 : Tensile (left) and compressive (right) Contours of principal stress for Case 2.

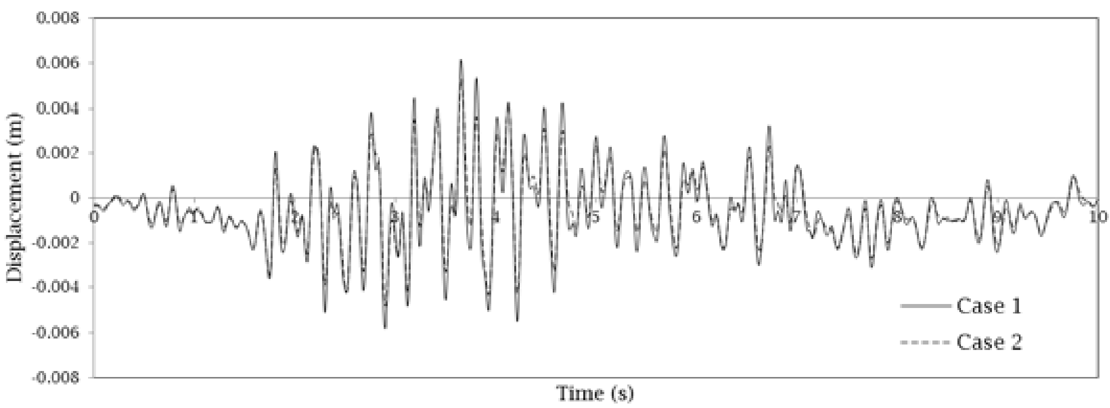


Figure 11 : Relative displacement of crest with respect to heel for both cases.

5. CONCLUSION

Homogeneous material assumption for concrete gravity dam body is common in dam engineering practice. Although it might be a good assumption for conventional dams, for dams built by the method of RCC placement, this loses its viability. In this paper, the effects of considering lift joints in the body of an existing RCC dam was investigated. For this goal, a numerical model was solved under two separate cases. Case 1 considered homogeneous concrete for dam body without any lift joints present and case 2 included a total of 25 lift joints along dam height. A non-perfect bond between lifts was introduced in this case. For both cases the concrete remains linear so that the effects of lift joints consideration are more clear.

As results show, when lift joints are present, the pattern of stress development in the dam body changes. This change is not limited to the stress pattern in the dam body. In fact, considering lift joints in the dam body, sensibly changes the peak values of stress in the dam body as well. These results show that homogeneous assumption for dam body doesn't always work in favor and a more realistic modelling of the dam body could help get better sense of dam behavior and responses.

REFERENCES

ACI 207 1R. Mass concrete for dams and other massive structures. ACI Committee, USA; 1987.

ACI 207 5R-99. Roller-compacted mass concrete. ACI manual of concrete practice. Part 1, USA; 2004.

Araujo JM, Awruch AM. Cracking safety evaluation on gravity concrete dams during the construction phase. Comput Struct 1998;66 (1):93–104.

Bayraktar, A., Sevim, B., Altunıs¸ık A. C., T¨urker, T., Kartal, M. E., Akk¨ose, M., and Bilici, Y.: Comparison of near and far fault ground motion effects on the seismic performance evaluation of dam-reservoir-foundation systems, Int. Water Power Dam Construct. (Dam Engineering), 19, 1–39, 2009.

Bielak, Jacobo, Loukakis, Kostas, Hisada, Yoshiaki, and Yoshimura, Chiaki. Domain reduction method for three-dimensional earthquake modeling in localized regions, part i: Theory. Bulletin of the seismological Society of America, 93(2):817–824, 2003.

Huang, Y. S.: Analysis on seismic safety of RCC gravity dam with cutting transverse joints, 7th International Symposium on Safety Science and Technology (ISSST), Hangzhou, China, 26–29 October, Part A, 8, 1784–1790, 2010.

Japan Concrete Institute. Standard specifications for design and construction of concrete structures. Part 2 (construction), Tokyo; 1986.

Liapichev, Y. P.: Seismic stability and stress-strain state of a new type of FSH-RCC dams, 4th International Symposium on Roller Compacted Concrete Dams, Madrid, Spain, 17–19 November, 2003.

Raous, M., Cangémi, L., & Cocu, M. A consistent model coupling adhesion, friction, and unilateral contact. Computer methods in applied mechanics and engineering, 177(3-4), 383-399, 1999.

Yoshimura, Chiaki, Bielak, Jacobo, Hisada, Yoshiaki, and Fernández, Antonio. Domain reduction method for three-dimensional earthquake modeling in localized regions, part ii: Verification and applications. Bulletin of the Seismological Society of America, 93(2):825–841, 2003.