FLEXIBLE FOUNDATION EFFECT ON SEISMIC ANALYSIS OF CONCRETE GRAVITY DAMS

EFFET DE FONDATION FLEXIBLE SUR L'ANALYSE SISMIQUE DES BARRAGES POIDS EN BÉTON

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Résumé- L'étude du comportement des barrages face aux charges sismiques est un facteur clé pour les exigences de sécurité des barrages. L'un des problèmes les plus importants dans l'évaluation du comportement sismique du barrage-poids en béton est l'interaction barrage-réservoir-fondation. Les pressions hydrodynamiques générées en raison des forces sismiques et de l'interaction fluide-structure-sol (SFS) sont inévitables. Dans le présent travail, la fondation a été considérée de deux manières: (a) fondation rigide, (b): fondation flexible. ANSYS a permis d'analyser le barrage en béton d'Oued Fodda, situé dans la Wilaya de Chlef au nord-ouest de l'Algérie. La pression hydrodynamique de l'eau du réservoir est modélisée sous forme de masse ajoutée en utilisant l'approche de Westergaard. Les déplacements horizontaux maximaux et les principales contraintes du barrage sont présentés ainsi que le comportement sismique du barrage est examiné pour les deux cas étudiés: barrage à fondation rigide et barrage à fondation flexible. En outre, les emplacements des dommages dans le barrage en béton sont évalués.

Mots - clés : Réponse sismique, Barrage-poids en béton, fondation flexible, interaction barrage-réservoir-fondation.

Abstract- Investigation of the behavior of dams against seismic loads is a key factor for dam safety requirements. One of the most important problems in evaluation of seismic behavior of concrete gravity dams is dam-reservoir-foundation interaction. Hydrodynamic pressures generated due to seismic forces and Fluid-Structure-Soil Interaction (FSS) are inevitable. In the present work, the foundation has been considered in two ways: (a) rigid foundation, (b): flexible foundation. ANSYS was used to analyze the concrete dam of Oued Fodda, located in the Wilaya of Chlef in north-western Algeria. The hydrodynamic pressure of the reservoir water is modeled as added mass using the Westergaard approach. The maximum horizontal displacements and principal stresses of the dam are presented as well as seismic behavior of dam is examined for the two cases studied : dam with rigid foundation and dam with flexible foundation. Besides, the damage placements in the concrete dam are evaluated.

Keywords: Seismic response, Concrete gravity dams, Foundation flexibility, Dam-reservoir-foundation interaction.

1-Introduction

The dam system is complex and full of uncertainties. Almost for all the countries in the world, dams are a vital part of the nation's infrastructure, providing economic, environmental, and social benefits. The benefts of dams, however, are countered by the risks they can present, such as overtopping of Banqiao Dam.

There are several phenomenons affecting the dynamic behavior of concrete dams to seismic excitations. These are generally the dam-foundation and dam-reservoir interaction. To avoid the afore mentioned considerations, for structures built on rock such as concrete dams, it is commonly considered that the use of massless foundation can be a reasonable assumption, which has been implemented in several studies [1–17]. It has been reported that the use of the massless foundation can lead to conservative results: Chopra[19] indicated that the massless foundation system can increase the stress and crest displacement of arch dams by a factor of 2 to 3 depending on the elastic moduli of the foundation. Yim and Chopra investigated the seismic response of SDOF structures supporting on a fexible soil under the impact of transient uplift with considering some parameters such as earthquake intensity, structural slenderness ratio, p-delta effect, foundation's mass, and flexibility [20-21]. Huda et al., [22] studied the influence of a thin layer interface element between a dam and rock foundation considering the effect of sediment on seismic response of the dam when the dam was subjected to a horizontal earthquake component. Spanos and Koh [23] in the same years, examined the stochastic response of a rigid block under the influence of random base vibration by modelling the subsoil with distributed springs and dampers (Winkler model). Ghaemian et al., [24] showed that the effects of foundation's shape and mass on the linear response of arch dams are considerable. The dam–foundation interaction effects are typically presented by a "standard" mass-less foundation model [25]. For the structure on the rigid foundation, the input seismic acceleration gives rise to an overturning moment and transverse base shear. As the rock is very stiff, these two stress resultants will not lead to any (additional) deformation or rocking motion at the base. For the structure founded on flexible soil, the motion of the base of the structure will be different from the free-field motion because of the coupling of the structure-soil system. This process, in which the response of the soil influences the motion of the structure and response of the structure influences the motion of the soil, is referred to as soil-structure interaction (SSI) presented by Wolf (1985) [26].

This study aims to enrich the studies related to the seismic response of Concrete gravity dams. Three-dimensional finite element model is used to investigate the effects of foundation flexibility and dam-reservoir-foundation interaction on the seismic response of concrete gravity dam with full reservoir. For illustrative purposes, the Oued Fodda concrete gravity dam, located in Chlef (north-western Algeria), is selected as an example. The hydrodynamic pressure of the reservoir water is modelled as added mass using the Westergaard approach. The effect of foundation flexibility has been obtained by considering various dam-foundation rock interaction ratios Ed/Ef i.e. modulus of elasticity of foundation Ef to modulus of elasticity of dam concrete Ed. The different numerical analyses are analyzed linearly using ANSYS code [27].

2- Effect of hydrodynamic pressure

The effect of hydrodynamic pressure is considered according to the added mass technique initially proposed by Westergaard [28]. Assuming that the water reservoir is non-viscous and incompressible and its movement of small amplitude, the equation which governs the hydrodynamic pressure is expressed by :

$$\nabla^2 P = 0 \qquad (1)$$

The solution of this equation is proposed by Westergaard and is used in the present work to calculate the hydrodynamic pressure imposed on the upstream face of the dam body during an earthquake.

3- Numerical model

3.1- Material Properties

The Oued Fodda concrete gravity dam is located approximately 20 km of Oued Fodda (Chlef), in north-western Algeria, and founded over a massive limestone known as “Koudiat Larouah”. The reservoir is mainly used for irrigation purposes. The capacity of the dam is 125.5 hm3. The maximum height “H” and base width of the dam are 101 m and 67.5 m, respectively. The dam crest is 5 m wide and the maximum height of the reservoir water is considered as 96.4 m. The dimensions of the dam-foundation system are shown in figs (2.3).

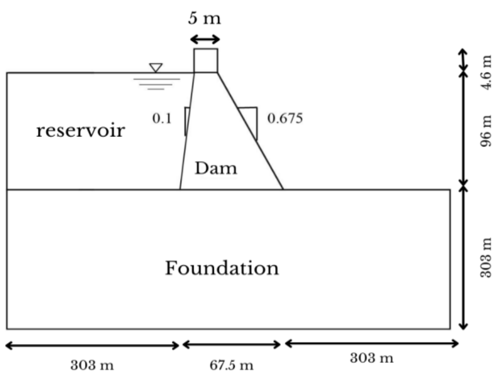

Figure 1 : Transverse section and dimensions

Figure 1 : Coupe transversale et dimensions

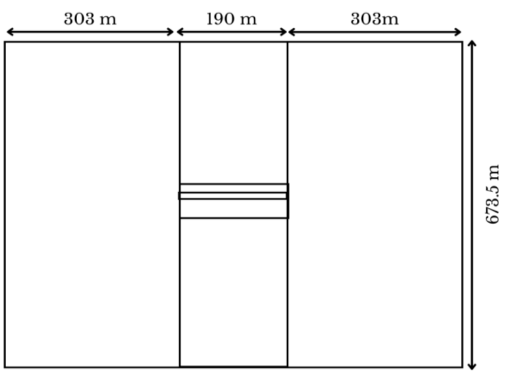

Figure 2 : Top view and dimensions

Figure 2 : Vue de dessus et dimensions

The material properties of Oued Fodda dam including its foundation are reported in Table1 below.

Tableau 1 : Material properties of Oued Fodda concrete gravity dam and its water reservoir

Table 1: Propriétés matérielles du barrage-poids en béton d’Oued Fodda et de son réservoir d'eau

Material	Material properties		
	Modulus of elasticity (MPa)	Poisson’s ratio	Mass density (kg/m³)
Concrete (dam)	**24600**	**0.20**	**2640**
Rock (foundation)	**20000**	**0.33**	**2000**
Reservoir water	**2070**	**0.49**	**1000**

The modulus of elasticity of the foundation was changed from 0.5 to 4.0 times the modulus of elasticity of the dam, as considered in the literature [29, 30]. However, for reasons of space and in order to better illustrate the possible differences in behavior, only the results obtained for extreme conditions of flexible and rigid soil (E_f / E_d = 0.5 and 4).

3.2-Finite Element Model of Dam-Foundation System

A three-dimensional (3D) discretization by finite elements (figure 2), is used for the modelling of the dam-foundation system. This finite element model is created using software ANSYS [27]. ANSYS is one of the leading commercial finite element programs in the world and can be applied to a large number of applications in engineering.

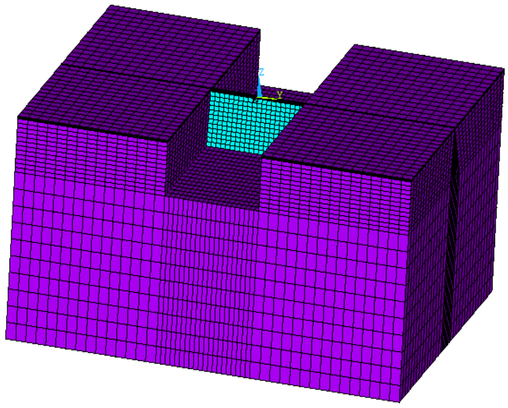

Figure 3 : Finite element discretization of the dam-foundation system

Figure 3 : Discrétisation par éléments finis du système barrage-fondation

The solid finite elements (Solid4185) used in the analysis have four nodes and 2 × 2 × 2 integration points. the element (SURF154) available in the ANSYS library represents this approach. This involves distributing the mass of the fluid over the contact surface between the reservoir and the dam and / or foundation soil.

A three-dimensional (3D) finite element model with 39750 solid finite elements (Solid185) is used to model Oued Fodda dam and the foundation soil. 900 finite element model (SURF154) is used to model the fluid. It is generally accepted that concrete dams have viscous damping ratios of 2% to 5% [9]. The damping for the entire structural system is modelled by Rayleigh damping. In this study, a Rayleigh damping of 5% is applied to both the dam and the foundation.

4- Numerical Results and Discussion

This study investigates the seismic response of Oued Fodda concrete gravity dam considering barrage-foundation interaction. For this purpose, the horizontal component of the 1980 El Asnam earthquake acceleration scaled by factor of 2.5 is utilized in analyses (Fig.4).

In 1980, El Asnam Province has already been shaken by the strong earthquake (M7). Unfortunately, we only have a record of a replica of this earthquake with peak ground acceleration (PGA) 0.132 g. Consequently, we chose the record of replica earthquake with a scaling factor of 2.5 to obtain an earthquake acceleration record with PGA 0.33 g, nearly equal to PGA of record of the strong earthquake (M7) which occurred in 1980. The linear and nonlinear time history analyses are performed using ANSYS [27].

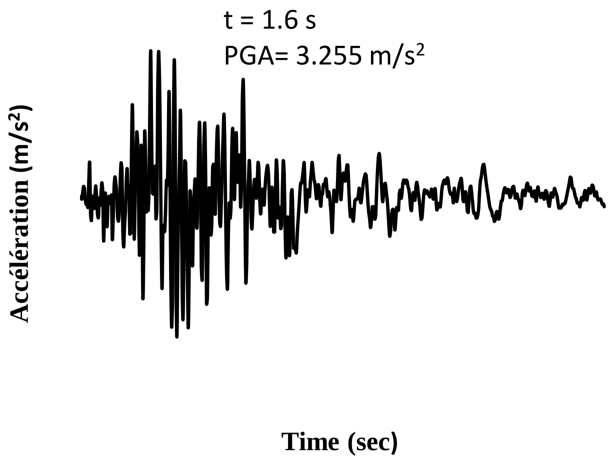

Figure 4: Time history of horizontal acceleration for 1980 El Asnam earthquake record scaled by factor of 2.5

Figure 4: Historique temporel de l'accélération horizontale pour le tremblement de terre d'El Asnam de 1980, mis à l'échelle par un facteur de 2,5

4.1- Horizontal displacements

Fig. 5 shows the time history of horizontal displacement at the dam crest in upstream face for dam with rigid foundation and dam with flexible foundation.

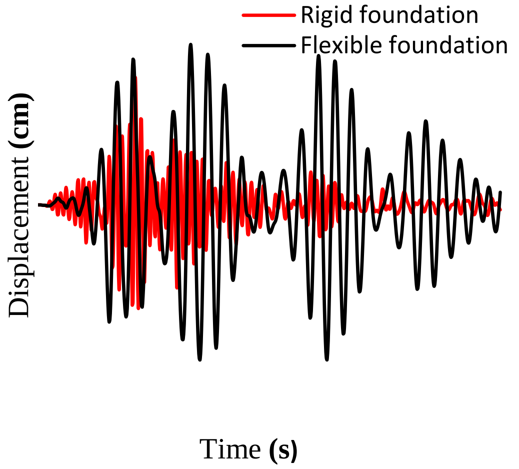

Figure 5: Time history of horizontal displacement at the dam crest in upstream face

Figure 5 : Déplacement horizontal en fonction du temps à la crête du barrage en face amont

From figure 5, it can be observed that in the case of the dam with a rigid foundation, the maximum horizontal displacement at the crest is 14.1 cm, while in the case of the dam with a flexible foundation, it is 17.8 cm. This indicates that there is approximately 20 % increase in the amplitude of displacement at the peak in the case of the flexible foundation, results indicate that the foundation flexibility has a significant impact on dam displacements.

4. 2- Variation of stresses

Figs. 6 and 7 represent the maximum principal tensile stress contours in upstream face of the dam for dam with rigid foundation and dam with flexible foundation cases.

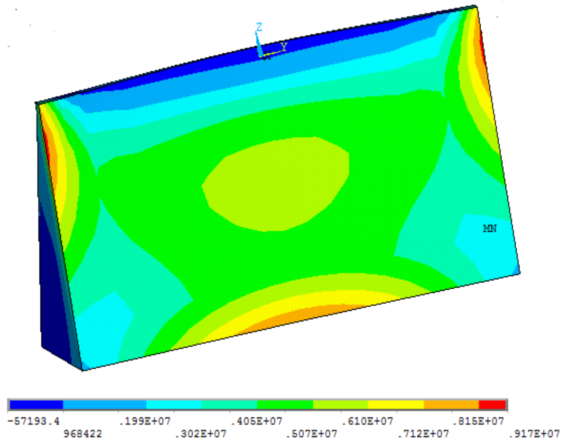

Figure 6: Maximum principal Tensile stress contours of the dam with flexible foundation

Figure 6 : Contours des contraintes de traction principales maximales du barrage avec fondation flexible

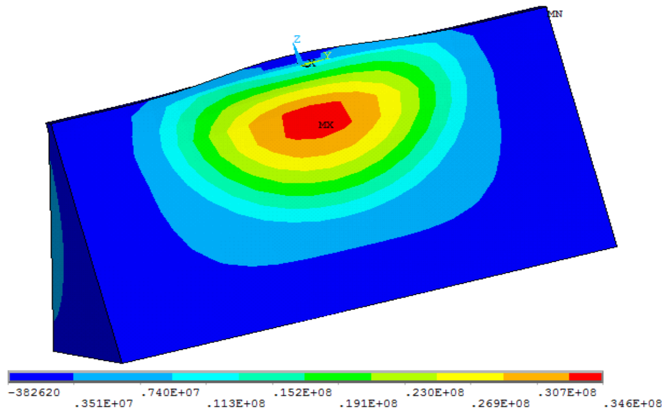

Figure 7: Maximum principal Tensile stress contours of the dam with rigid foundation

Figure 7: Contours des contraintes de traction principales maximales du barrage avec fondation rigide

It is observed that the maximum principal stresses obtained from rigid foundation case are higher than ones obtained from flexible foundation case due to the effect of foundation flexibility was taken into account, Which is considered as stresses damper.

In addition, the maximum principal stresses occur at the middle region of the dam crest, upper and lower parts along the symmetry central axis and upper extremity regions of the dam.

Figs. 8 and 9 illustrates the maximum principal tensile strain contours in upstream face of the dam for dam with rigid foundation and dam with flexible foundation cases.

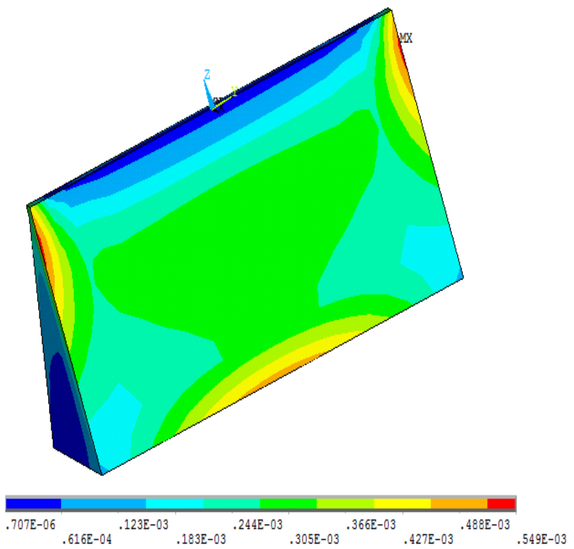

Figure 8: Maximum principal tensile strain contours in upstream face of the dam with flexible foundation

Figure 8: Contours de la déformation de traction principale maximale en face amont du barrage avec fondation flexible

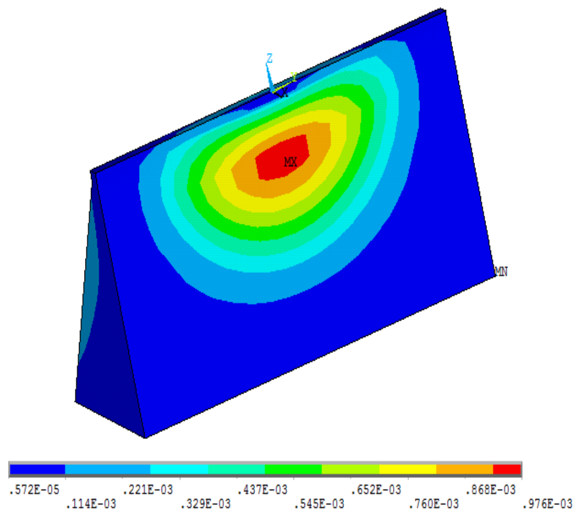

Figure 9: Maximum principal tensile strain contours in upstream face of the dam with rigid foundation

Figure 9 : Contours de la déformation de traction principale maximale en face amont du barrage avec fondation rigide

It is seen that the principal tensile strains are higher under the effect of foundation flexibility was taken into account and it is seen that these strain contours occur where the maximum principal tensile stresses occurred. However, the obtained values of maximum strains into the dam are lower than the admissible strains of the concrete [31-32].

Figure 10 shows the time history of shear stress at heel in both cases .

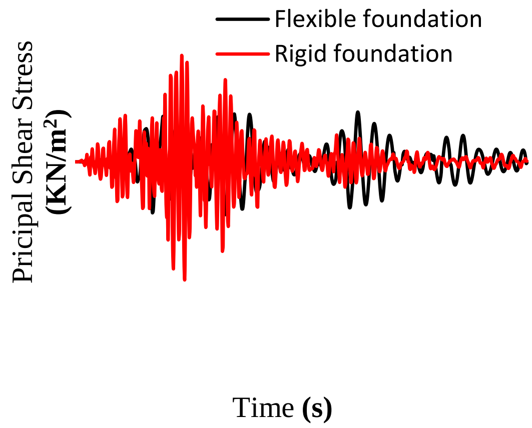

Figure 10: Time History for Principal Shear Stress at Dam Crest

Figure 10: Historique temporel de la contrainte de cisaillement principale à la crête du barrage

Figure 10 shows the time history principal shear stress at heel for the two cases studied. For the structure on the rigid foundation, the seismic acceleration gives rise to a moment of overturning and transverse shear. As the rock is very stiff, these two stress resultants will not lead to any (additional) deformation or rocking motion at the base. For the structure founded on flexible soil, the motion of the base of the structure will be different from the free-field motion because of the coupling of the structure-soil system.

5- Conclusions

This study presents the three-dimensional seismic response of Oued Fodda concrete gravity dam considering the effects of flexibility of the foundation on the seismic response .

From the numerical results obtained in the study, the following conclusions can be drawn:

-The displacement is found to have increased when the flexibility of the foundation was considered compared to the assumption of rigid foundation.

- Stresses increase when the flexibility of the foundation is considered with respect to the assumption of a rigid foundation.

- The principle stresses are generally lower in flexible foundation case during earthquake, Which is considered as stresses damper.

- The generated strains occurred in the acceptable intervals for the concrete employed in the dam body.

- The flexibility of the foundation should be taken into account in the numerical analyses to evaluate the critical response of the dam.

The dam with a flexible foundation is more excited than the dam with a rigid foundation, which justifies the difference in stresses and displacements for the two cases studied. This is due to the fact that the modulus of elasticity of the foundation for the case of the dam with flexible foundation is lower than the modulus of elasticity of the soil for the case of the dam with a rigid foundation.

References

[1] Leger P., Boughoufalah M., Earthquake input mechanisms for time-domain analysis of dam-foundation systems. Eng. Struct., 1989; 11(1) :37–46.

[2] Bayraktar A., Hançer E., Akköse M., Influence of base-rock characteristics on the stochastic dynamic response of dam–reservoir–foundation systems, Eng. Struct., 2005; 27(10):1498–508.

[3] Long Y., Zhang C., Xu Y., Nonlinear seismic analyses of a high gravity dam with and without the presence of reinforcement. Eng. Struct., 2009;31(10):2486–94.

[4] Bayraktar A., Altunişik A.C., Sevim B., Kartal M.E., Türker T., Bilici Y. Comparison of near-and far-fault ground motion effect on the nonlinear response of dam–reservoir–foundation systems. Non-linear Dyn., 2009;58(4):655–73.

[5] Akköse M., Şimşek E. Non-linear seismic response of concrete gravity dams to near-fault ground motions including dam-water-sediment-foundation interaction. Appl. Math., Model 2010;34(11):3685–700.

[6] Bayraktar A., Türker T., Akköse M., Ateş Ş., The effect of reservoir length on seismic performance of gravity dams to near and far-fault ground motions. Nat. Hazards 2010;52(2):257–75.

[7] Sevim B., Altunsik A.C., Bayraktar A., Akköse M., Calayir Y., Water length and height effects on the earthquake behavior of arch dam-reservoir-foundation systems. KSCE J Civ Eng 2011;15(2):295–303.

[8] Wang H., Feng M., Yang H., Seismic nonlinear analyses of a concrete gravity dam with 3D full dam model. Bull. Earthq. Eng., 2012;10(6):1959–77.

[9] Seyedpoor S.M., Salajegheh J., Salajegheh E., Shape optimal design of materially nonlinear arch dams including dam-water-foundation rock interaction using an improved PSO algorithm. Optimiz. Eng., 2012;13(1):79–100.

[10] Ardebili M.H., Mirzabozorg H., Effects of near-fault ground motions in seismic performance evaluation of a symmetric arch dam. Soil Mech. Found. Eng., 2012;49(5):192–9.

[11] Zhang S., Wang G., Effects of near-fault and far-fault ground motions on nonlinear dynamic response and seismic damage of concrete gravity dams. Soil Dyn. Earthq. Eng., 2013;53:217–29.

[12] Pan J., Xu Y., Jin F., Zhang C., A unified approach for long-term behavior and seismic response of AAR-affected concrete dams. Soil Dyn. Earthq. Eng., 2014;63:193–202.

[13] Arici Y., Binici B., Aldemir A., Comparison of the expected damage patterns from two- and three-dimensional nonlinear dynamic analyses of a roller compacted concrete dam., Struct. Infrastruct. Eng., 2014;10(3):305–15.

[14] Wang G., Wang Y., Lu W., Zhou C., Chen M., Yan P., XFEM based seismic potential failure mode analysis of concrete gravity dam–water–foundation systems through incremental dynamic analysis., Eng. Struct., 2015;98:81–94.

[15] Amina T.B., Mohamed B., André L., Abdelmalek B., Fluid–structure interaction of Brezina arch dam: 3D modal analysis. Eng. Struct., 2015;84:19–28.

[16] Hariri-Ardebili M.A., Seyed-Kolbadi S.M., Kianoush M.R., FEM-based parametric analysis of a typical gravity dam considering input excitation mechanism., Soil Dynamique Earthq. Eng., 2016;84:22–43.

[17] Hariri-Ardebili M.A., Seyed-Kolbadi S.M., Saouma V.E., Salamon J., Rajagopalan B., Randomfinite element method for the seismic analysis of gravity dams., Eng. Structures ,2018;171:405–20.

[19] Chopra A.K., Earthquake analysis of arch dams: factors to be considered., J. Struct. Eng., 2012;138(2):205–14.

[20] Yim, Chik-Sing, and Anil K., Chopra., "Earthquake response of structures with partial uplift on Winkler foundation." Earthquake engineering & structural dynamics, 12.2 (1984): 263-281.

[21] Yim, Solomon C-S., and Anil K., Chopra., "Simplified earthquake analysis of multistory structures with foundation uplift." Journal of Structural Engineering, 111.12 (1985): 2708-2731.

[22] Huda, A. M., et al., "Modelling the effects of sediment on the seismic behaviour of kinta roller compacted concrete dam." Pertanika J. Sci. & Technol., 18.1 (2010): 43-59.

[23] Spanos, Pol D., and Aik-Siong Koh., "Analysis of block random rocking." Soil Dynamics and Earthquake Engineering 5.3 (1986): 178-183.

[24] Ghaemian, Mohsen, Ali Noorzad, and M.R. Moradi Moghaddam. "Foundation effect on seismic response of concrete arch dams including dam-reservoir interaction." EUROPEAN EARTHQUAKE ENGINEERING 19.3 (2005): 49.

[25] US. Army Corps of Engineers (USACE), (2003) “Time-History Dynamic Analysis of Concrete Hydraulic Structures;” Chapter 2-Analytical Modeling of Concrete Hydraulic Structures, Chapter 3-Time-History Numerical Solution Techniques”, EM 1110-2-6051.

[26] Wolf, J. P., "Dynamic SoilStructure Interaction. PrenticeHall." Inc., Englewood Cliffs, New Jersey (1985).

[27] ANSYS, Theory user’s manual, Swanson Analysis Systems Inc, Houston, PA, USA, 2012.

[28] Westergaard, Harold Malcolm. "Water pressures on dams during earthquakes." Transactions of the American society of Civil Engineers 98.2 (1933): 418-433.

[29] Tan Hanchen, Chopra Anil K., Dam-foundation rock interaction effects in earthquake response of arch dams. J. Struct. Eng., 1996;122(5):528–38.

[30] Chopra Anil K., Earthquake analysis of arch dams: factors to be considered., J. Struct. Eng., 2012;138(2):205–14.

[31] Swaddiwudhipong S., Lu H.R., Wee T.H., Direct tension test and tensile strain capacity of concrete at early age, Cement and Concrete Research, No. 12, 33(2003) 2077-84.

[32] Sutherland B., Experimental and analytical analysis of the stress-strain diagram of frp-confined concrete with different loading rates, M.S. Thesis, Department of Civil Engineering, Kansas State University, USA, 2006.