EFFECT OF DYNAMIC FLUID-STRUCTURE INTERACTION PHENOMENON ON EARTHQUAKE RESPONSE OF CONCRETE GRAVITY DAMS - CASE STUDY: OUED FODDA DAM

EFFET DU PHÉNOMENE D'INTERACTION DYNAMIQUE FLUIDE-STRUCTURE SUR LA RÉPONSE SISMIQUE DES BARRAGES-POIDS EN BÉTON - ÉTUDE DE CAS : BARRAGE D'OUED FODDA

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Résumé - Cet article présente une étude numérique de l'effet du phénomène d'interaction dynamique fluide-structure sur la réponse sismique non-linéaire des barrages-poids en béton. A cet effet, le barrage-poids en béton d'Oued Fodda, situé à Chlef (nord-ouest de l'Algérie), est sélectionné dans cette étude. Les analyses sismiques non-linéaires sont effectuées à la fois pour le cas du barrage à vide et du barrage plein afin de présenter l'effet de la pression hydrodynamique de l'eau du réservoir sur le comportement sismique du barrage en béton. L'interface d'interaction entre le barrage et le réservoir d'eau est modélisée à l'aide des éléments de contact surface-surface à trois dimensions (3D) basés sur la loi de frottement de Coulomb, assurant l'interaction entre le barrage et le réservoir d'eau. La pression hydrodynamique de l'eau du réservoir est modélisée à l'aide des éléments finis fluides à trois dimensions (3D) basés sur l'approche lagrangienne. Le modèle de Drucker-Prager est pris en compte dans l'analyse non-linéaire du béton du corps du barrage. Selon les analyses par éléments finis, les déplacements horizontaux maximaux et les contraintes principales dans le corps du barrage sont présentés et le comportement sismique du barrage est étudié pour le cas du barrage à vide et du barrage plein. De plus, les situations de dommages potentiels du béton du barrage sont évaluées. Les différentes analyses numériques sont effectuées à l'aide du logiciel ANSYS.

Mots - clés : Barrage-poids en béton, Interaction dynamique fluide-structure, Approche lagrangienne, Éléments de contact, Réponse sismique non-linéaire.

Abstract - This paper presents a numerical investigation of the effect of dynamic fluid-structure interaction phenomenon on nonlinear seismic response of concrete gravity dams. For this purposes, the Oued Fodda concrete gravity dam, located in Chef (northwestern part of Algeria), is selected in this study. Nonlinear seismic analyses are carried out by using both empty and full reservoir cases, to present the effect of hydrodynamic pressure of the reservoir water on the seismic behavior of the concrete dam. The interaction interface between the dam and reservoir of water is modeled by using three-dimensional (3D) surface-to-surface contact elements based on the Coulomb's friction law, which ensure interaction between the dam and the water reservoir. The hydrodynamic pressure of reservoir water is modeled using three-dimensional (3D) fluid finite elements based on lagrangian approach. The Drucker-Prager model is considered in the nonlinear analysis for concrete of dam body. According to finite element analyses, the maximum horizontal displacements and principal stresses in the dam body are shown and seismic behavior of the dam is investigated for empty and full reservoir cases. In addition, potential damage situations of dam concrete are evaluated. The different numerical analyses are performed using ANSYS software.

Keywords: Concrete gravity dam, Dynamic fluid-structure interaction, Lagrangian approach, Contact elements, Nonlinear seismic response.

1. Introduction

Concrete gravity dams represent complex constructive systems of strategic importance. They are particularly used for electricity generation, water supply, flood control, irrigation, recreation, and other purposes. They are a fundamental part of the society's infrastructure system.

The building of new dams as well as the evolution and improvement of existing ones create an important need of developing modern tools and design methods allowing for taking into account realistically and completely the soil-structure-fluid interaction [1-6]. The seismic response of concrete gravity dams is a complex problem due to the fluid-structure and soil-structure interaction phenomenon. During an earthquake ground motion, the dam is exposed to dynamic forces due to hydrodynamic pressures of reservoir fluid that may produce crack and damage in the body dam [7-9].

In the literature, two approaches may be used to model the fluid-structure interaction phenomenon, the coupling method and contact elements. For the first approach, the main objective of the coupling approach is to hold equal the displacements between two reciprocal nodes in the normal direction to the interaction interface. In the second approach, the contact interface between the structure and the fluid is modeled by contact elements which provide the friction contact. In recent years, the contact problems became a part of the discipline of contact mechanics [10-12], which has allowed to treat effectively the different contact phenomenons in engineering field and its applications.

This study aims to present the effect of dynamic fluid-structure interaction on the nonlinear earthquake response of concrete gravity dams. Oued Fodda concrete gravity dam, located in Chlef, Algeria, is chosen in this numerical investigation. For this purpose, a three-dimensional (3D) finite element discretization is used to model the dam-reservoir interaction system using the ANSYS finite element code [13]. The hydrodynamic pressure of reservoir water is modeled utilizing three-dimensional fluid finite elements based on lagrangian approach [14&15]. In the nonlinear analysis, the Drucker-Prager model [16] is employed for concrete of the dam. Dam-reservoir interaction interface is modeled with three-dimensional surface-to-surface contact elements based on the Coulomb's friction, which assure interaction between the dam and water reservoir.

2. Contact mechanics

Many contact problems involve deformations of the bodies that are in contact. To illustrate the contact concept, consider two bodies B^α approach each other during a finite deformation process and come into contact on parts of their boundaries denoted by Γ_c (Fig. 1). We observe that two points, X^1 and X^2, in the initial configuration of the bodies which are distinct can occupy the same position in the current configuration, $\varphi(X^1) = \varphi(X^2)$, within the deformation process. Let us consider two elastic bodies B^α, $\alpha = 1,2$, each occupying the bounded domain. The boundary Γ^α of a body B^α consists of three parts: Γ_σ^α with prescribed surface loads, Γ_u^α with prescribed displacements, and Γ_c^α, where the two bodies B^1 and B^2 come into contact [12].

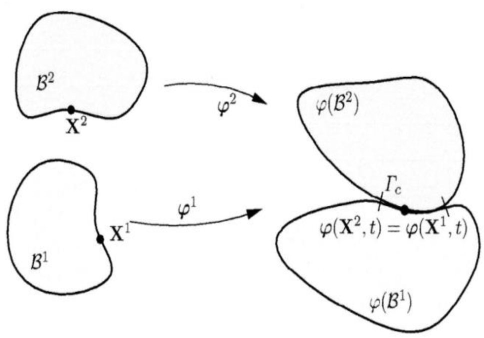


Figure 1 : Finite deformation contact

Figure 1 : Contact de déformation finie

We introduce two variables defining the contact: signed distance between the two surfaces or "gap" g and contact pressure P. The mathematical condition for non-penetration is stated as $g \geq 0$ which precludes the penetration of body B^1 into body B^2. Contact takes place when g is equal to zero. In this case, the contact pressure p in the contact interface must be nonzero. If the bodies come into contact, $g = 0$ and $P < 0$. If there is a gap between the bodies, $g > 0$ and $P = 0$. This leads to the statements

$$g \geq 0; \quad P \leq 0; \quad P\,g = 0 \qquad (1)$$

which are known as Hertz-Signorini-Moreau conditions [12].

Contact problems require significant computer resources to solve. They present two significant difficulties. First, the regions of contact are not known in general until the problem is run. Depending on the loads, material, boundary conditions, and other factors, surfaces can come into and go out of contact with each other in a largely unpredictable and abrupt manner. Second, most contact problems need to account for friction.

2.1. Friction model

In the basic Coulomb friction model, two contacting surfaces can carry shear stresses up to a certain magnitude across their interface before they start sliding relative to each other. This state is known as sticking. The Coulomb friction model below [13] shown in Fig. 2 defines an equivalent shear stress τ, at which sliding on the surface begins as a fraction of the contact pressure p. This stress is:

$$\tau = \mu p + c \qquad (2)$$

where μ is the friction coefficient and c specifies the contact cohesion. Once the shear stress is exceeded, the two surfaces will slide relative to each other. This state is known as sliding. The maximum contact friction stress can be introduced so that, regardless of the magnitude of normal contact pressure, sliding will occur if the friction stress reaches this value. At the contact interface, the connection behavior is divided into two kinematic states:

If the shear stress is less than the maximum friction stress, no relative displacement takes place in the contact region. This is named sticking which can be described by the condition:

$$\tau_{max} < \mu p + c \qquad (3)$$

Once the shear stress becomes higher than the maximum friction stress, the contact bodies move relative to each other. This is named sliding which can be formulated by :

$$\tau_{max} \geq \mu p + c \qquad (4)$$

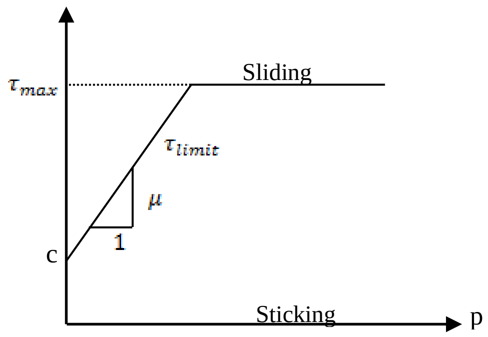


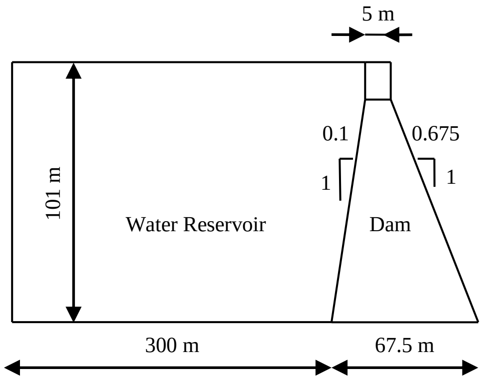
Figure 2 : Coulomb friction model [13]

Figure 2 : Modèle de friction de Coulomb [13]

3. Numerical model

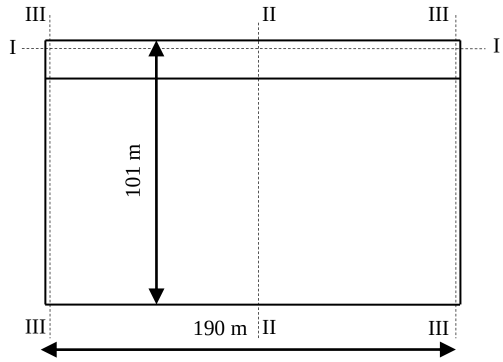
3.1. Material properties of Oued Fodda dam

Chosen dam is situated on Oued Fodda River and approximately 20 km of Oued Fodda City, Chlef, Algeria. The reservoir is mainly used for irrigation purposes. The capacity of the dam is 125.5 hm^3. The maximum height and base width of the dam are 101 m and 67.5 m, respectively. The dam crest is 190 m in length and 5 m wide and the maximum height of the reservoir water is considered as 101 m. The reservoir width is 300 m. The transverse and longitudinal sections of the dam-reservoir coupled system are shown in Fig. 3.



a) Transverse section and dimensions

a) Coupe transversale et dimensions



b) Longitudinal section and dimensions

b) Coupe longitudinale et dimensions

Figure 3 : Sections and dimensions of the Oued Fodda concrete gravity dam

Figure 3: Sections et dimensions du barrage-poids en béton d'Oued Fodda

The material properties for both the dam and its water reservoir are given in Tab. 1. According to the Drucker-Prager model [16], the cohesion and the angle of internal friction of the dam body are assumed as to be 2.50 MPa and 35°, respectively. In addition, the tensile strength and the compressive strength of the concrete of the dam are 1.6 MPa and 20 MPa, respectively.

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

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

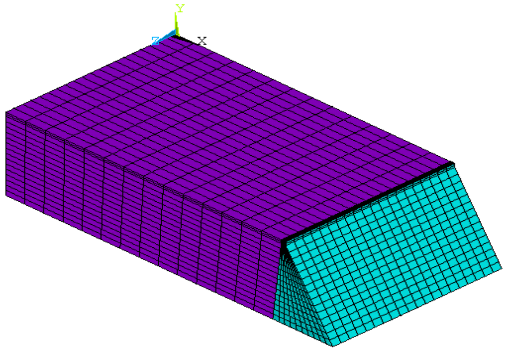
Material	Material properties		
	Modulus of elasticity (MPa)	Poisson's ratio	Mass density (kg/m^3)
Dam (concrete)	24600	0.20	2640
Reservoir water	2070	-	1000

3.2. Finite element model of dam-reservoir interaction system

The formulation of the dam-reservoir interaction system is represented using the Lagrangian approach [14&15], which considers that the fluid is assumed linear-elastic, incompressible, inviscid, and irrotational. The dam-resevoir interaction system is investigated using the three-dimensional finite element model shown in Fig. 4. A three-dimensional finite element model with 3400 solid finite elements (Solid45) is used to model Oued Fodda dam. Besides, a three-dimensional finite element model with 4760 fluid finite elements (Fluid80) is used to model the reservoir water. The fluid element (Fluid80) is used to model fluids contained within vessels having no net flow rate. The fluid element is particularly well suited for calculating hydrostatic pressures and fluid-solid interactions [13]. In addition, 340 contact-target element pairs are employed to model dam-reservoir interaction interface.

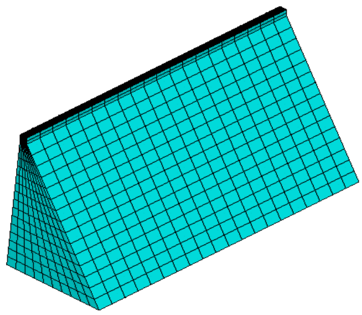
3.3. Modeling of dam-reservoir contact interface

The seismic response of a concrete dam depends upon its contact interaction with the water reservoir. This interaction interface between the dam and reservoir of water is modeled by using contact elements. These elements can present the contact and sliding of the water along the dam-reservoir interface and provide the friction response by the properties of normal and tangential shear stiffness at contact interface.



a) Dam body in full reservoir case

a) Cas du barrage plein



b) Dam body in empty reservoir case

b) Cas du barrage à vide

Figure 4 : Finite element model of Oued Fodda concrete gravity dam

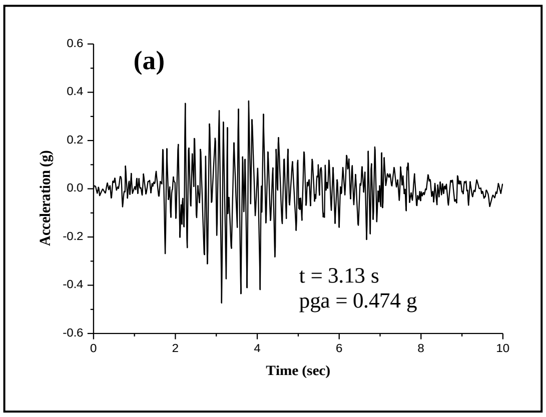
Figure 4 : Modèle d'éléments finis du barrage-poids en béton d'Oued Fodda

In this study, three-dimensional contact elements which represent the friction contact are established between the surfaces of volumes for three-dimensional system. Surface-to-surface contact elements generated by ANSYS software [13] are chosen. These contact elements use a target surface (Targe170) and a contact surface (Conta174) to form a contact pair. In addition, "no separation" contact model is employed in this purpose which allows the sliding of contact surfaces. The Coulomb friction and contact friction stress are available in these elements.

4. Numerical analysis

4.1. Nonlinear earthquake response of Oued Fodda dam

This study investigates the three-dimensional nonlinear seismic response of Oued Fodda concrete gravity dam considering contact elements at dam-reservoir interaction interface. For this purpose, the horizontal and vertical components of 1967 Koyna earthquake are utilized in analyses (Fig. 5). The horizontal component is applied along the river axis. The Drucker-Prager model [16] is used in the nonlinear analysis for concrete of the dam body. All numerical analyses are carried out using ANSYS [13]. According to the numerical analyses, the maximum horizontal displacements and principal stresses in the dam are presented for both empty and full reservoir cases.



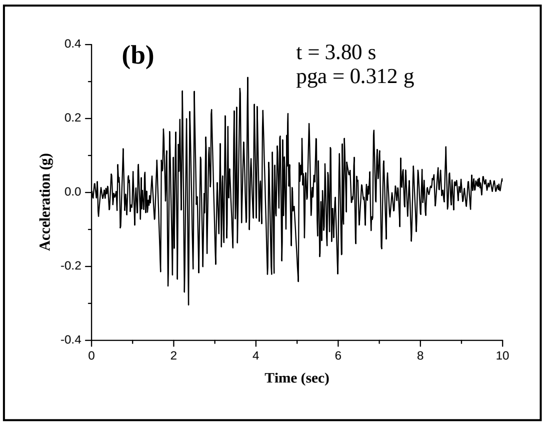


Figure 5 : Acceleration records of 1967 Koyna earthquake: (a) : Horizontal component and (b) : Vertical component

Figure 5 : Enregistrements d'accélération du séisme de Koyna en 1967 : (a) : composante horizontale et (b) : composante verticale

4.1.1. Horizontal displacements

The time history of horizontal displacement at the dam middle crest in upstream face is presented in Fig. 6 for empty and full reservoir cases. The horizontal displacement at crest point increases from 3.82 cm in empty reservoir case to 8.63 cm in full reservoir case. This indicates that there is about 126 % rise in the magnitude of the crest displacement in full reservoir case. The Fig. 7 shows the maximum horizontal displacement contours at the dam crest for empty and full reservoir cases. It is obvious that the horizontal displacements obtained from full reservoir case are higher than ones obtained from empty reservoir case due to the effect of fluid-structure interaction phenomenon.

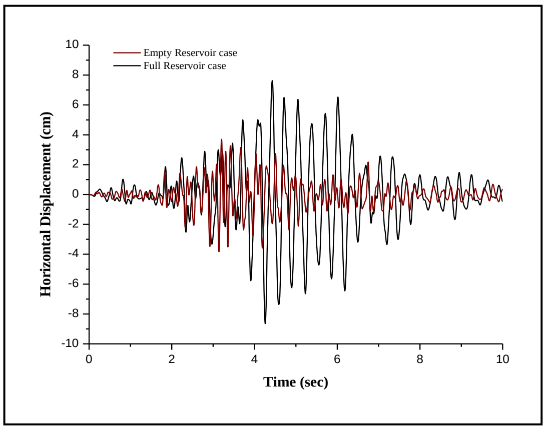
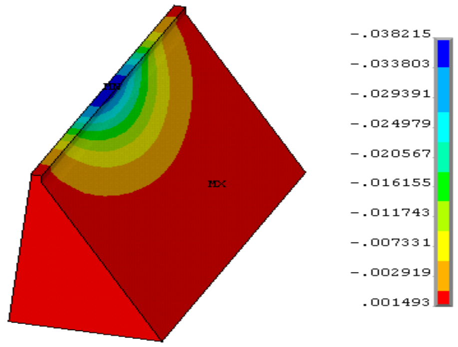


Figure 6 : Time history of horizontal displacement at the dam crest in upstream face for empty and full reservoir cases

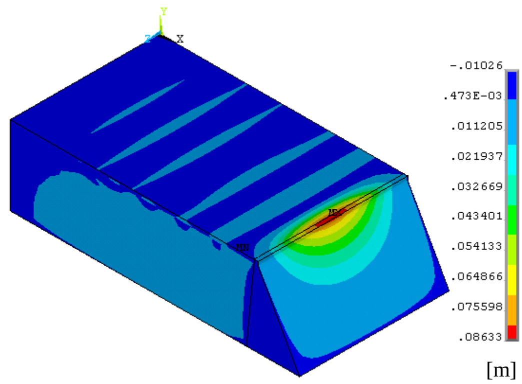
Figure 6 : Déplacement horizontal en fonction du temps à la crête du barrage en face amont pour le cas du barrage à vide et du barrage plein



(a) Empty reservoir case

(a) Cas du barrage à vide

[m]



(b) Full reservoir case

(b) Cas du barrage plein

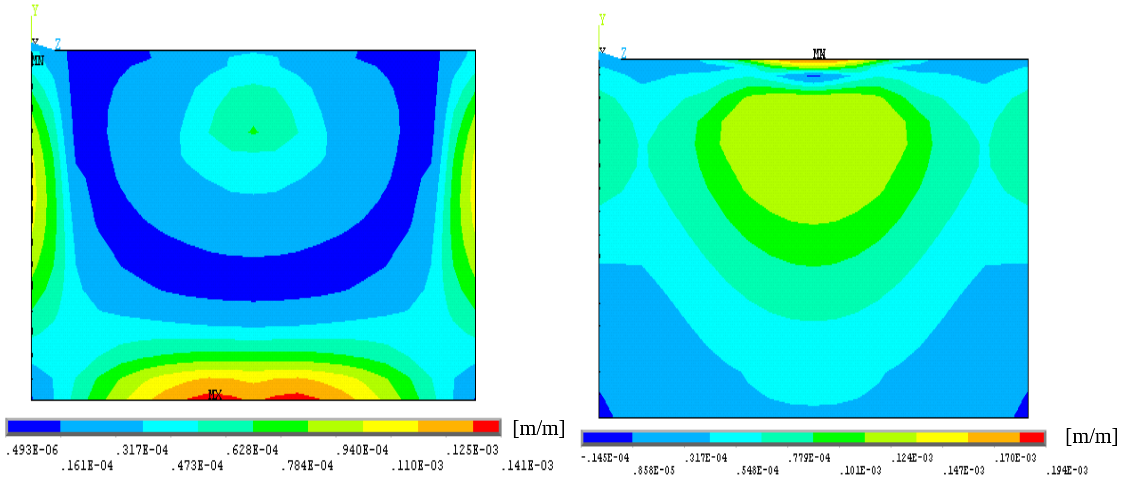
Figure 7 : Maximum horizontal displacement contours of the dam

Figure 7 : Contours des déplacements horizontaux maximaux du barrage

Fig. 8 illustrates the maximum principal tensile strain contours in upstream face of the dam for empty and full reservoir cases. It is seen that the principal tensile strains are higher under the effect fluid-structure interaction.

4.1.2. Principal stresses

Figs. 9 and 10 represent the maximum principal tensile and compressive stress contours in upstream face of the dam for both empty and full reservoir cases. It is observed that the maximum principal stresses obtained from full reservoir case are higher than ones obtaine



a) Empty reservoir case b) Full reservoir case

a) Cas du barrage à vide b) Cas du barrage plein

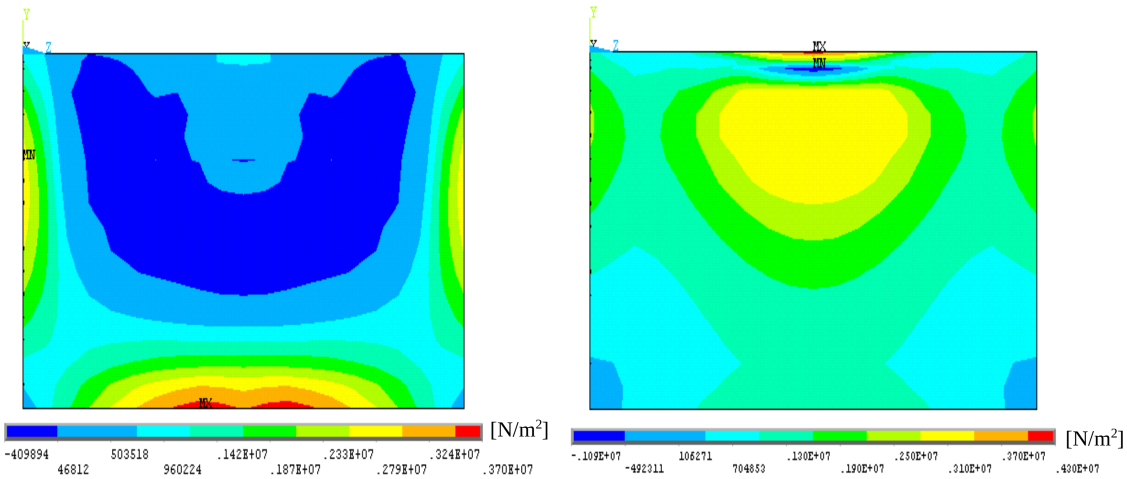
Figure 8: Maximum principal tensile strain contours in upstream face of the dam

Figure 8 : Contours des déformations principales maximales de traction en face amont du barrage

From empty reservoir case due to the effect of hydrostatic and hydrodynamic pressure of the reservoir water. 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.

Fig. 11 illustrates the time history of principal stresses at the dam crest in upstream face for empty and full reservoir cases.

The maximum principal tensile and compressive stresses increase from 1.34E3 kN/m^2 and -7.71E2 kN/m^2 in empty reservoir case to 4.30 E3 kN/m^2 and -2.11 E3 kN/m^2 in full reservoir case. Therefore, for full reservoir model, an increase of 221 % and 174 % respectively, in the magnitude of maximum principal tensile and compressive stresses is noticed. It is obvious that the principal tensile and compressive stresses are greatly higher under the effect of hydrodynamic interaction of reservoir water.

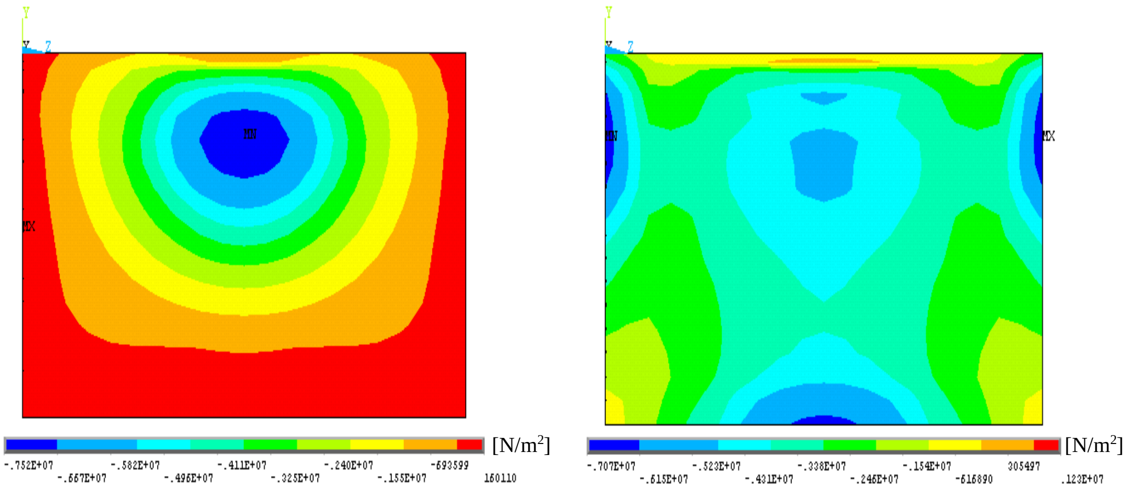


a) Empty reservoir case b) Full reservoir case

a) Cas du barrage à vide b) Cas du barrage plein

Figure 9 : Maximum principal tensile stress contours in upstream face of the dam

Figure 9 : Contours des contraintes principales maximales de traction en face amont du barrage

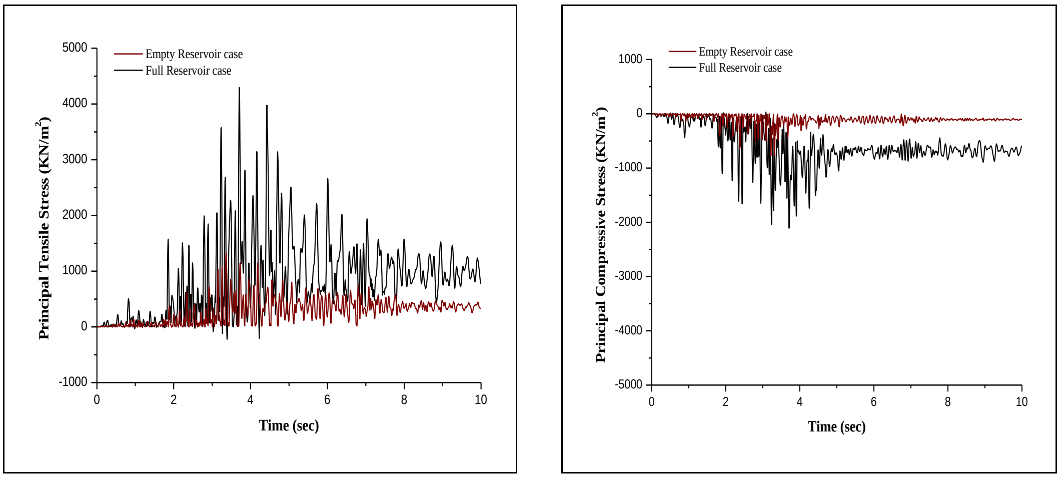


a) Empty reservoir case b) Full reservoir case

a) Cas du barrage à vide b) Cas du barrage plein

Figure 10: Maximum principal compressive stress contours in upstream face of the dam

Figure 10 : Contours des contraintes principales maximales de compression en face amont du barrage



(a) Principal tensile stresses b) Principal compressive stresses

(a) Contraintes principales de traction b) Contraintes principales de compression

Figure 11 : Time history of principal stresses at the dam crest in upstream face for empty and full reservoir cases

Figure 11 : Contraintes principales en fonction du temps à la crête du barrage en amont pour le cas du barrage à vide et du barrage plein

5. Conclusions

This study presents the nonlinear seismic response of Oued Fodda concrete gravity dam considering dynamic fluid-structure interaction phenomenon. For this purpose, a numerical investigation in three-dimensional (3D) of the effect of hydrodynamic interaction and sliding of the water along the dam-reservoir interface is performed. The interaction interface between the dam and reservoir of water is modeled by using surface-to-surface contact elements based on the Coulomb's friction law. The hydrodynamic pressure of reservoir fluid is modeled using fluid finite elements based on Lagrangian approach. The Drucker-Prager model [16] is used in the nonlinear analysis for concrete of dam body.

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

- The fluid-structure interaction phenomenon increases the horizontal displacements of the dam.
- The hydrodynamic pressure of the reservoir water increases the principal stresses in the dam body.

- The maximum principal tensile 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. Hence it is expected to appear cracks in these parts causing damage in the dam.

- The hydrostatic and hydrodynamic pressure of the reservoir water should be taken into account in the numerical analyses to evaluate the critical response of the dam.

The fluid-structure interaction problem is a complex phenomenon. This phenomenon depends upon the material pairing of the bodies constituting the contact interface between the structure and fluid. This description is adapted to the use of contact elements which can identify the parts to be analyzed for the interaction. Therefore, the contact elements should be taken into account in the modeling of the fluid-structure interaction phenomenon in seismic analysis of concrete gravity dams to achieve more reliable results, due to the capacity of these elements to present the interaction and sliding of the fluid along the fluid-structure interface.

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