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3D NUMERICAL SIMULATION OF SEISMIC FAILURE OF CONCRETE GRAVITY DAMS CONSIDERING BASE SLIDING

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Abstract: The sliding of dam base along dam-foundation rock interface during earthquake excitation can decrease the earthquake response of the dam. The present study reveals a numerical simulation of the seismic failure response for Oued Fodda concrete gravity dam, located in northwest of Algeria, considering base sliding. Nonlinear finite element analyses are performed for Oued Fodda dam-foundation rock system. The Smeared crack approach is used to present cracking of dam concrete under the 1980 El Asnam earthquake (M7) using Willam and Warnke failure criterion. The hydrodynamic pressure of the reservoir water is modeled as added mass using the Westergaard approach. The sliding behavior of contractions joints is modeled by surface-surface contact elements that provide the friction contact at dam-foundation interface. Drucker-Prager model is considered for dam concrete in nonlinear analysis. According to numerical analyses, several cracks may appear due to tension particularly at middle upper parts located along the symmetry central axis of the dam in both upstream and downstream faces. Although the dam sliding on its foundation reduces the magnitude of principal tensile stresses in dam body; however, the reduction magnitude is generally not large enough to preclude the cracks propagation in dam body.

Keywords: Concrete gravity dam; sliding; seismic failure; 3D seismic response.

1. Introduction

The Concrete-rock interface behavior plays a significant factor in earthquake stability of concrete dams against the sliding at dam-foundation rock contact interface due to presence of contraction joints along the contact interface. The Dam sliding phenomenon along dam-foundation rock interface during earthquake leads to significantly reduce the maximum magnitude of principal tensile stresses in the dam [1-7]. However, does the decrease amount is generally sufficient to prohibit the cracking propagation in dam structure? This is what we will find out in this investigation.

One of major problems for earthquake failure of concrete dams is the initiation and propagation of cracks in the concrete [8]. Various approaches were used to predict and capture the cracks in dam body: the smeared crack approach [9-10], plastic-damage model [11-12] and discrete crack approaches [13-15]. The Smeared crack approach and plastic-damage model, which are regrouped into the family of continuum crack approaches, can introduce an excellent framework to characterize the first damage phase and are computationally adapted for complex engineering domains [16].

Many studies exposed the effect of contraction joints on dynamic response of concrete dams employing three-dimensional (3D) analyses. The earthquake response of Outardes 3 concrete gravity (CG) dam was presented by Azmi and Paultre [17] considering the influence of joints using nonlinear joint elements. Wang et al. [18] utilized a 3D finite element model to carry out the nonlinear behavior analysis of CG dams, in which the dynamic contact was taken into consideration between dam blocks. Their results demonstrated that the dam seismic performance depends upon the cohesion degree between the monoliths. The seismic response analysis of roller-compacted concrete dams (RRC) was studied by Kartal [19] considering the contraction joints at dam-reservoir-foundation interface. Arici et al. [20-21] performed the nonlinear seismic analyses of a RRC dam using 2D and 3D models. The results showed that the 3D analysis of the dam is significanty different from that resulted from the 2D analysis. This comparative study revealed the necessity and importance of taking into account 3D analysis for such as these gravity structures constructed in relatively narrow canyons for seismic safety assessment. Ouzandja et al. [22] modeled the dam-reservoir interaction interface using friction contact to study the effect of dynamic fluid-structure interaction on the response of CG dams. Wang et al. [12] investigated the influence of contraction joints on seismic damage behavior of Guandi gravity dam formed of 23 monoliths using hard and soft contact models. The analyses revealed that the contraction joints had a significant effect on the dam cracking hazard. Karabulut and Kartal [23] presented the linear and nonlinear seismic analyses of Cine RCC dam using welded contact model at dam-foundation rock interface considering the effect of boundary conditions. Liang et al. [24] studied the seismic fragility of concrete arch dams considering sliding failure mode along dam-foundation rock interface employing the cohesion and friction. The results indicated that the levels of damage can be different, and the residual cohesion decreases the slipage amplitude development and enhances the earthquake stability of dam arch-foundation system. Ftima et al. [25] exhibited a new simulation strategy of CG dams based on advanced grillage method using no-tension link elements that represent the structural connection betweent the monoliths along longitudinal direction. The study pointed out that the proposed approach provides good results compared to those obtained in practise practice.

The sliding of gravity dam on its foundation decreases the principal tensile stresses into the dam. This study aims to examine the seismic failure behavior of CG dams considering base sliding using ANSYS software [26]. Oued Fodda dam, constructed in a high seismic activity zone of Algeria, is selected in this numerical investigation. The Smeared crack approach is used to predict the dynamic damage of dam concrete due to a multiaxial stress state using Willam and Warnke failure criterion [27]. Friction contact model, which is repeesented by surface-to-surface contact elements based on the Coulomb’s friction, is employed to model the joints along dam-foundation rock interface. The added mass approach [28] is employed to model the reservoir fluid hydrodynamic effect on dam-fluid and foundation-fluid interfaces using surface finite elements. Drucker-Prager model [29] is considered in nonlinear response for dam concrete.

2. Concrete failure criterion

Concrete material model can predict the failure of fragile materials for both cracking and crushing failure modes, which is available with concrete element Solid65. Concrete failure criterion due to a multiaxial stress state is defined by the form [27] as follows:

$$\frac{F}{f_c} - S \geq 0 \tag{1}$$

Where:

F: function of principal stress

S: surface of failure formulated in terms of the principal stresses and concrete material properties

f_c: ultimate compressive strength

The concrete material failure will occur when Eq. (1) is satisfied. Fig. 1 shows 3D failure surface of stress states that are biaxial or nearly biaxial. The function F and the failure surface S are given in terms of principal stresses σ1, σ2, and σ3 where:

$$\sigma_1 = \max(\sigma_{xp}, \sigma_{yp}, \sigma_{zp}) \tag{2}$$

$$\sigma_3 = \min(\sigma_{xp}, \sigma_{yp}, \sigma_{zp}) \tag{3}$$

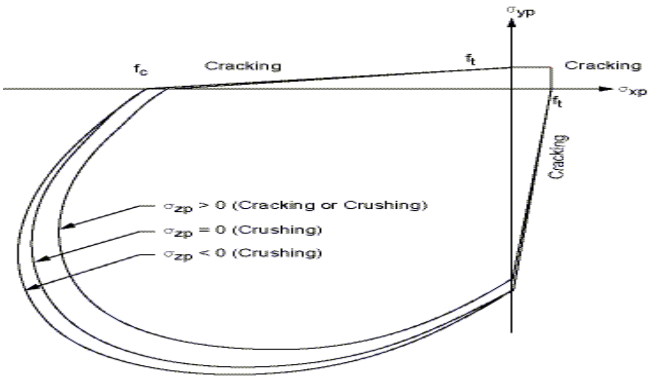


Fig. 1 - Surface of failure with nearly biaxial stress [26]

The concrete failure surface presented in Fig. 1 is divided into four domains according to different failure ways as:

$0 \geq \sigma_1 \geq \sigma_2 \geq \sigma_3$ (compression-compression-compression)

The crushing failure can occur in the concrete material provided the failure criterion is satisfied.

2. $\sigma_1 \geq 0 \geq \sigma_2 \geq \sigma_3$ (tensile-compression-compression)

If the failure criterion is satisfied, the cracking can appear in plane perpendicular to σ_1 in this case.

3. $\sigma_1 \geq \sigma_2 \geq 0 \geq \sigma_3$ (tensile-tensile-compression)

If the failure criterion is satisfied, the cracking can happen in planes perpendicular to principal stresses σ_1 and σ_2.

4.$\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq 0$ (tensile-tensile-tensile)

If the failure criterion is satisfied, the cracking can show in the planes perpendicular to principal stresses σ_1, σ_2, and σ_3.

3. Numerical example

3.1. Introduction to Oued Fodda CG dam and material properties

The chosen example in this study proposes Oued Fodda CG dam (Fig. 2), located in Chlef at the northwest territory of Algeria, classified as of high seismic activity zone in the national seismic code. This region (El Asnam) suffers constantly from seismic activities. Four seismic events shaked the region during the last century. The El Asnam earthquake (M7) (1980) is last earthquake that destroyed more than 70% of the city. The geometric configuration of Oued Fodda dam-foundation system is given in Fig. 3.

Fig.2 - Oued Fodda concrete gravity dam

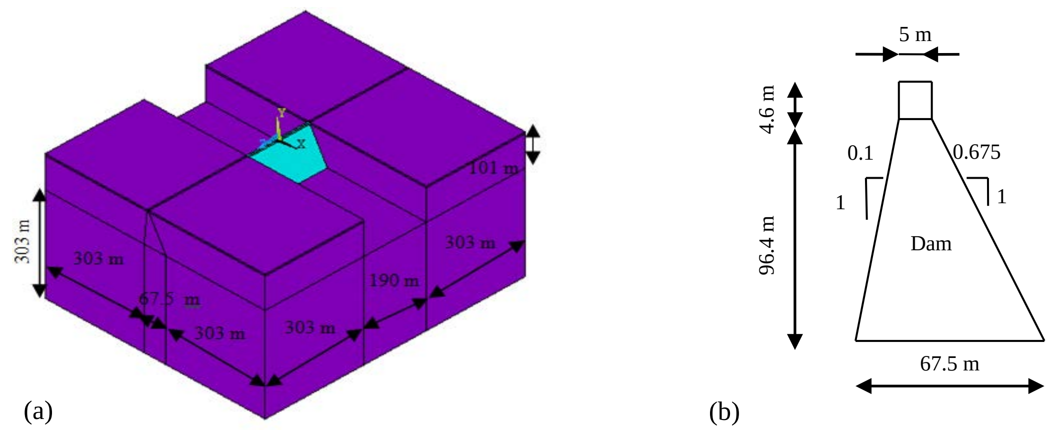


Fig. 3 - Oued Fodda dam-foundation rock system dimensions: (a) dam-foundation rock system; and (b) dam body

The material properties of studied dam-foundation rock system are recapitulated in Table 1. The cohesion and the angle of internal friction of dam concrete required in nonlinear response according to the Drucker-Prager model [29] are taken as 2.50 Mpa and 35°, respectively. The tensile and compressive strengths of dam concrete are 1.96 MPa and 20.3 MPa, respectively.

Table 1

Material properties of Oued Fodda dam-foundation rock system

Material	Material properties		
	Modulus of elasticity (MPa)	Poisson's ratio	Mass density (kg/m3)
Concrete dam	24600	0.20	2640
Foundation rock	20000	0.33	2000

3.2. Finite element model

Fig. 4. shows the finite element modeling of dam-foundation rock system. A 3D discretization by using solid elements (Solid45) is suggested to model the foundation rock, resulting in 37050 elements of this type. Solid elements (Solidd65) are adopted to model the concrete dam, resulting in 2700 elements. The hydrodynamic effect of reservoir fluid is modeled employing the Westergaard approach [28]. This technique, which is an approximate approach, replaces the fluid with equivalent mass distributed uniformly on dam-fluid and foundation-fluid interfaces, i.e., the fluid is represented as structural masses added to that of the dam and foundation.

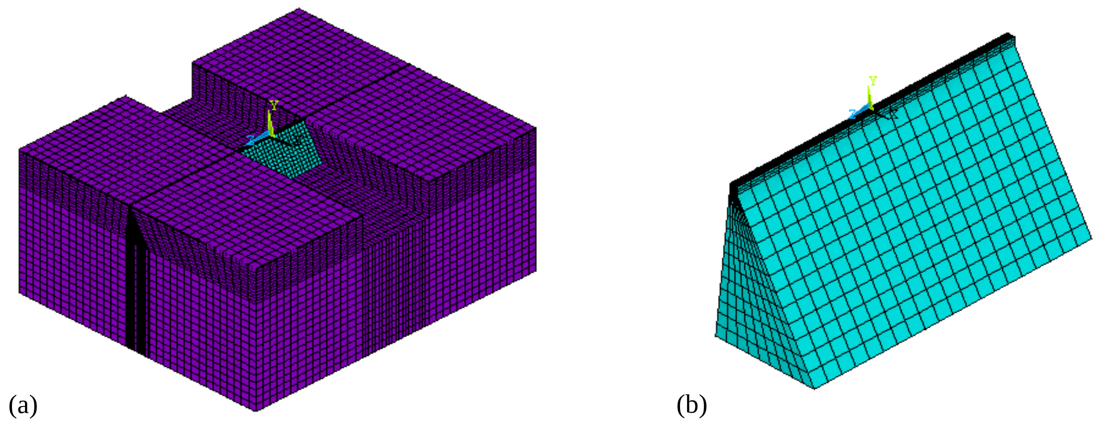


Fig. 4 - Oued Fodda dam-foundation rock system dimensions: (a) dam-foundation rock system; and (b) dam body

In this study, 3D surface elements (Surf154) are considered to model the reservoir fluid, resulting in 900 elements. In addition, the sliding behavior of contraction joints along dam-foundation interface are modeled by 3D surface-to-surface contact elements based on the Coulomb's friction, which take a target surface (Targe170) and a contact surface (Conta174) to make a contact pair, available in ANSYS finite element Code [26].

3.3. Dam-foundation rock interface modeling

The earthquake response of concrete dam is depended upon its connection to foundation rock. The friction contact model can be employed in the joints. In effect, concrete dam does not directly contact with the foundation rock. According to this reason, the use of contact elements in finite element simulation can provide more realistic results. The dam may slide on the surface of the foundation rock by using this element. It This element provides ability for tangential shear deformation. This work assumes that the concrete dam and foundation rock are independent deformable bodies by using contact elements. 3D contact elements based on the Coulomb's friction law are employed for this objective.

In this work, the dam-foundation rock interface properties are enumerated as follows: normal stiffness (Knn) equal to 240 Gpa/m, and transverse shear stiffness (Ktt) equal to 24 Gpa/m. In addition "no separation" contact model, which allows the sliding of surfaces, is considerd in dam-foundation bottom interface. "Standard" contact model, which allows the sliding and separation of surfaces, is used in dam-foundation side interface.

4. Nonlinear earthquake behavior of Oued Fodda dam

This study presents a numerical investigation of the cracking behavior for Oued Fodda dam under seismic load. Nonlinear analyses are conducted for dam-foundation rock system, in which the dam base sliding is taken into account. Dam region incurred a severe earthquake, 1980 El Asnam earthquake (M7), which caused significant material and human losses. However, it was not available only seismic replica record of this earthquake. The stream direction is subjected to horizontal component of seismic replica record with peak ground acceleration (PGA) of 0.132 g, which is scaled by factor 2.5 to attain to a PGA of 0.33 g (Fig. 5) equal roughly to evaluated PGA of 1980 El Asnam earthquake (M7).

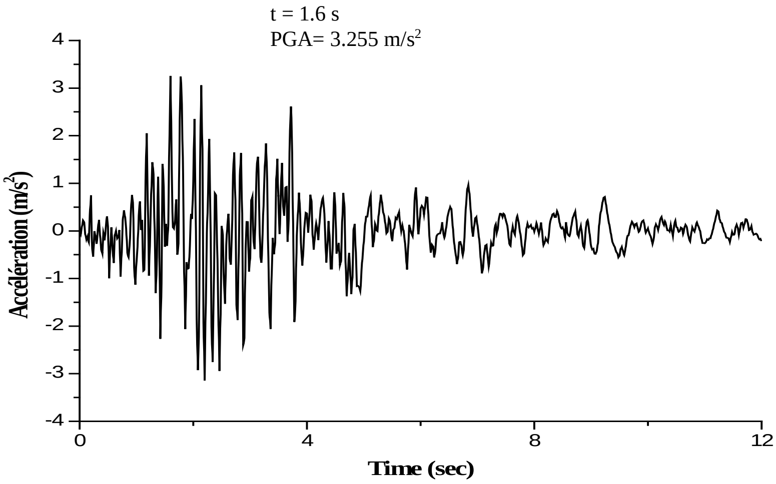


Fig. 5 - Horizontal component of 1980 El Asnam earthquake replica record scaled by factor of 2.5

The distribution of maximum horizontal displacements in upstream face along the dam crest is presented in Fig. 6. As can be seen, the maximum displacement at the middle crest attains value of 6.82 cm. Fig. 7 shows the contours of maximum horizontal displacements of the dam during earthquake. It is observed that the dam tends to slide along dam-foundation rock interface, which is known as sliding failure. In general, when the dam is allowed to slip on its foundation, the sliding phenomenon is accompanied by energy dissipation within in the interface zone that affects the performance and earthquake response of the dam.

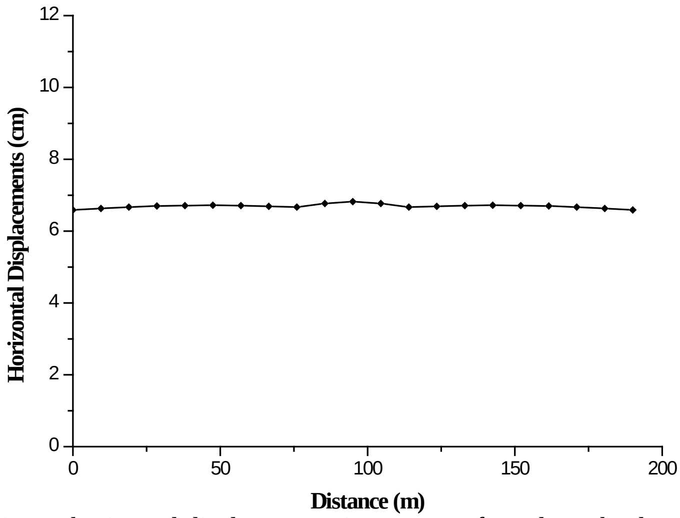


Fig. 6 - Maximum horizontal displacements in upstream face along the dam crest

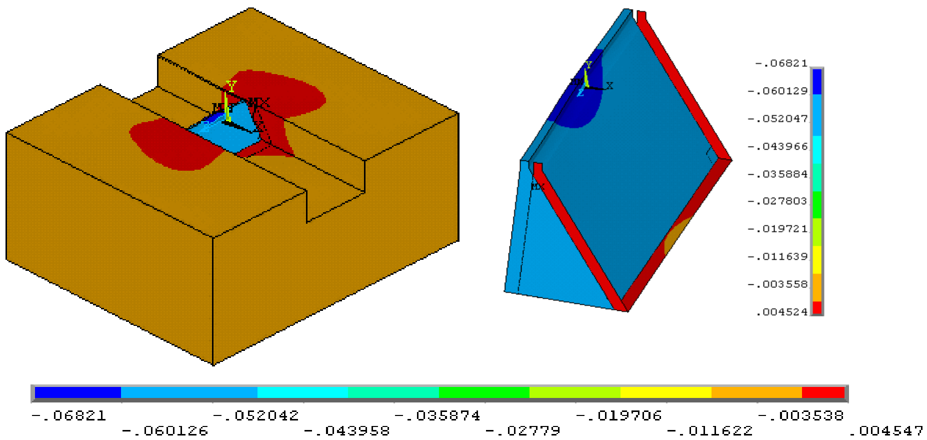


Fig. 7 - Maximum horizontal displacement contours of the dam (Unit: m)

The horizontal displacement time history at the middle crest is illustrated in Fig. 8, in which the maximum displacement is 6.82 cm. Fig. 9 represents the sliding displacement time history at the heel and toe located along dam symmetry central axis. It is obvious that the sliding time histories for both heel and toe of the dam are quite similar to each other as the maximum sliding displacement is approximately 6.10 cm. This is because that the presence of joints at dam-foundation rock interface lowers the stiffness in interface zones and thus leads to sliding of the dam on its foundation.

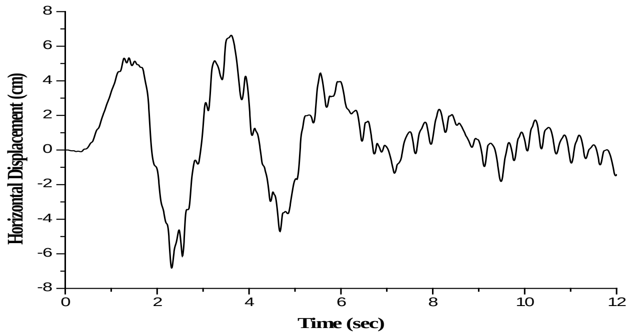


Fig. 8- Time history of horizontal displacement at the middle crest

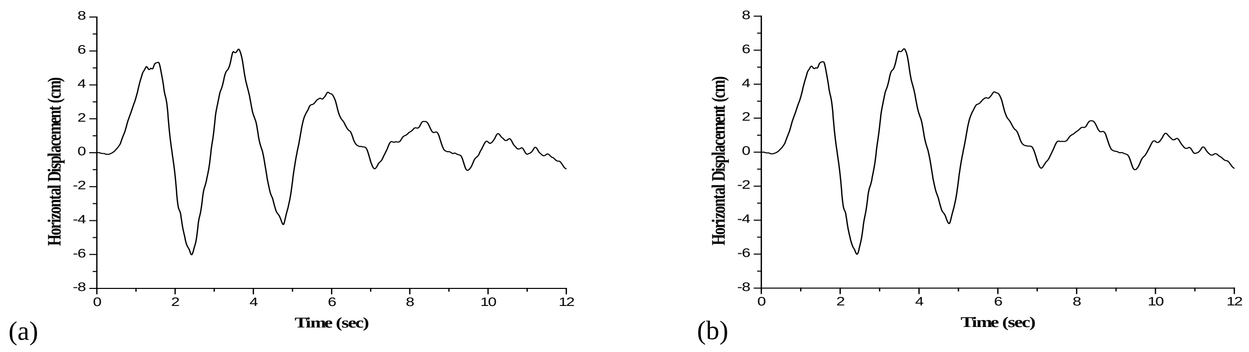


Fig. 9 - Time history of sliding displacement at: (a) middle heel; and (b) middle toe

The contours of maximum principal tensile stresses in upstream and downstream faces of the dam appear in Fig. 10. It is evident in Fig. 10 that the maximum stresses occur at middle upper parts located along dam central axis; from here, it is predicted to manifest cracks in these stressed parts. Profiles of final cracking of Oued Fodda dam in upstream and downstream faces, where the maximum tensile stresses occurred, are shown in Fig. 11. As may be shown, several cracked elements may appear due to tension particularly at middle upper parts of the dam.

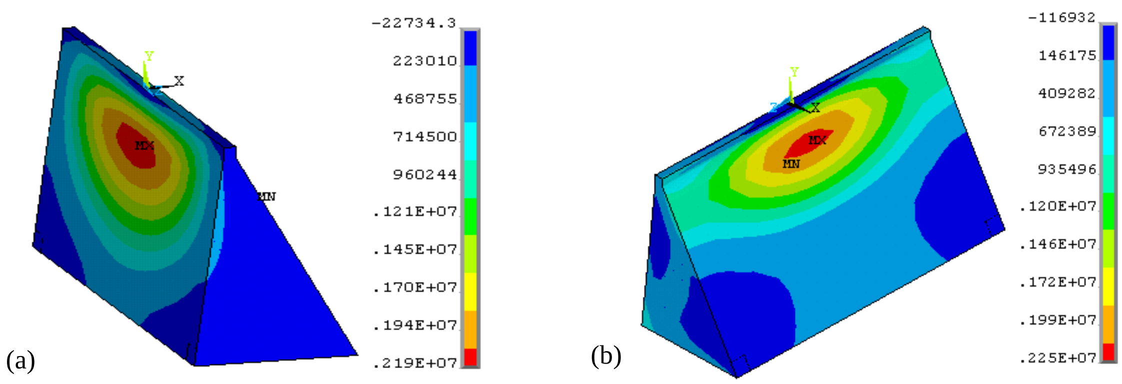


Fig.10 - Maximum principal tensile stress contours of the dam:
(a) upstream face; and (b) downstream face (Unit: Pa)

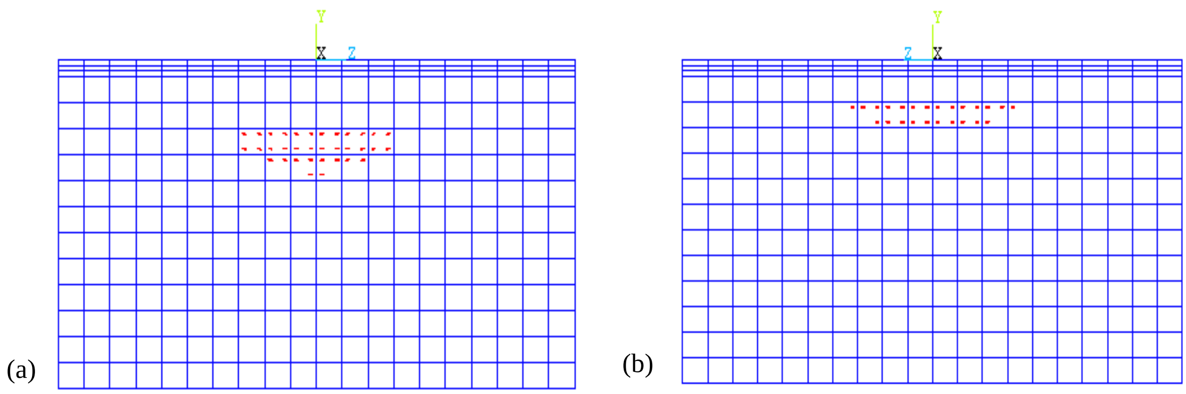
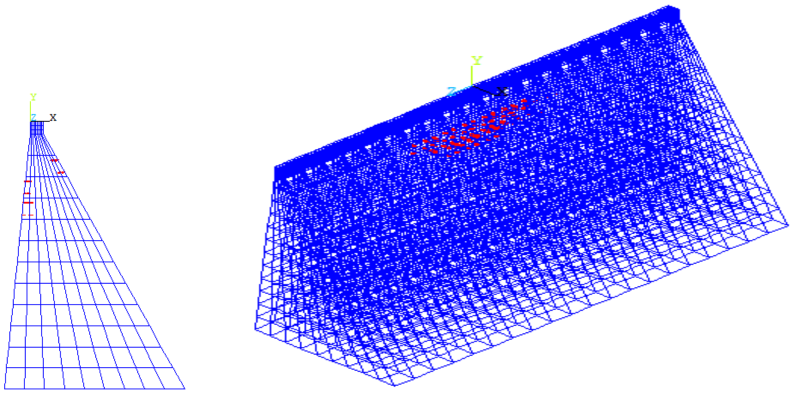


Fig. 11 - Final cracking profiles of Oued Fodda dam: (a) upstream face; and (b) downstream face

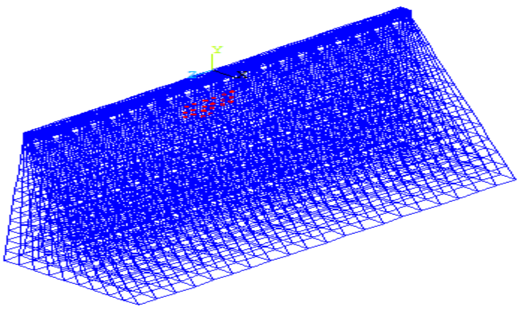
Fig. 12 illustrates also the final cracking profile of entire Oued Fodda dam for both upstream and downstream faces. In general, the dam sliding along dam-foundation rock interface reduces the value of principal tensile stresses in dam body; but, the decrease value is generally not considerable to avoid the cracks propagation especially, at middle upper parts.



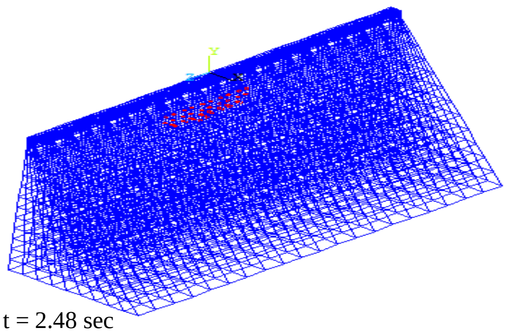
Dam cross section

Fig. 12 - Final cracking profile of entire Oued Fodda dam for both upstream and downstream faces

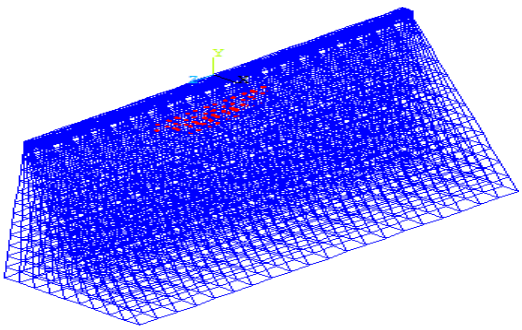
The evolution process of cracks propagation in dam body under earthquake in terms of time is presented in Fig. 13, in which the first cracks can be observed at middle upper parts located along dam central axis in upstream face at the time of 2.47 sec. With continuation and passage of time, more elements incur the damage and cracking area expands more in both upstream and downstream until the time of 2.555 sec. These fractures may give rise to instability and failure of dam structure.



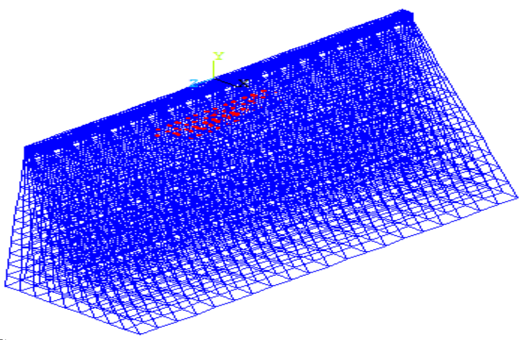
(a) t = 2.47 sec



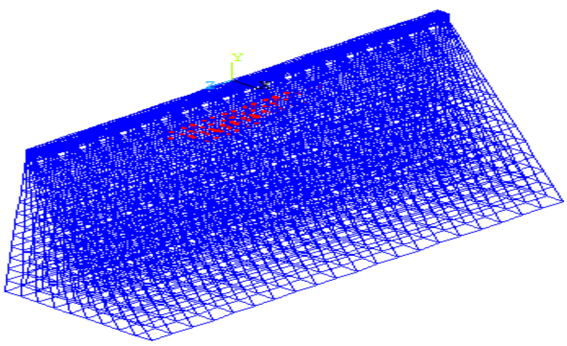
(b) t = 2.48 sec



(c) t = 2.545 sec



(d) t = 2.55 sec



(e) t = 2.555 sec

Fig. 13 - Process of cracking propagation in the dam

5. Tensile strength effect of dam concrete

In order to present the tensile strength effect of concrete on the dam cracking response. 3D earthquake analysis is conducted with taking the concrete tensile strength of 2.30 Mpa. Fig. 14 depicts the profiles of final cracking of Oued Fodda dam in upstream and downstream faces.

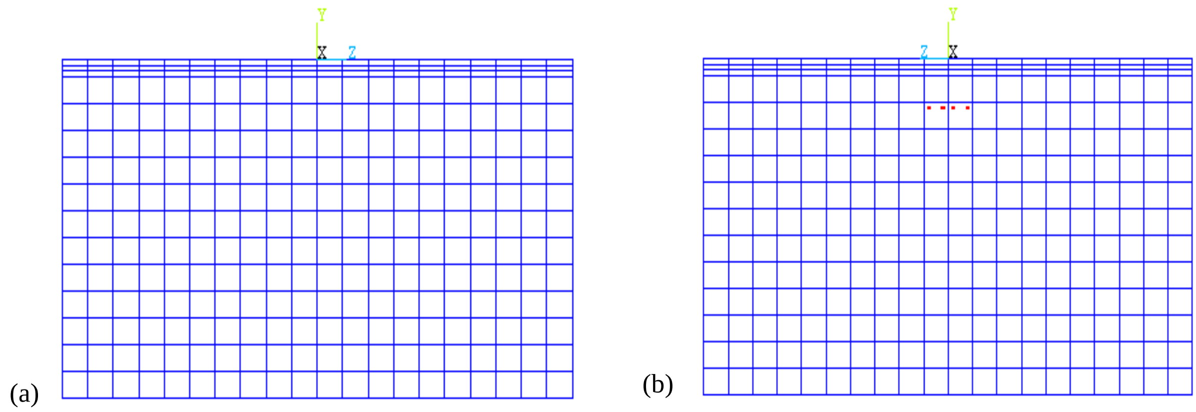


Fig. 14 - Final cracking profiles of Oued Fodda dam: (a) upstream face; and (b) downstream face

It is observed that there isn't any crack in upstream face. This is because that the resulting maximum principal tensile stresses during earthquake in this face are lower than the concrete cracking stress.

6. Conclusions

In this paper, a numerical investigation of the earthquake cracking response for Oued Fodda dam is investigated using 3D finite element analyses considering the sliding of contraction joints along dam-foundation dam interface. Material and contact nonlinearity are taken into consideration in this study. Based on the study of the seismic damage behavior of Oued Fodda dam, we can draw the following conclusions:

1- Earthquake nonlinear behavior is closely depended upon the structural feature of dam-foundation rock interface zone.

2- The Maximum tensile stresses occur at middle upper parts, which are considered as stressed regions, located along the symmetry central axis of the dam in both upstream and downstream faces.

3- Several cracked elements may appear at middle upper parts. It is preferable to use higher tensile strength concrete in these parts to decrease the predicted cracking and reinforce the stability and safety of dam.

4- Contraction joints can decrease the dam stiffness in interface zones and leads to larger nonlinear analysis for dam-foundation rock system.

5- Material and contact nonlinearity should be taken into account in dynamic behavior evaluation of the dam to achieve more reliable analyses.

6- Use of contact elements in finite element numerical analysis can provide more realistic results.

7- The Increasing the tensile strength of concrete leads to reduce the dam cracking.

The dam sliding, which can be verfied by providing the shear keys at the dam base, minimizes the intensity of principal tensile stresses in dam body; but, the diminution intensity is generally not considerable to interdict the propagation of cracks, especially at middle upper parts of the dam in both upstream and downstream faces.

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