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DETERMINISTIC SEISMIC DAMAGE ANALYSIS FOR CONCRETE GRAVITY DAMS: A CASE STUDY OF OUED FODDA DAM

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Abstract: One of the major dangers for seismic damage of concrete dams is the propagation of cracks in dam concrete. The present study undertakes a numerical investigation of the seismic damage for Oued Fodda concrete gravity dam, located in the northwest of Algeria, considering the impacts of properties of joints along the dam-foundation rock interface and cross-stream earthquake excitation. Three-dimensional transient analyses for coupled dam-foundation rock system are carried out using Ansys software. The hydrodynamic effect of reservoir fluid is modelled using the added mass approach. The smeared crack approach is utilised to present the seismic damage of dam concrete using the Willam and Warnke failure criterion. The dam-foundation rock interface joints are presented with two ways, adhesive joints and frictional joints. The Drucker–Prager model is considered for dam concrete in nonlinear analyses. Consideration of the study results indicates that the frictional joints model can reduce the seismic response and damage hazard of the dam body to a better extent compared with the adhesive joints model. Furthermore, the application of cross-stream earthquake excitation reveals the significant effect on cracking response of the dam in the two models of joints.

Key words: concrete dam, seismic damage, adhesive joints, frictional joints, smeared crack approach

1. INTRODUCTION

One of the major hazards of concrete dams subjected to strong earthquakes is the damage and failure of the dam concrete [1]. The need for ensuring a suitable degree of earthquake safety of such structures has attracted great interest from researchers in the field of dam engineering, and has prompted them to carry out measures of innovation and development of numerical models that can predict and capture the cracks in the dam structure. These approaches are classified into two categories: the first, the family of continuum cracking approaches, includes the smeared crack approach [2–4] and the plastic-damage constitutive model [5–8]. The fracture mechanics approach [9,10] and the extended finite element method (XFEM) [11–14], which belong to the family of discrete crack approaches, constitute the second category. The continuum crack approaches can introduce an excellent framework to characterise the first damage phase and insert parameters of internal failure to depict the stiffness degradation of solid materials without variating the topology of finite element model. These approaches are better suited to resolving the complex problems of the engineering area [15].

The earthquake behaviour of the concrete dam is based on its connection joints to the foundation rock [16–21]. The impact of contraction joints on the earthquake performance of concrete dams was cited by many researchers utilising the three-dimensional (3D) response [22–25]. Many researchers demonstrated the impact of contraction joints on the earthquake performance of concrete dams utilising the three-dimensional (3D) response. The nonlinear behaviour of concrete gravity (CG) dams was exposed by Wang et al. [26] considering the dynamic contact between dam blocks. Study results demonstrated that the dam's seismic performance depends upon the adhesion degree between the monoliths. Kartal [27] investigated the earthquake behaviour of roller-compacted concrete (RCC) dams considering the joints at dam-reservoir-foundation interface. Wang et al. [28] analysed the seismic response of concrete dam-reservoir-foundation system with effects of contraction joints and cracking of the dam concrete. Their analysis demonstrated that the dam failure mode depends upon the ground motion variation along the dam-foundation rock interface. Yilmazturk et al. [29] presented the nonlinear seismic analyses of an RRC dam using 2D and 3D models. The results showed that the 3D analysis of the dam is significantly different from that resulting from the 2D analysis. This comparative study revealed the necessity and importance of considering 3D analysis for gravity structures such as these constructed in relatively narrow canyons for seismic safety assessment. Ouzandja et al. [30] used the contact element to model the joints along the dam-reservoir interaction interface for the study of the effect of dynamic fluid-structure interaction on the response of CG dams. In their investigation, Omidi and Lotfi [31] analysed the seismic failure of concrete dams considering the impact of the joints between the concrete blocks. The analysis showed that the cracking increases in the area of middle cantilevers due to opening the joints. Wang et al. [7] investigated the influence of contraction joints on seismic damage behaviour of Guandi gravity dam using hard and soft contact models. The analyses revealed that the contraction joints had a significant effect on the dam cracking hazard. The seismic

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fragility of concrete arch dams was studied by Liang et al. [32] considering the sliding failure mode along the dam-foundation rock interface employing cohesion and friction. The study indicated that the levels of damage can be different, and the residual cohesion decreases the slippage amplitude development and enhances the earthquake stability of the concrete dam-foundation system. Ftima et al. [33] used a new modelling approach of CG dams based on the grillage method employing no-tension link elements that represent the structural connection between the monoliths. The study pointed out that the proposed approach provides good results compared to those obtained in practice. Khassaf et al. [34] exhibited the impact of contraction joints on structural response of concrete dams. Their work indicated that the optimum picking of the disposition of these joints leads to improvement in the dam earthquake stability. In Daneshyar and Ghaemian's study [35], dynamic analysis of arch dams with adhesive and frictional joints was conducted. The analysis gave rise to the inference that, in comparison with the adhesive joints model, the frictional joints model can be considered to affect the distribution of maximum stresses to a farther extent.

The present study displays the effects of contact conditions in dam-foundation rock interface and transverse earthquake excitation on the damage seismic behaviour of Oued Fodda dam, constructed in a high seismic activity zone of Algeria. The dam-foundation rock interface joints are presented with two ways, adhesive joints and frictional joints. The frictional joints model is modelled by surface-to-surface contact elements based on Coulomb's friction, which provide friction contact at the interface. The smeared crack approaches used to predict the damage of dam concrete due to a multiaxial stress state using the Willam and Warnke failure criterion [36]. The added mass approach [37] is employed to model the reservoir fluid hydrodynamic effect on dam-fluid and foundation-fluid interfaces. The Drucker–Prager model[38] is used in nonlinear analyses for dam concrete. All transient analyses are realised using ANSYS software [39].

2. FAILURE CRITERION OF CONCRETE

The Willam and Warnke failure criterion [36], defined below by Eq.(1), is used to predict the concrete failure, for both cracking and crushing failure modes, due to a multiaxial stress state.

$$\frac{F}{f_c} - S \geq \quad (1)$$

Where: F: denotes a function of the principal stress state (σ_{xp}, σ_{yp}, and σ_{zp}). S: the failure surface expressed in terms of the principal stresses and material properties of concrete, f_c: the maximal compressive strength and σ_{xp}, σ_{yp}, and σ_{zp}: the principal stresses in the principal directions.

If Eq. (1) is satisfied, the concrete element will crack or crush. Fig. 1 manifests the 3D failure surface projection for stress states that are biaxial or nearly biaxial. Both the function F and the failure surface S are expressed in terms of principal stresses denoted as σ_1, σ_2, and σ_3, where:

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

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

The failure of concrete is divided into four domains according to different failure modes as:

1. $0 \geq \sigma_1 \geq \sigma_2 \geq \sigma_3$

The concrete is presumed to be crushed provided the failure criterion is satisfied.

2. $\sigma_1 \geq 0 \geq \sigma_2 \geq \sigma_3$

If the failure criterion is satisfied, the cracking occurs in the plane perpendicular to principal stress σ_1.

3. $\sigma_1 \geq \sigma_2 \geq 0 \geq \sigma_3$

If the failure criterion is satisfied, the cracking occurs in the plane perpendicular to principal stresses σ_1, and σ_2.

4. $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq 0$

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

(a)
(b)

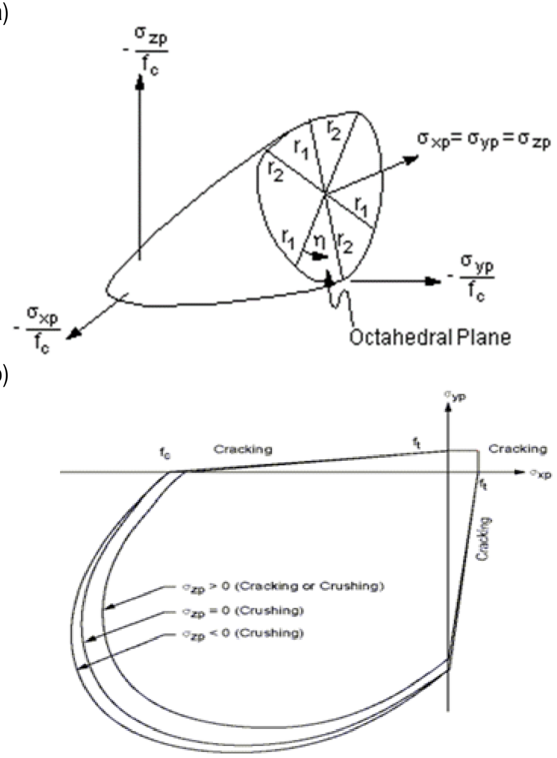

Fig. 1. Failure surface of concrete: (a) in principal stress space; and (b) in principal stress plane [39]

3. CASE STUDY OF OUED FODDA DAM

The selected model in this numerical application presents the Oued Fodda CG dam, located in Chlef at the northwest territory of Algeria, classified as falling under a high seismic activity zone according to the national seismic code. This region (El Asnam) suffers constantly from seismic activities. Four seismic events have shaken the region during the last century. The 1980 El Asnam earthquake (M7) is the most recent major earthquake, which destroyed more than 70% of the city. The geometry of Oued Fodda dam-foundation rock system is given in Fig. 2.

The material properties of the studied dam and its foundation rock are recapitulated in Table 1. Nonlinear response is based on the Drucker–Prager model [38], in which the cohesion and angle of internal friction of the dam concrete are 2.50 MPa and 35°, respectively. The dynamic tensile and compressive strengths of dam concrete are 2.3 MPa and 24 MPa, respectively.

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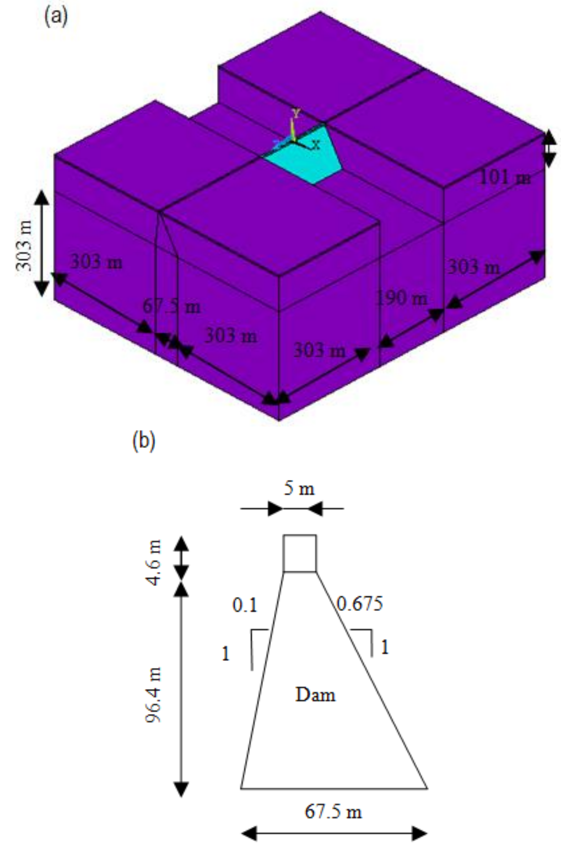

Fig. 2. Geometry of Oued Fodda dam-foundation rock system: (a) dam-foundation rock system; and (b) dam body

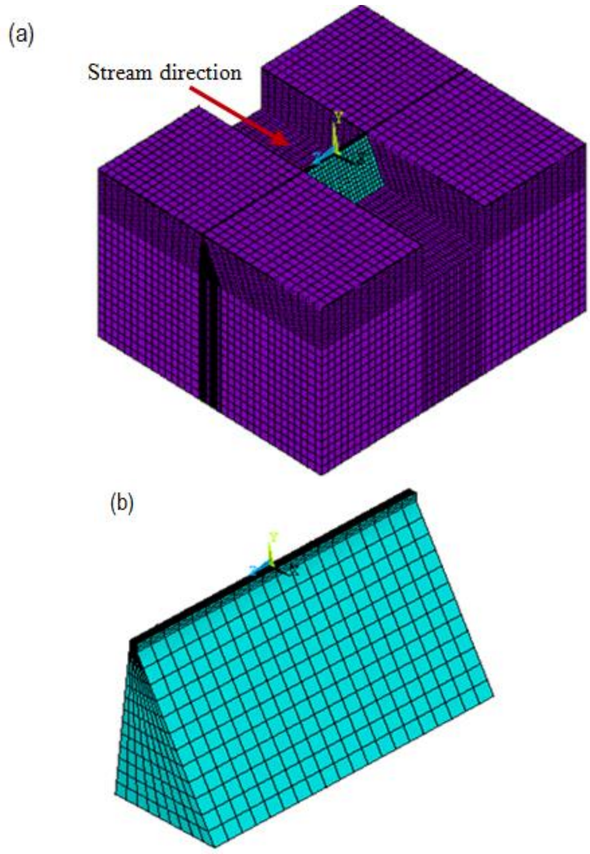

Fig. 3. 3D finite element modeling of Oued Fodda dam-foundation rock system: (a) dam-foundation rock system; and (b) dam body

Tab. 1. Material properties of Oued Fodda dam-foundation rock system

Material	Material properties		
	Modulus of elasticity (MPa)	Poisson's ratio	Mass density (kg/m^3)
Concrete dam	24600	0.20	2640
Foundation rock	20000	0.33	2000

3.1. Finite element discretization of dam-foundation rock system

The finite element modelling of dam-foundation rock system is shown in Fig. 3. The dam body is modelled by eight-node solid elements (Solid65); the model contains 2,700 elements and 2,850 nodes. The foundation rock domain is discretised using eight-node solid elements (Solid45); the model consists of 37,050 elements and 41,640 nodes. The hydrodynamic effect of reservoir fluid is modeled employing the Westergaard approach [37]. This technique, which is an approximate approach, replaces the fluid with equivalent mass distributed uniformly on dam-fluid and foundation-fluid interfaces; that is, the fluid is represented as added structural masses to that of the dam and foundation.3Dsurface elements (Surf154) are considered in the modelling of the added mass approach in this study, resulting in 900 elements. Additionally, the contraction joints along dam-foundation rock interface are represented by 3D surface-to-surface contact elements based on Coulomb's friction, which take a target surface (Targe170) and a contact surface (Conta174) to make a contact pair, available in ANSYS code [39].

3.2. Modelling of dam-foundation rock interface contraction joints

The dam-foundation rock interface behaviour plays a role as a significant factor in securing the earthquake stability of concrete dams due to the presence of contraction joints along the interface. The contraction joints are generally modelled by two formulations: adhesive joints and frictional joints. In effect, a concrete dam does not directly establish contact with the foundation rock. According to this reason, the use of contact elements, which represent the friction contact, in finite element analyses can provide more realistic results. The concrete dam may slip over its foundation rock by utilising these elements. These elements, which are defined between the surfaces of volumes, provide the friction behaviour by normal and tangential shear stiffness. During the course of the investigation, the presumption that the concrete dam and the foundation rock are independent deformable bodies is used when the frictional joints model is employed, and that they are dependent deformable bodies is used when the adhesive joints model is employed. 3D contact elements based on Coulomb's friction law are employed in this application.

The following are the joints properties of dam-foundation rock contact interface employed in this simulation: normal stiffness (Knn) equal to 240 GPa/m, and transverse shear stiffness (Ktt) equal to 24 GPa/m. Additionally, the 'no separation' contact model, which allows the sliding of surfaces, is considered in dam-foundation bottom interface. The 'standard' contact model, which allows the sliding and separation of surfaces, is used in dam-foundation side interface.

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4. NONLINEAR EARTHQUAKE ANALYSIS OF OUED FODDA DAM

The seismic damage response of the Oued Fodda dam is presented in this study. Nonlinear seismic analyses are performed for the Oued Fodda dam-reservoir-foundation rock system considering the impacts of contact conditions in dam-foundation rock interface and transverse earthquake excitation using 3D finite element models. The smeared crack model based on the Willam and Warnke failure criterion [36] is used to present seismic cracking of dam concrete. The stream direction is subjected to the horizontal component of the 1980 El Asnam seismic replica record with a peak ground acceleration (PGA) of 0.132 g scaled by a factor of 2.5 to obtain a PGA of 0.33 g (Fig. 4), equal roughly to an estimated PGA of the 1980 El Asnam earthquake (M7), which, unfortunately, was not registered.

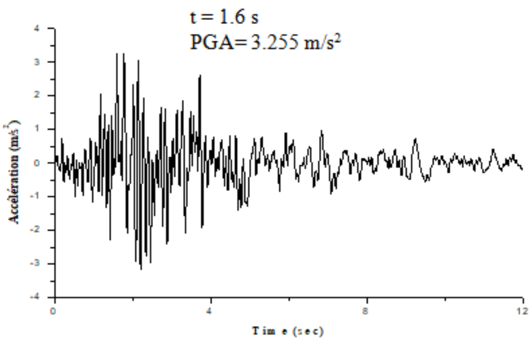


Fig. 4. Horizontal component of 1980 El Asnam earthquake replica record scaled by factor of 2.5

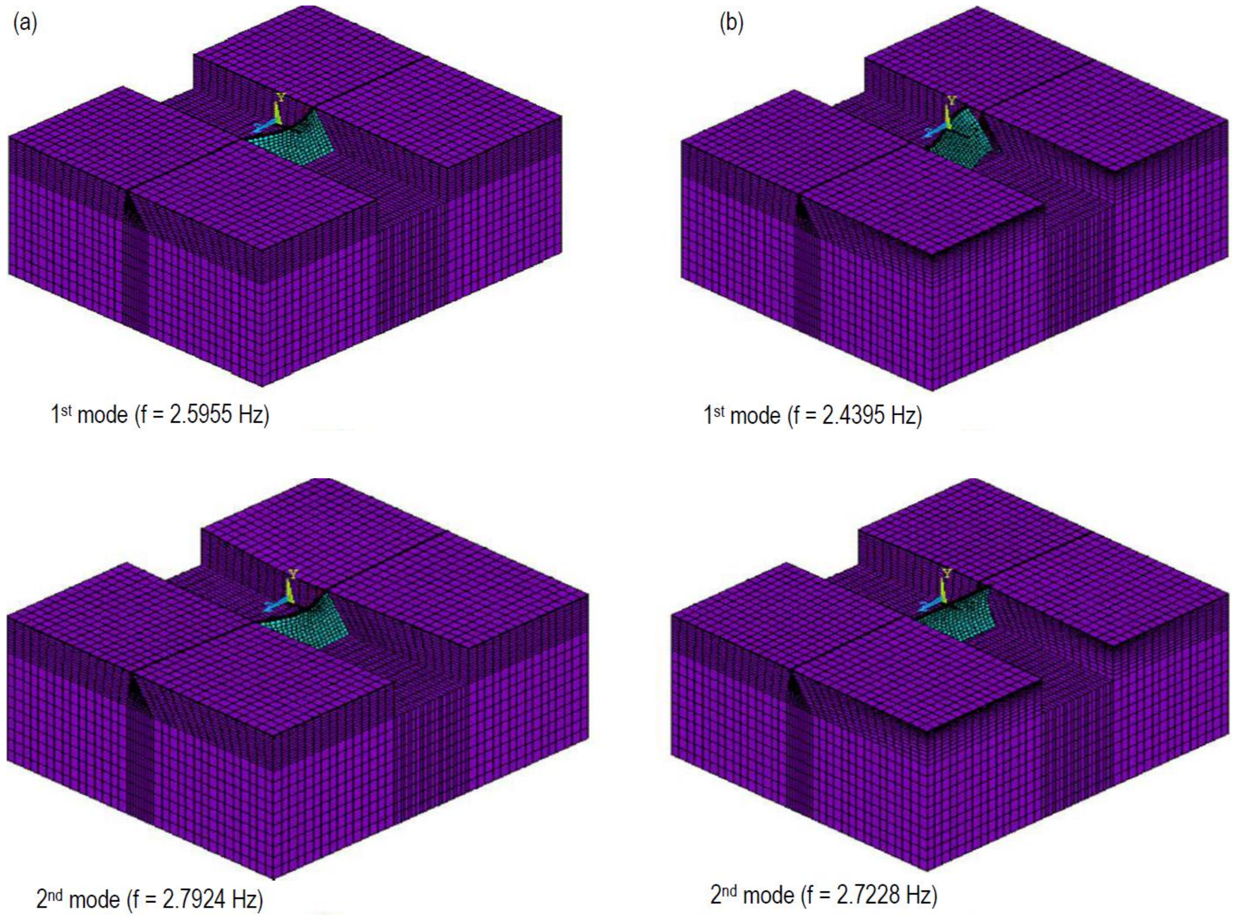
4.1. Modal analysis

The modal analysis results of the first five natural frequencies of the dam-foundation rock system are recapitulated in Table 2 for the adhesive and frictional joints models. The natural frequency values are similar with an average difference of 5.25%, 2.50%, 0.81%, 3.48% and 1.45%, respectively. In general, the natural frequency of free vibration depends upon the mass and stiffness matrix of the dam-foundation rock system, but it is not related to contact conditions between the dam and its foundation.

Tab. 2. First five natural frequencies of Oued Fodda dam-foundation rock system

Mode number	Adhesive joints model		Frictional joints model	
	Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)
1	2.5955	0.3853	2.4395	0.4099
2	2.7924	0.3581	2.7228	0.3673
3	2.8422	0.3518	2.8191	0.3547
4	3.0696	0.3258	2.9629	0.3375
5	3.0930	0.3233	3.0483	0.3281

The first three mode shapes of the two studied models are plotted in Fig. 5. As may be seen, the dam can slide along the dam-foundation rock interface in the frictional joints model due to the presence of connection joints at the interface plane.



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DOI 10.2478/ama-2023-0039 *acta mechanica et automatica, vol.17 no.3 (2023)*

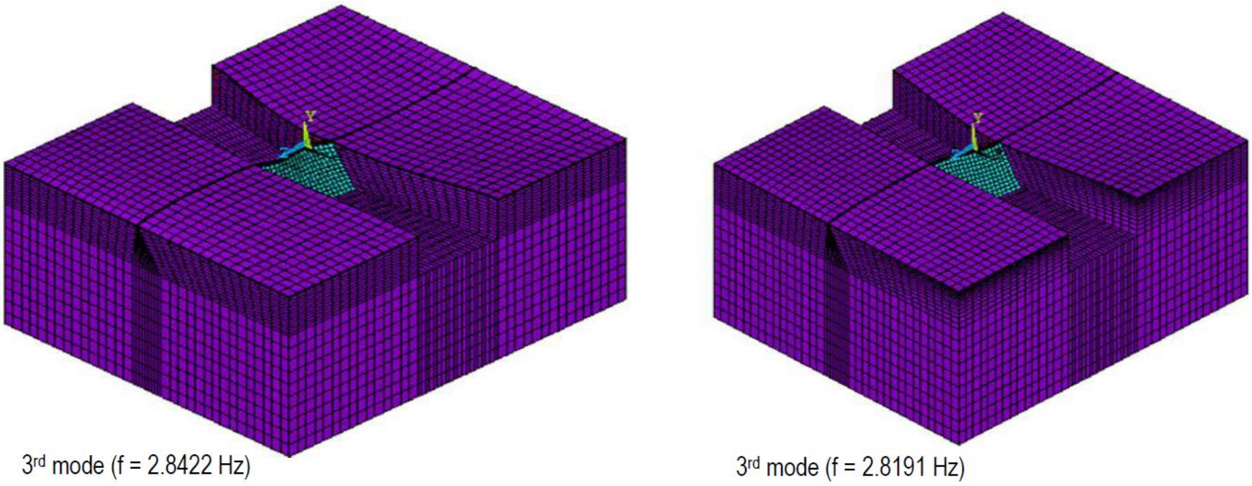

Fig. 5. First three mode shapes of Oued Fodda dam-foundation rock system: (a) adhesive joints model; and (b) frictional joints model

4.2. Dynamic analysis

The repartition of maximum horizontal displacements in the upstream face along the dam crest is presented in Fig. 6 for the adhesive and frictional joints models. As may be seen, the maximum displacements resulting from the frictional joints are smaller than those from the adhesive joints. This reduction in displacement response is due to the dissipation of energy into the interface zone for the frictional joints model when the dam is authorised to slide on its foundation rock. Fig. 7 shows the envelopes of maximum horizontal displacements of the dam during an earthquake for the adhesive and frictional joints models. As can be seen from Fig. 7(b), the dam structure tends to slide along the dam-foundation rock interface, which is known as sliding failure. In general, the sliding failure of a CG dam reduces the deformation response and affects the seismic performance of the dam.

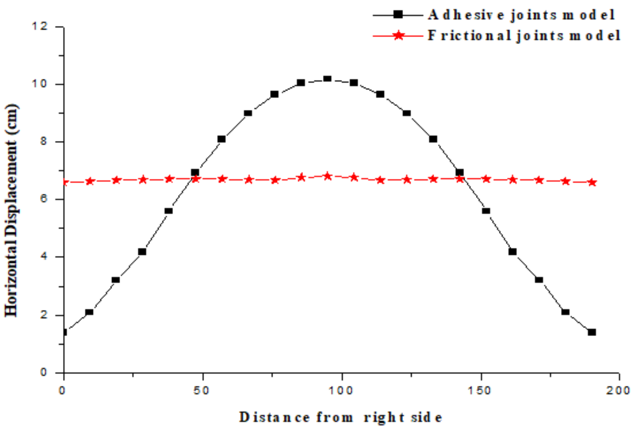

Fig. 6. Distribution of maximum horizontal displacements in upstream face along the dam crest

The time history of horizontal displacement at the upstream middle crest located along the dam central axis is illustrated in Fig. 8 for both of the two joints formulations, in which the maximum displacement at the crest reduces from 10.17 cm for the adhesive joints model to 6.82 cm for the frictional joints model. Fig. 9 represents the time history of horizontal and sliding displacements at the heel and toe located along dam symmetry central axis for the two models of joints.

It is obvious that the time histories of horizontal and sliding displacements for both the toe and heel of the dam are similar to each other, in that the maximum displacement at the heel (or toe) increases from 1.57 cm for the first model to 6.04 cm for the second model. This is explained by the presence of joints along the dam-foundation rock interface, which decrease the stiffness in interface zones, thus leading to sliding of the dam along the interface plane.

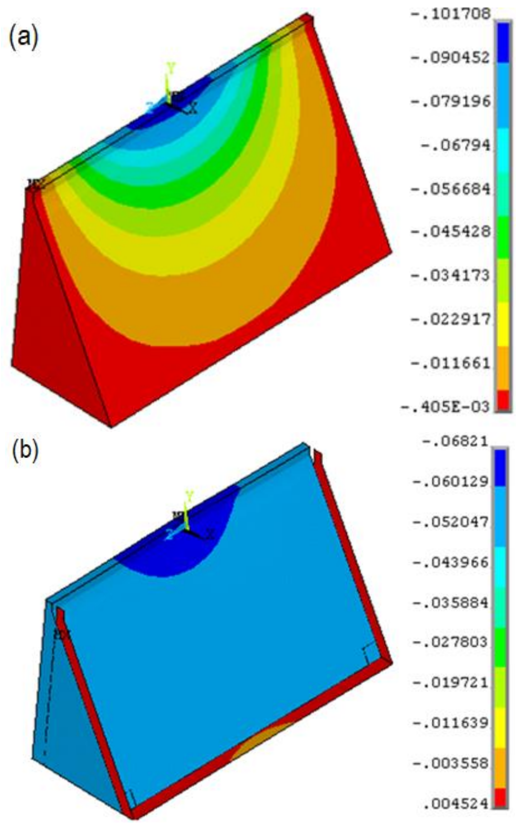

Fig. 7. Envelopes of maximum horizontal displacements for the dam: (a) adhesive joints model; and (b) frictional joints model (Unit: m)

The profiles of final damage in the upstream and downstream faces of the Oued Fodda dam are compared in Figs. 10 and 11, respectively, for the adhesive joints model and the frictional joints model. As can be seen, several damaged elements may appear

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due to tension, particularly at right and left upper lateral extremities and middle bottom parts for both upstream and downstream faces in the first model, while a few of them at middle upper parts along dam central axis in the second model due to the sliding failure of the dam, which reduces the amount of maximum tensile stresses in the dam body.

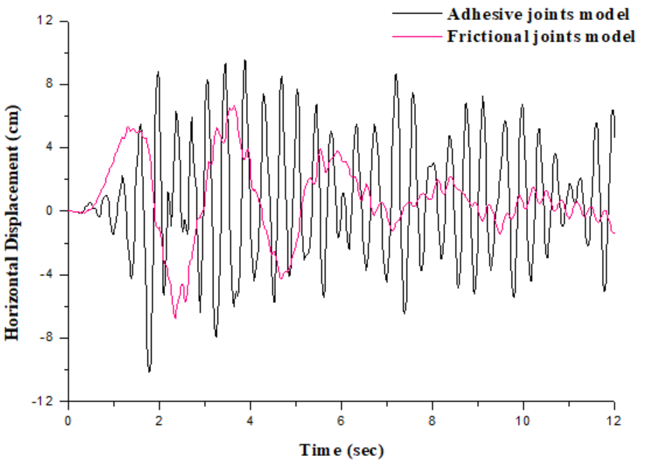

Fig. 8. Time history of horizontal displacement at the dam crest for adhesive and frictional joints models

Figs. 12 and 13 depict the evolution process of crack propagation in both of the two faces of the dam under an earthquake. In the first model, the first cracks can appear at middle bottom parts. After that, the cracking occurs at right and left upper lateral extremities and it is observed that the damaged area expands more to grow at middle bottom parts. In the last step, cracks keep growing up at all these parts that the cracks touched. These fractures may give rise to instability and failure of the dam structure. In the second model, the cracks start at middle upper parts located along dam central axis in both faces. With continuation as well as passage of time, the damaged elements become increasingly vulnerable to complete deterioration, which is definitively attributable to the fact that there is a progressive expansion in the cracked area.

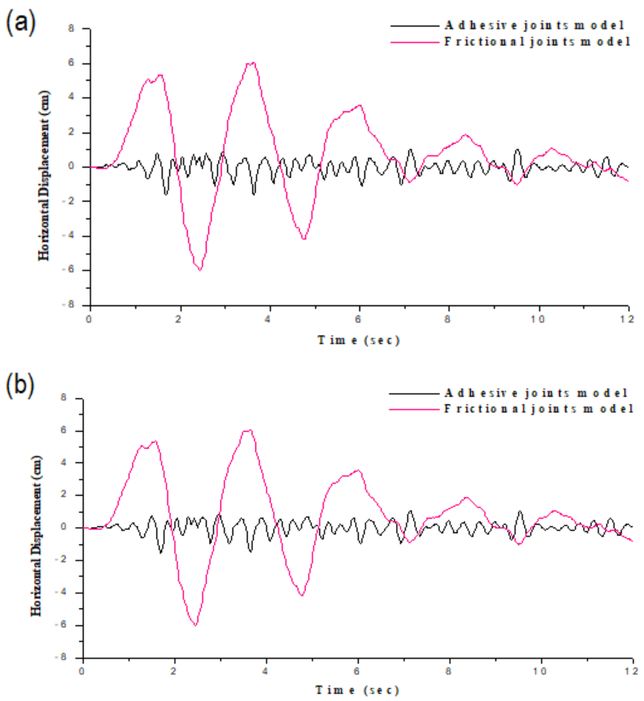

Fig. 9. Time history of horizontal and sliding displacements at: (a) heel; and (b) toe of the dam

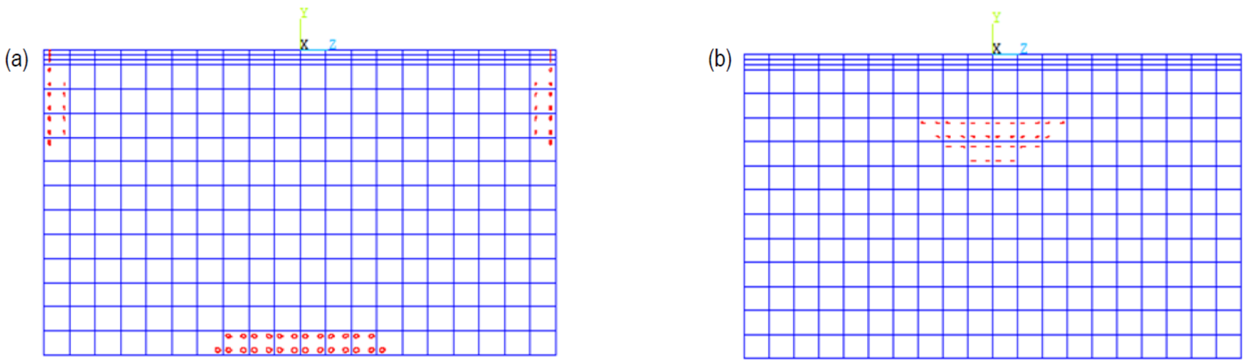

Fig. 10. Profiles of final damage in upstream face of Oued Fodda dam: (a) adhesive joints model; and (b) frictional joints mode

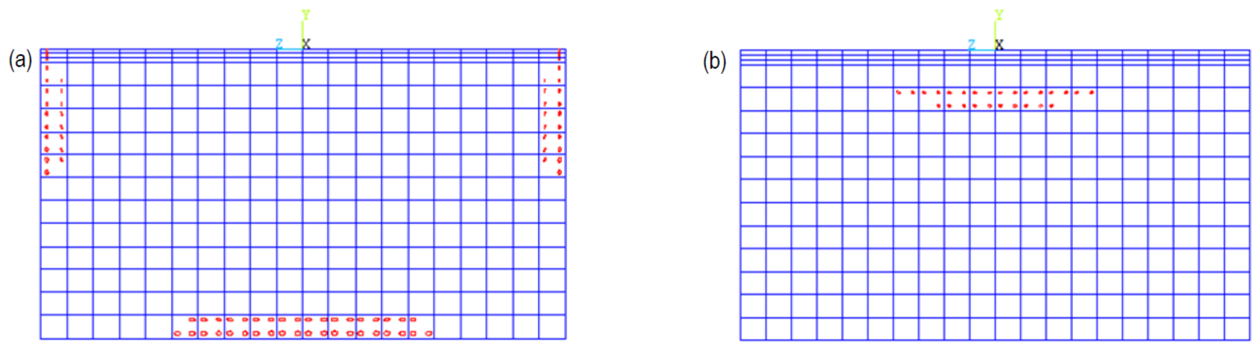

Fig. 11. Profiles of final damage in downstream face of Oued Fodda dam: (a) adhesive joints model; and (b) frictional joints model

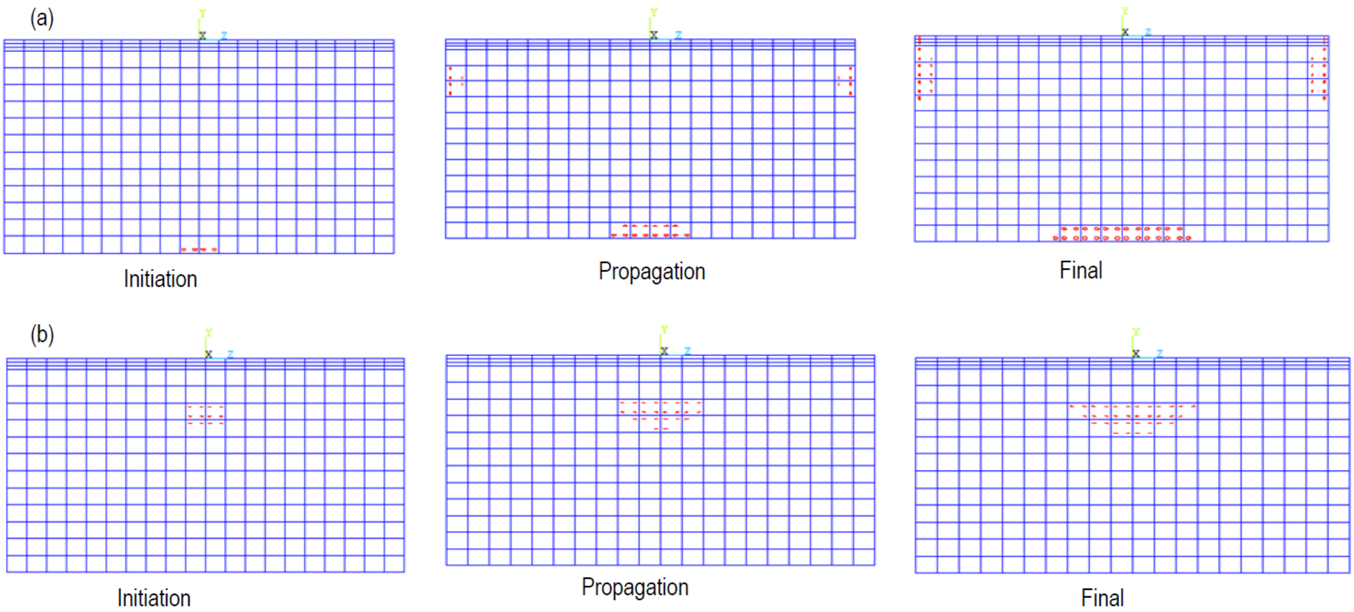

Fig. 12. Process of crack propagation in upstream face of Oued Fodda dam: (a) adhesive joints model; and (b) frictional joints mode

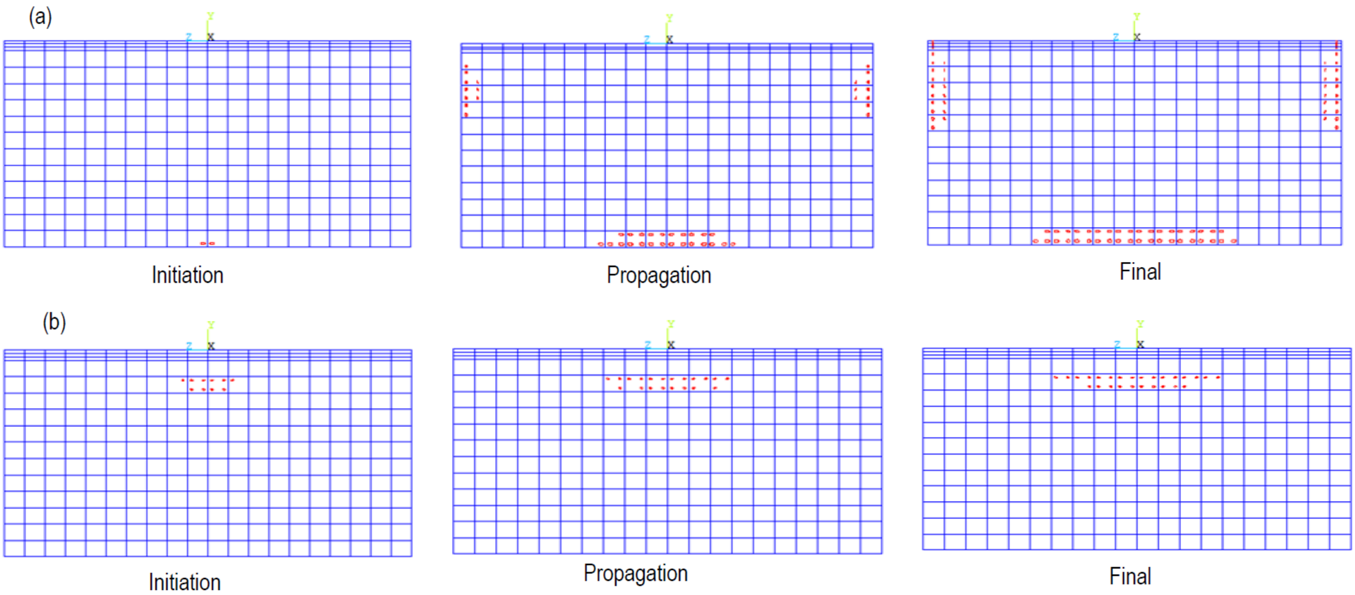

Fig. 13. Process of crack propagation in downstream face of Oued Fodda dam: (a) adhesive joints model; and (b) frictional joints model I

5. EFFECTS OF CROSS-STREAM SEISMIC MOVEMENT ON THE DAM DAMAGE RESPONSE

In order to present the effects of both the contact conditions and cross-stream seismic excitation on the cracking response of the CG dam, the Oued Fodda dam-foundation rock system presented in Section 3 is subjected to the 1980 El Asnam earthquake (M7) in a stream-cross direction. The distribution of maximum cross-stream displacements in upstream face along the dam crest is shown in Fig. 14 for the adhesive and frictional joints models. It is observed that the distribution of displacements is generally convergent in the two joints models as the maximum displacement at the middle crest attains a value of 2.81 cm. On the other hand, the envelopes of maximum cross-stream displacements of the dam for the adhesive and frictional joints formulations, depicted in Fig. 15, are also similar to each other with a small difference. This is owing to the fact that the dam related to the frictional joints model cannot slide, except for a very limited sliding at upper lateral parts, shown in Fig. 15(b), due to the effect of lateral rock blocks located along the dam-foundation right and left side interfaces that prevent the sliding of the dam along the cross-stream direction.

Fig. 16 represents the time history of stream-cross displacement at the upstream middle crest located along dam central axis for both of the two joints models. As indicated in Fig. 16, the displacement time histories are similar to each other. The time history of stream-cross displacement at both heel and toe of the dam is illustrated in Fig. 17. The profiles of final damage in up stream and downstream faces of the Oued Fodda dam under cross-stream earthquake excitation are illustrated in Figs. 18 and 19, respectively. It is observed that the time histories of stream-cross displacement at both heel and toe and the damage profiles for both the adhesive joints and frictional joints models are also similar to each other. In general, the earthquake performances of the dam under the adhesive and frictional joints models are generally similar, and thus the effect of the frictional joints model is

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negligible in the case of cross-stream seismic movement. It is also important to note that when the excitation is applied in the inverse direction, the cracks are still the same but the damage profile is inversed.

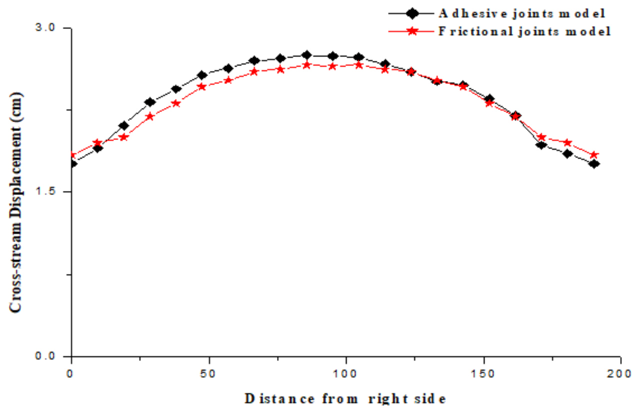
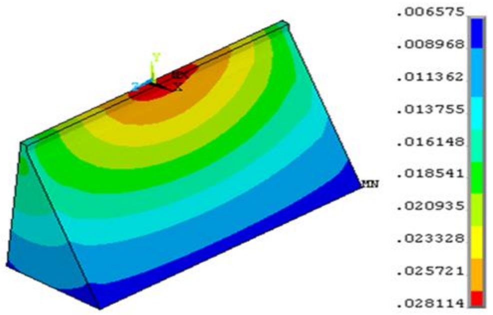


Fig. 14. Distribution of maximum cross-stream displacements in upstream face along the dam crest

(a)



(b)

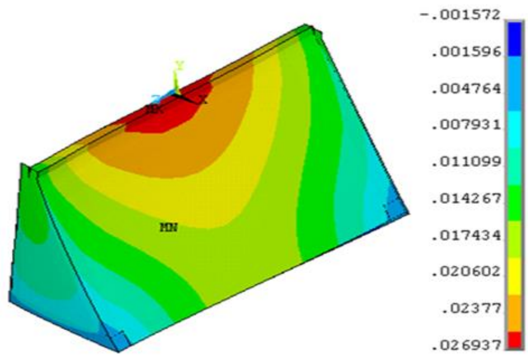


Fig. 15. Envelopes of maximum cross-stream displacements for the dam: (a) adhesive joints model; and (b) frictional joints model (Unit: m)

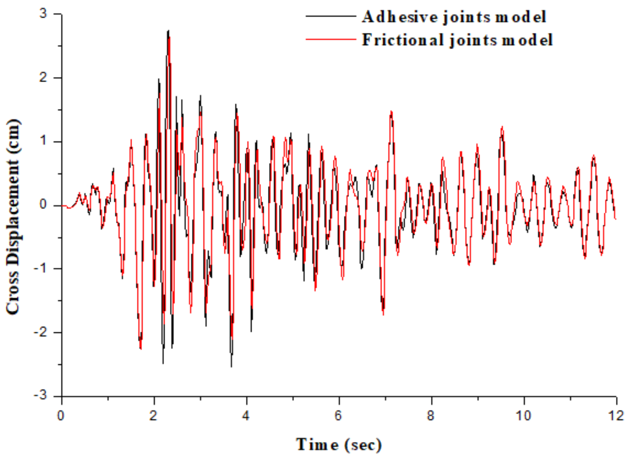
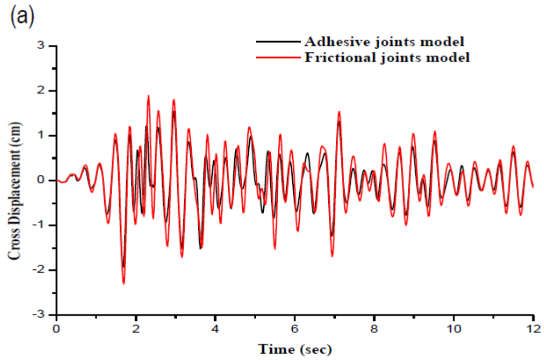


Fig. 16. Time history of cross-stream displacement at the dam crest for adhesive and frictional joints models

(a)



(b)

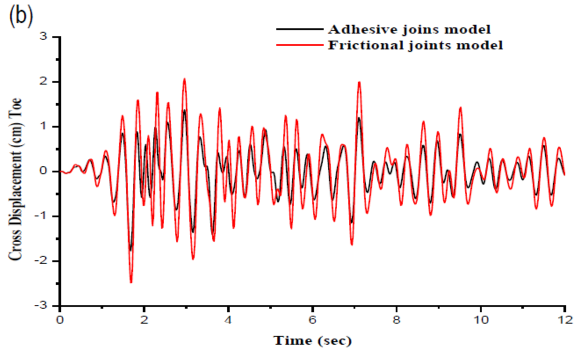
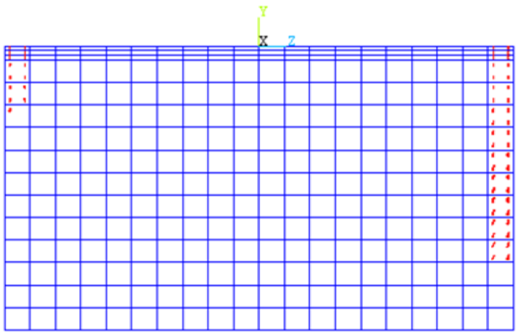


Fig. 17. Time history of cross-stream displacements at: (a) heel; and (b) toe of the dam

(a)



(b)

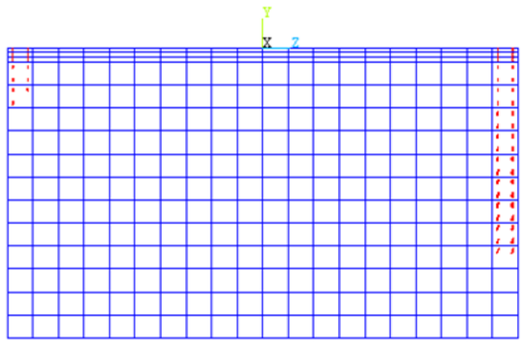


Fig. 18. Profiles of final damage in upstream face of Oued Fodda dam: (a) adhesive joints model; and (b) frictional joints model

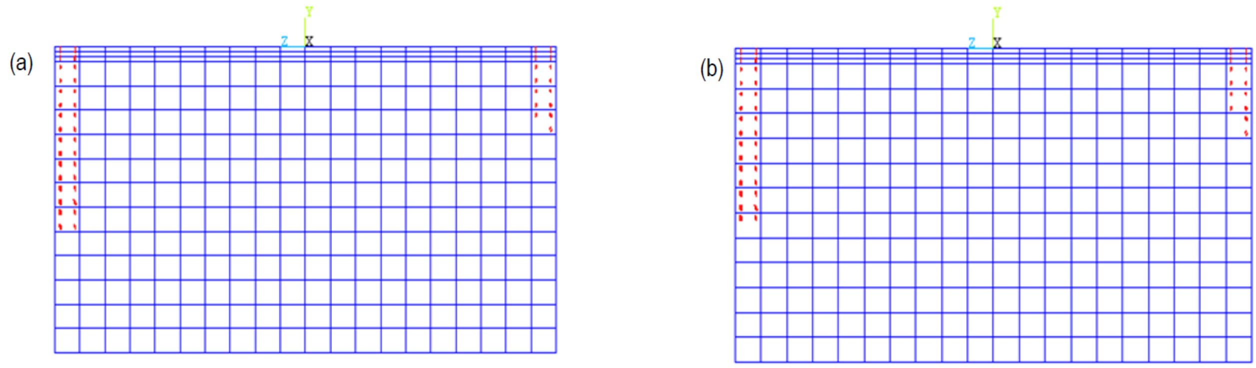


Fig.19. Profiles of final damage in downstream face of Oued Fodda dam: (a) adhesive joints model; and (b) frictional joints model

6. CONCLUSIONS

The present study presents the effects of contraction joints and cross-stream seismic excitation of the earthquake damage behaviour of the Oued Fodda dam using 3D finite element analyses. The material and contact nonlinearity are considered in this numerical investigation. We can draw the following conclusions from this study:

1. The nonlinear earthquake performance of the dam depends closely upon the properties of the joints model along the dam-foundation rock interface zone.
2. The frictional joints model can reduce the seismic response and damaged areas in the dam and lead to more stable solutions.
3. It is preferable to use higher tensile strength concrete in the damaged parts to decrease the predicted cracking and reinforce the stability and safety of the dam.
4. Frictional joints formulation may decrease the dam stiffness in interface zones and leads to larger nonlinear analysis for dam-foundation rock system.
5. Material and joints nonlinearity should be considered in dynamic performance analyses of the dam to achieve more reliable results.
6. A more realistic model of dam-foundation system may be obtained considering the frictional joints along dam-foundation rock interface.
7. Seismic interaction between the dam and foundation rock produced by cross-stream earthquake movement can result in significant damage to the dam.

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