Cracks Analysis in Zavin Concrete Dam Using Fracture Mechanics Approach

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Abstract

Most of the existing concrete dams are subjected to cracking. These cracks are caused by various factors such as construction practices, curing, loads and volume change of mass concrete which reduce the efficiency, failure or instability of concrete dams. Using fracture mechanics as a new method to estimate stability and durability of concrete dams is recommended in scientific publications in worldwide. This study aimed to apply the principles and criteria of linear elastic fracture mechanics to evaluate the propagation of cracks in body and foundation of Kalat concrete gravity dam -that is located in the northern province of Khorasan Razavi, Iran- subjected to the worst-case loading, including the extraordinary loading case due to earthquake with full reservoir. For this purpose, ZENCRACK-v 7.7 and ABAQUS-v 6.10.1 software were utilized and nonlinear analysis of finite element are performed. Subsequently, linear elastic fracture mechanics criteria including stress intensity factor and maximum circumferential stress were calculated for existing cracks in various parts of dam body and foundation and stability of initial cracks, kinking angle and extension of them were determined. Based on the obtained results, crack propagation in areas near to both dam abutments is investigated. To do so, a plain strain condition is assumed that only expanded in longitudinal and transverse axes, but with being away from abutments toward dam center, crack growth logged from plain strain condition and expanded in the vertical direction. Also, under earthquake load with 10 second duration, maximum tension and compression stress were occurred between 2.32 to 4.26 seconds.

Keywords: Fracture Mechanics, Stress Intensity Factor, Toughness, Concrete Dams, Cracks Propagation

1. Introduction

One of the most important hazards that threatened stability of concrete dam is crack propagation in dam body and foundation, which may lead to failure of dam. These cracks cause water penetration and create extra pressure in dam body that caused propagation of cracks to downstream and finally resulting in slip of isolated parts of dam body. Due to the sensitive issue of cracking in concrete dams and lack of sufficient accuracy to conventional techniques that are not able to accurately predict the propagation of cracks in concrete dams. Hence, it is needed to perform complete and precision analysis about cracks

propagation in concrete dams using new and advanced methods like fracture mechanics. Facture mechanics concepts have been successfully applied to study the cracking phenomena in dams [1-8]. However, almost all the investigations have been made to assess the crack stability at the interface of concrete/rock foundation [1-5, 7] and very few studies are reported regarding the cracks at the other places such as crest of dam, corners, around the inspection galleries etc. [1].

In the present study two criteria of fracture energy and stress intensity factor are used to estimate crack propagation process. In the former criterion, crack propagation initiated when sufficient energy for crack growth and overcome material resistance

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provided. In other words, crack growth happens by reaching the rate of the energy relief (G) to its critical amount (Gc) which is assumed to be material property. The latter criterion is the stress intensity factor (SIF) that crack propagation starts when they reached to their critical amounts, called fracture toughness [8]. Within the assumption of linear elastic fracture mechanics (LEFM), at the tip of crack propagation in pure opening mode (mode I) in a brittle material, a stress singularity arises which is characterized by the stress intensity factor. The stress components for the infinite cracked plate shown in figure 1 under tension using Westergaard complex stress function are [9]:

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\cos\frac{3\theta}{2}\right)$$ (1)

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\cos\frac{3\theta}{2}\right)$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\sin\frac{\theta}{2}\cos\frac{3\theta}{2}$$
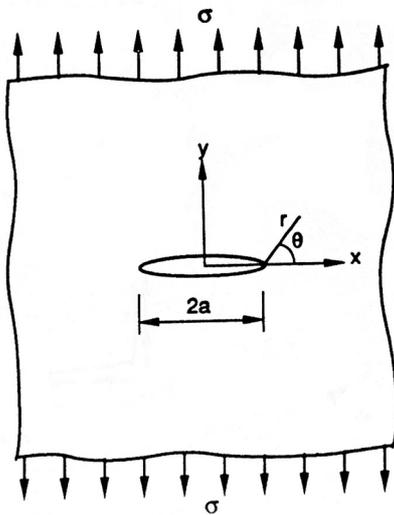
Figure 1. infinite plate with crack subjected to tension

Where K_I is the stress intensity factor (SIF) for tension mode and may be defined as:

$$K_I = Lim_{r \to 0}\sqrt{2\pi r}.\sigma_y(r, \theta = 0)$$ (2)

For the infinite cracked plate, the stress intensity factor is:

$$K_I = \sigma\sqrt{\pi.a}$$ (3)

The displacements at the crack tip for the plane stress condition are obtained as:

$$u = 2(1+\upsilon)\frac{K_I}{E}\sqrt{\frac{r}{2\pi}}\cos\frac{\theta}{2}(1 - 2\upsilon + \sin^2\frac{\theta}{2})$$ (4)

$$v = 2(1+\upsilon)\frac{K_I}{E}\sqrt{\frac{r}{2\pi}}\sin\frac{\theta}{2}(2 - 2\upsilon - \cos^2\frac{\theta}{2})$$

Based on the linear elastic fracture mechanics (LEFM) assumptions, the stress, strain, and displacement fields in the near crack-tip region are determined using the stress intensity factors. Therefore, fundamental to the use of the finite element method for LEFM is the extraction of accurate SIF's corresponding to the finite element results. Techniques for extraction of SIF's fall into two directories; direct approaches which correlate SIF's with finite element results directly, and energy approaches which first compute energy release rates. In general, the energy approaches are more accurate and should be used preferentially. However, the direct methods have utility and the expressions are simpler. Some methods for extracting SIF's are: Crack Tip Opening Displacement (CTOD), Displacement Correlation Method (DCT), Virtual Crack Extension Method, Modified Crack Closure Integral (MCCI) and J-Integral Energy Method [9-11].

2. Dam description

Zavin concrete dam is located in 95 kilometers from Mashhad city (capital of Khorasan Razavi province in Iran), in Zavin section with geographical location 59° 54′ east longitude and 43° 36′ north latitude which was completed in 2002 (Figure 2).

Zavin dam is a concrete gravity concrete dam with 42-meter height from the river bed and 132-meter crest length. In this study, 3D finite element analysis of Zavin dam was performed using ABAQUS software. For this purpose, 3D geometry of dam structure and foundation was modeled by the specifications and dimensions which were extracted from dam construction report [12], and shown in Figure 3(A).

Since placing supports at the bottom of dam body in numerical model caused severe stress

concentration at this points and incorrect answers for stress values around supports so, a part of foundation under and around dam body were modeled with it and support conditions were applied to the end parts of the foundation until support displacements don't effect on stresses developed on dam body. In Figure 3(B) dimensions of rock border around dam body and boundary conditions are shown. Also, concrete materials of dam body and rock foundation were considered elastic and homogenous. Mechanical and resistance properties of materials were shaped Zavin dam, is shown in Table 1. As the earlier

measures tension in dam body and foundation were small and placed in the elastic range.

In this study, prediction of the crack history and 3D simulation of crack propagation were done by ABAQUS and ZENCRACK software based on finite element analysis and fracture mechanics concept. It should be noted, in ZENCRACK software fracture mechanic parameters (stress intensity factor and Energy release rate) were measured based on CTOD and ENERGY methods in order to perform numerical analysis of the crack propagation [13].

Figure 2. Zavin concrete gravity dam located in the city of Kalat [11]

Table 1. Mechanical and Resistance Properties of Zavin Dam materials [11]

Poisson Coefficient	Static Modulus of Elasticity (GPa)	Specific Gravity (N/m^3)	Materials
0.17	21	24000	Dam Body
0.20	42	26600	Foundation
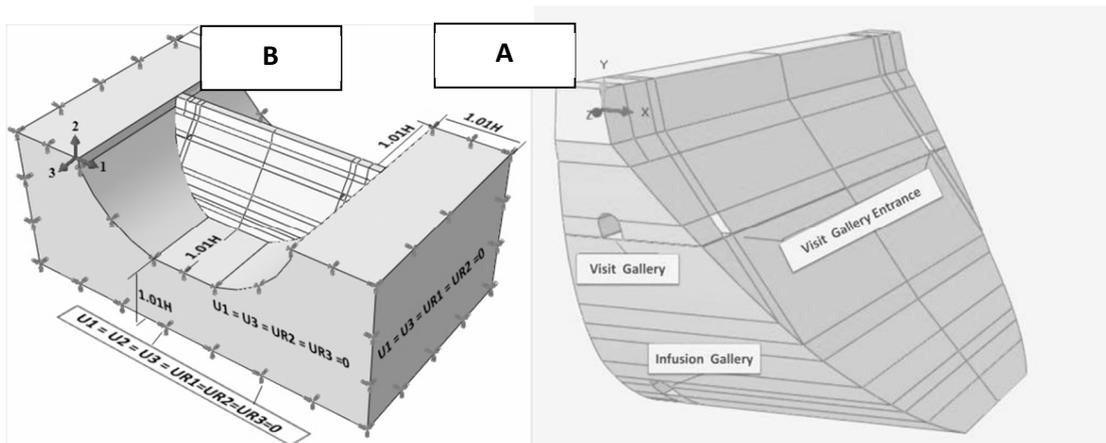
Figure 3. (A) 3D Geometry of Zavin dam and (B) Boundary conditions of model

3. Applied Loads

Between applied loads on dam body, sediment pressure force was not considered due to its negligible effect on created tension. Also, due dam site location and the small size of the dam reservoir, wind force wave effect and ice force weren't considered. Moreover, due to the dam's considerable thickness, the effects of temperature change and sensitivity to thermal tension were neglected and not considered [14]. In order to analysis Zavin dam against earthquake load, a combination of loads was considered in the modeling including hydrostatic force in normal water level, concrete dam body weight as linear acceleration in vertical direction and the inertia force to the dam body due to earth acceleration. This acceleration was considered according to the accelerogram of Figure 3, that is related to one of the latest earthquakes in north Khorasan [12], as variable accelerations in the period of 10 seconds in directions of horizontal and vertical was applied to the boundaries of foundation. Also, the hydrodynamic force due to the effect of earthquake on the reservoir's water volume was applied through the proposed method USBR with parabolic distribution and perpendicular to the upstream face of dam body from zero in normal level to the max value is in the bottom of dam. Then, dam body and foundation were meshed separately with second order, twenty-node, hexagonal, Brick elements (C3D20R) as shown in Figure 4. Also, mesh size was adopted by try and error method to capture stress concentrations around corners and the areas of abrupt changes with minimum number of used elements.

4. Dam Analysis

After building a numerical model, allocating the material properties, applying loads and boundary conditions then, finite element analysis of model was performed using ABAQUS software with dynamic relaxation method. In order to perform dam dynamic analysis, explicit method which is specialized for big models with short time dynamic responses, was used. The results of initial analysis of model (without crack) under combination of above loading by ABAQUS software is shown in Figure 5(A) and 5(B). The figure shows stress distribution in dam body and foundation.

Figure 5 showed that approximately whole parts of dam body except little parts at the both sides and heel of dam (in dam-foundation interface), wall and floor of both superior and inferior gallery, were under compressive stress. Therefore, initial cracks were considered in areas under tension with the length equal to area under tension. Accordingly, 12 initial cracks (4 cracks at the right side, 4 cracks at the left side and 4 cracks at the middle and dam heel) with 1 meter deep along the z-axis (except one case with depth of 2 meter along the y-axis) and 6-meter-long along x-axis (except 2 cases with the length of 8 meter) were considered by ZENCRACK software and crack propagation analysis was perform separately for each crack. For instance, position of 4 initial cracks at the right side of dam body is shown in Figure 6.

Before crack propagation analysis, due to enormous dimensions of model and for reaching higher precision results and decreasing crack analysis time, sub modeling techniques was utilized. Sub modeling method is one of the finite element analysis methods to reach to exact results in special region.

Crack analysis in Zavin dam model, must be done when various load types such as gravitational load, hydrostatic load, hydrodynamic load and earthquake load all together effect on dam body at the same time. Therefore, the effect of superposition forces on crack propagation should be considered. It should be noted that hydrodynamic and earthquake applied load were variable during the analysis and applied cyclic so they were responsible for creation and growth of cracks while, gravitational and hydrostatic load were constant. According to the acceleration in figure 7 during the earthquake, applied acceleration to lower boundaries of the model is variable resulted in variable earthquake forces. Loads caused by the earthquake are a function of the intensity of accelerations which applied to the foundation boundaries. So, with making the variable accelerations to a cyclic manner, we can convert the earthquake loads to the cyclic load. To do this, the rain-flow method was applied in the present study. The rain-flow counting algorithm is used in the analysis of fatigue data in order to reduce a spectrum of varying stress into a set of simple stress reversals [15-17]. Applying rain-flow method, acceleration-time graph for horizontal earthquake (presented in Figure 7(A)) converted to a counted spectrum in the form of acceleration-cycle graph (Figure 7(B)). Using these algorithms, the whole earthquake time history, included 999-line data of acceleration-time were transformed
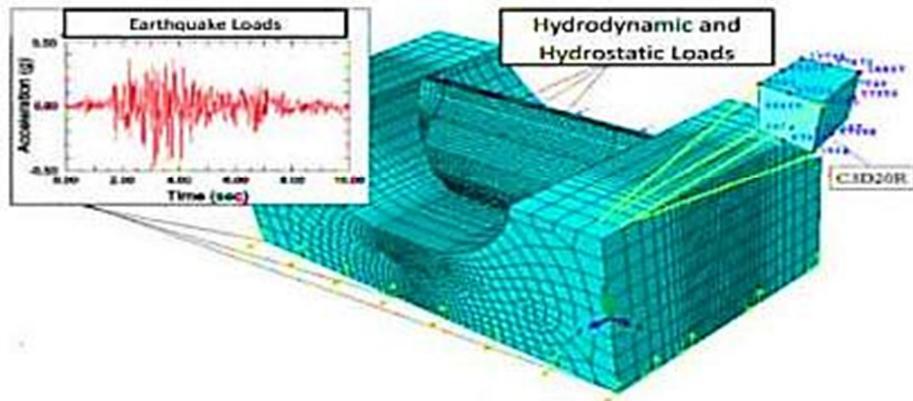
Figure 4. Mesh discretization of model and loads
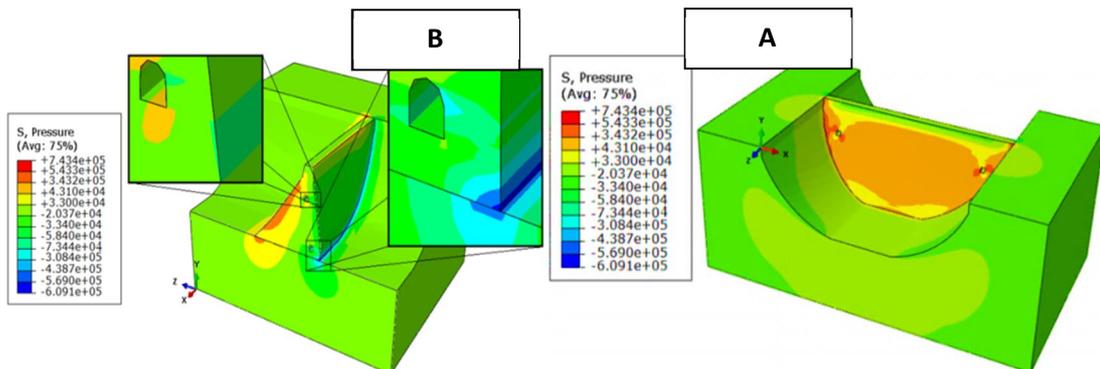
Figure 5: (A) distribution of maximum pressure and tension with the full reservoir and (B) distribution and place of maximum tension stresses with full reservoir under earthquake loading
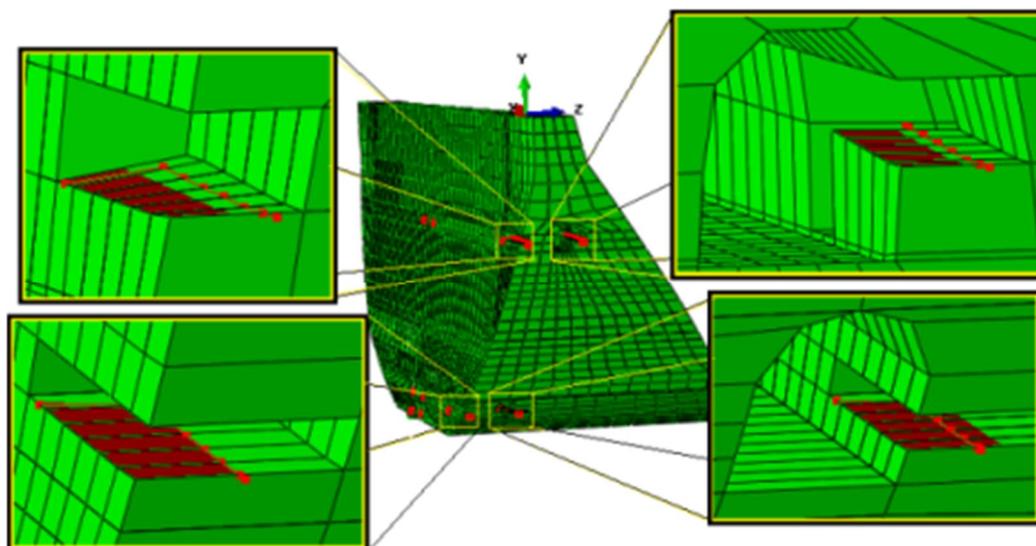
Figure 6: Showing 4 initial cracks considered at the right side of dam body
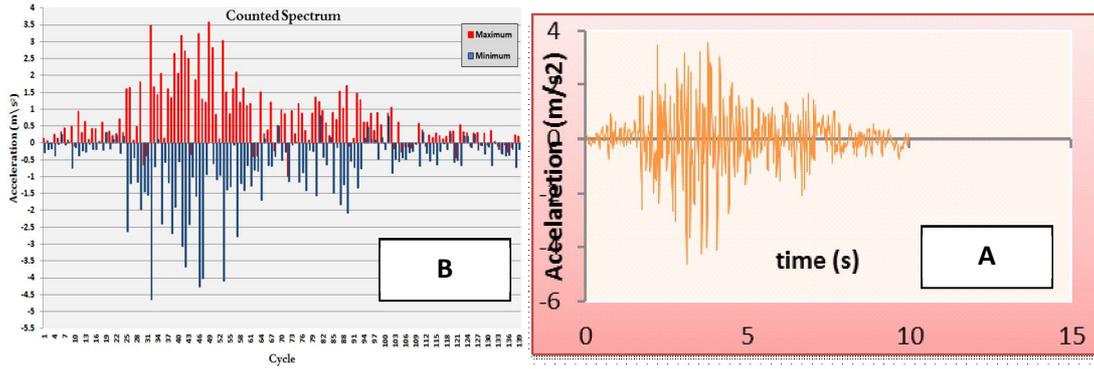
Figure 7. (A) horizontal earthquake accelerogram and (B) resulted counted spectrum using rain-flow algorithms

into 139 cycles, which every cycle has its own maximum and minimum dedicated acceleration.

After performing the cycle history process with ZENCRACK software and utilizing related coding, static and cyclic loads with variable amplitude were applied simultaneously to the cracked sub-models of Zavin dam model. Also, for stability assessment and crack propagation analysis fracture toughness (critical stress intensity factor KIc) for dam body and foundation were considered $K_{IC} = 2.3 MPa\sqrt{m}$ and $K_{IC} = 1.29 MPa\sqrt{m}$, respectively [3]. Finally, the crack propagation analysis was done for each sub model using ZENCRACK software.

5. Results and Discussion

After applying load combination on Zavin dam model, with considering initial cracks in the locations that there is a potential for cracks,

fracture mechanics parameters were obtained using CTOD and ENERGY method to perform crack propagation analysis. Length and direction of crack growth in variable locations of dam body at the time of the earthquake load were obtained by comparing the stress intensity factors with fracture toughness of material and so, critical points in terms of stability were determined. In this study 12 sub-models were considered around 2 dam galleries and dam-foundation interface. In the following, crack propagation results for just 5 sub-models out of 12 one, are shown. Figure 8 shows results for Sub-model 1 which is related to the area around the lower gallery, right abutment of dam and right wall of the tunnel. Figure 9 shows results for Sub-model 2 which is related to the area around the lower gallery, right abutment of dam and left wall of the tunnel.
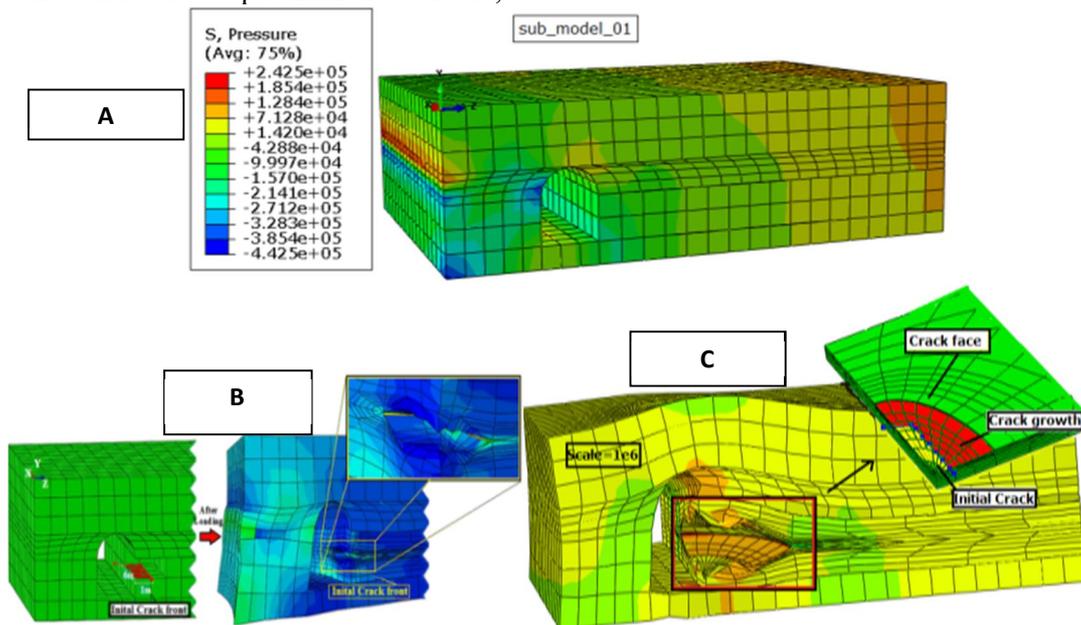
Figure 8. (A) sub-model 1 block, (B) initial crack before and after loading and (C) crack propagation result
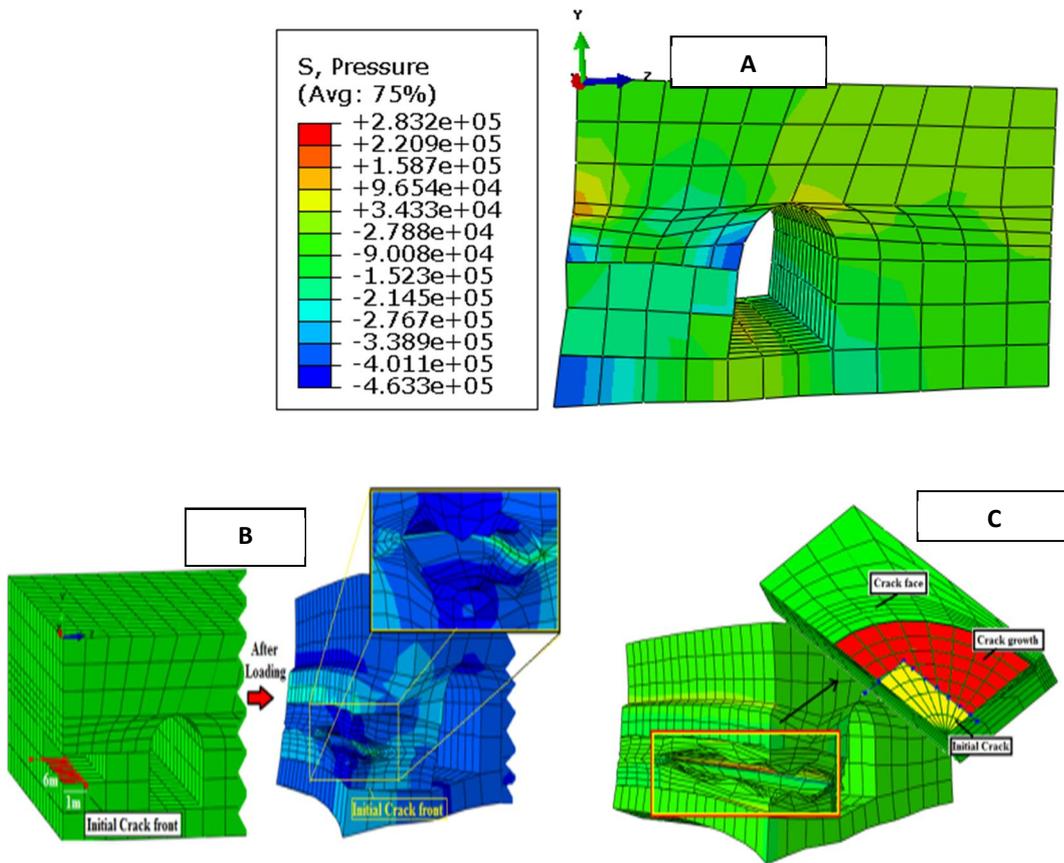
Figure 9. (A) sub-model 9 block, (B) initial crack before and after loading and (C) crack propagation result

Figure 10 shows results for Sub-model 4 which is related to the area around the top gallery, right abutment of dam and left wall of the tunnel.
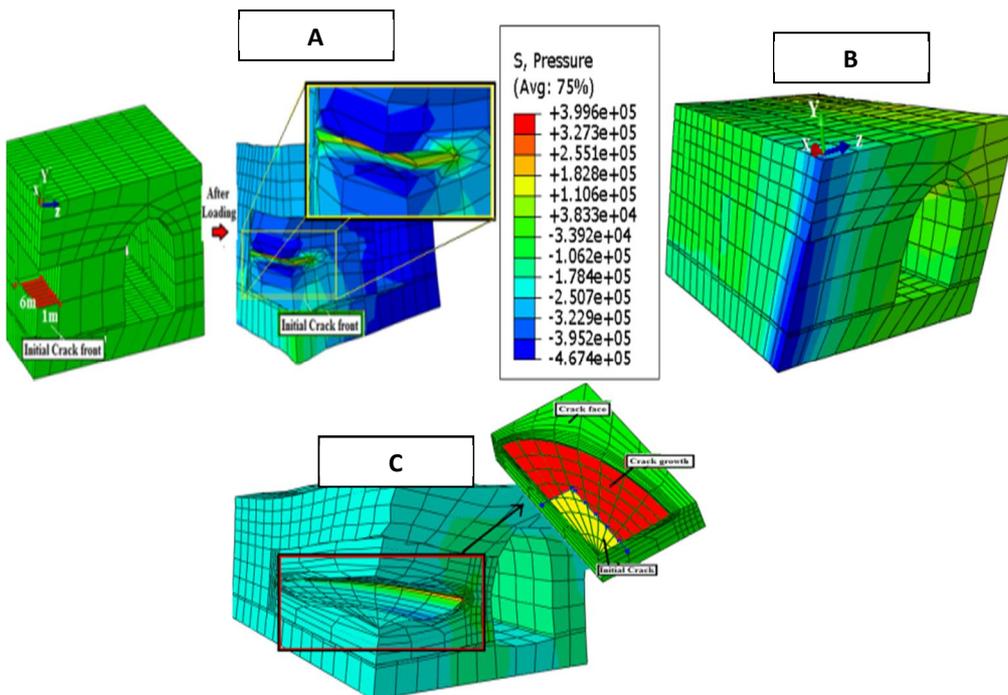
Figure 10. (A) sub-model 4 block, (B) initial crack before and after loading and (C) crack propagation result
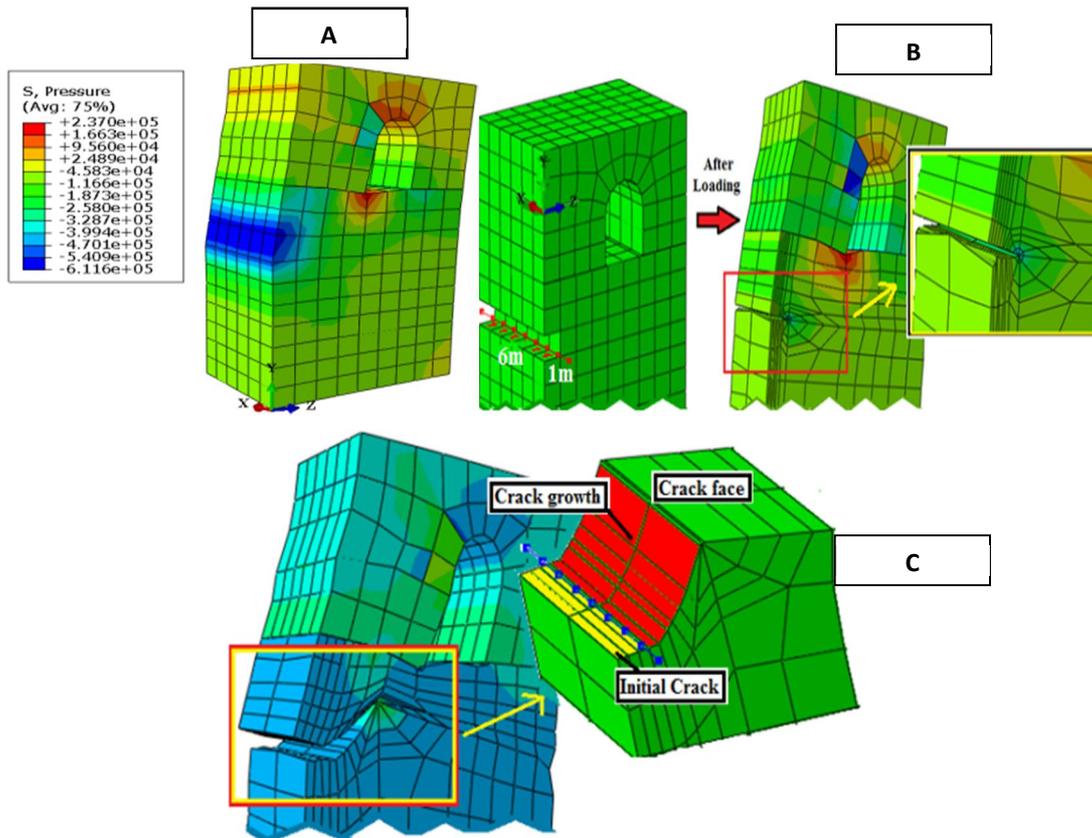
Figure 11. (A) sub-model 11 block, (B) initial crack before and after loading and (C) crack propagation result

Figure 11 shows results for Sub-model 11 which is related to the area connecting the dam body with the foundation and at the upstream face of dam.
Figure 12 shows results for Sub-model 12 which is related to the area connecting the dam body with foundation and at the upstream face of dam (like sub model 11) with vertical crack in the foundation stone.
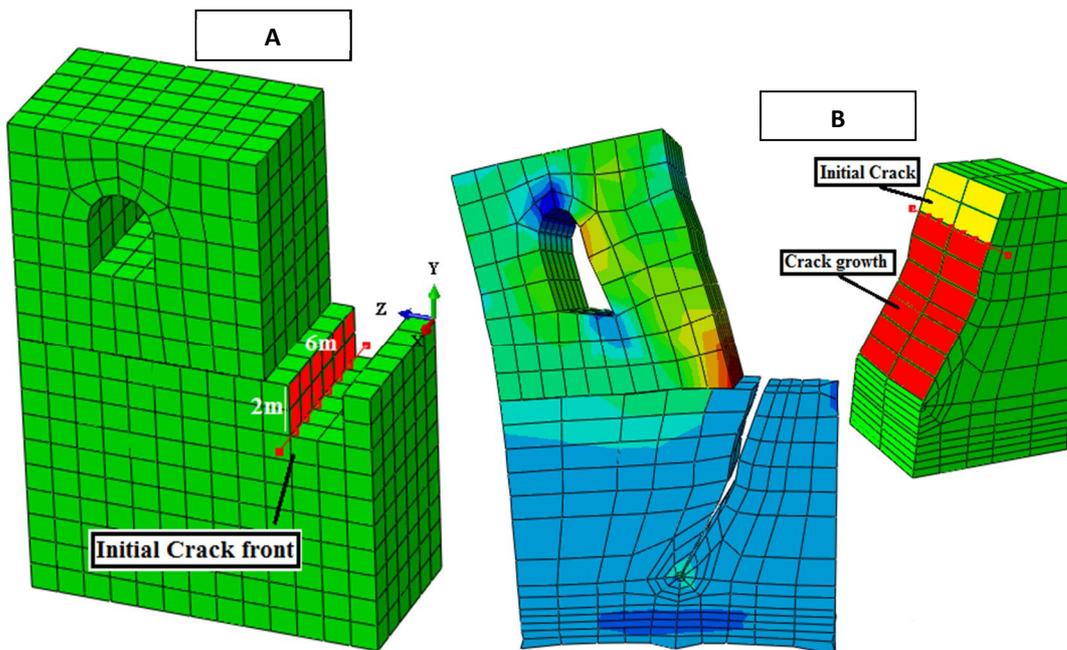
Figure 12. (A) sub-model 12 block, (B) initial crack before and after loading and (C) crack propagation result

In all sub models Figure (A) shows sub-model layout, Figure (B) shows initial crack (before and after the first loading) and Figure (C) shows crack growth in sub model with Scale 1E6. In the following, SIF history (stress intensity factor against crack length) for all sub-models is presented in Figure 13. The corresponding graphs show Crack length in X axis in meter and stress intensity factor in Y axis in ($Pa\sqrt{m}$). Also, numerical results of crack propagation analysis are shown in Table 2.
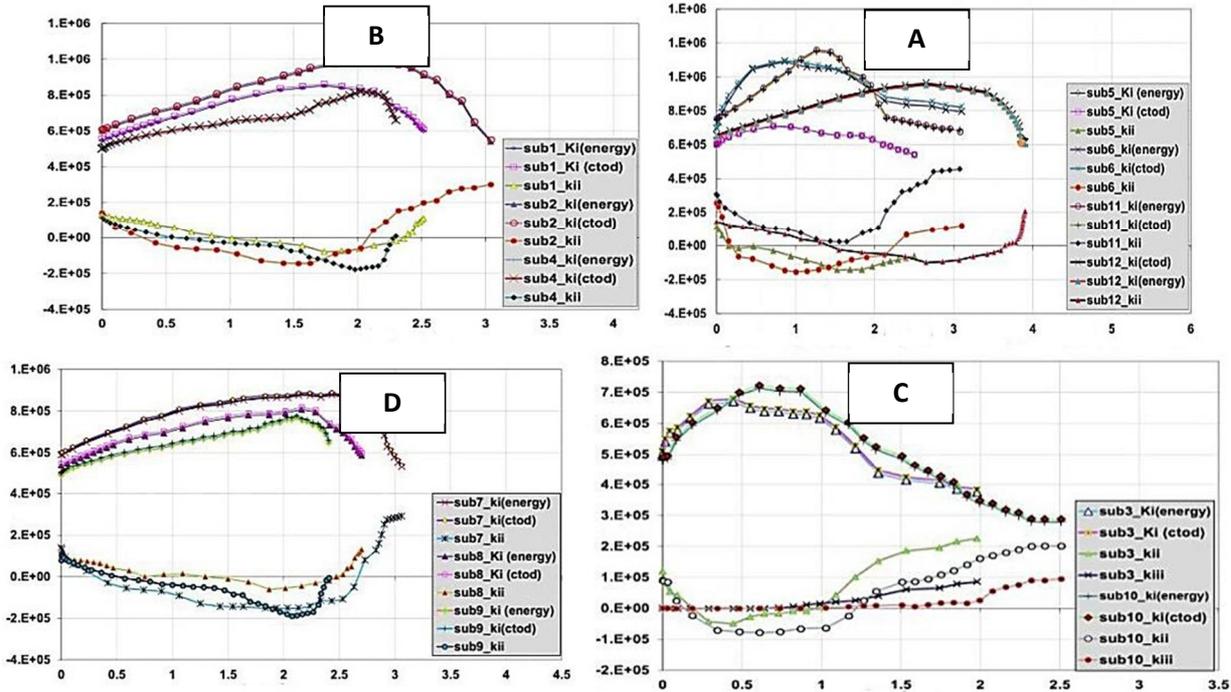
Figure 13. SIF history for all sub-models, (A) right abutment of dam body, (B) upstream face of dam, (C) left abutment of dam body and (D) entrance of both galleries

Table 2. Crack propagation results in all sub-models of Zavin Dam model

Fracture Toughness K_{IC} ($MPa\sqrt{m}$)	Stress Intensity Factor (K_I) ($MPa\sqrt{m}$)		Crack Growth Length in Different Directions (m)			Initial Crack Length in Different Directions (m)			Sub-Model No.
	CTOD	Energy	Z	Y	X	Z	Y	X	
2.36	0.8528	0.85180	-	2.51	-	2.5	1	-	6	1
2.36	0.9965	0.9963	-	3.04	-	2.5	1	-	6	2
2.36	0.6701	0.6695	1.98	.50	-	-	1	-	8	3
2.36	0.8099	0.8093	-	2	-	2.3	1	-	6	4
2.36	0.7094	0.7087	-	2.5	-1.6	-	1	-	6	5
2.36	0.1091	0.1091	-	3.15	-2	-	1	-	6	6
2.36	0.8789	0.8784	-	3.06	-	3	1	-	6	7
2.36	0.8091	0.8084	-	2.7	-	3	1	-	6	8
2.36	0.7698	0.7695	-	2.41	-	1.8	1	-	6	9
2.36	0.7139	0.7132	2.51	.85	-	-	1	-	8	10
2.36	0.1159	0.1159	-	2.5	3.08	-	1	-	6	11
1.29	0.9522	0.9518	-	2.3	3.90	-	-	2	6	12

Results showed that under earthquake load with 10 seconds duration, maximum tensile and compressive stresses occurred between 2.32 to 4.26 seconds and dam-foundation interface part, floor and wall of visiting galleries are more under tensile stress more time during the earthquake applying loads. Also, the crack growth in all regions connected to the dam abutments was in the plain strain condition which is extended just in longitudinal and transverse axes, but away the both abutments and inside dam core, crack growth was not plain strain and propagated along vertical axis because of supports effect.

Considering the stress intensity factor values in the regarding regions, the opening mode (first mode of crack propagation) was the dominant mode of crack growth in this model and considerable difference was seen between KI values with KII and KIII. Also, KIII (tearing mode) in all considered regions was near zero and does not have a significant role in the crack growth except near the upper gallery because effects of side abutments (confining effect on crack growth) and free surface in these opening. With comparison of the rate and direction of crack growth in different regions, it can be considered that in all regions away from the crest and getting close to the foundation, following the increase in tensile tensions, crack propagation is also increased and the maximum growth in crack length is happened in dam-foundation interface and surrounding regions. Moreover, the maximum crack growth in the whole model occurred in rock foundation. Away from both of side abutments and toward the middle section of dam, restriction of crack growth is reduced and the crack is propagated in vertical axis. It is noteworthy that, in the sub-models including galleries and it's around regions, the minimum growth is related to the crack propagation toward side abutments and the maximum growth is related to the crack propagation in the free surface of visiting galleries. The results of these two methods (CTOD, Energy) were very close and would be approved.

After analysis of the crack propagation, for determining the critical regions regarding dam instability, the maximum stress intensity factors of the first mode for every sub-model (KI max) was compared to the fracture toughness of the material involved. In all regions of dam body which has been considered, KI max was less than concrete fracture toughness (2.36 MPa$\sqrt{m}$) and also KI max

for crack growth in foundation was less than rock foundation fracture toughness (1.29 MPa$\sqrt{m}$), therefore dam stability against applied earthquake load is acceptable.

6. Conclusions

All concrete cracks suffering from cracking which is caused by various factors such as construction practices, curing, loads and volume change of mass concrete and resulted in failure or instability of concrete dams. Recently, fracture mechanics has been advocated in papers, as an alternative means to assess dam safety. In this study, finite element model of Zavin concrete gravity dam in north-east of Iran were analyzed under dynamic earthquake load using both ZENCRACK-v 7.7 and ABAQUS-v 6.10.1 software and propagation of some predicted initial cracks lying at several places in the dam body and foundation were studied based on fracture mechanic criteria. For more accurate results, 12 sub-models were considered around the regions of predicted initial cracks. Results showed that under earthquake load with 10 seconds duration, maximum tensile and compressive stresses occurred between 2.32 to 4.26 seconds and dam-foundation interface part, floor and wall of visiting galleries are more under tensile stress more time during the earthquake applying loads. Also, the crack growth in all regions connected to the dam abutments was in the plain strain condition which is extended just in longitudinal and transverse axes, but away the both abutments and inside dam core, crack growth was not plain strain and propagated along vertical axis because of supports effect. Finally, dam stability assessed by comparing the maximum stress intensity factors of the first mode for every sub-model in dam body and foundation with the fracture toughness of the material involved and consequently, dam stability against applied earthquake load was found.

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