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Crack Propagation Analysis in Concrete Gravity Dams Using Fracture Mechanics Concepts

Bina, K.
Ph.D. Student of Civil Engineering, Ferdowsi University of Mashhad and Faculty Member of Azad University of Mashhad, Mashhad, IRAN. e-mail: Ke_bi80@stu-mail.um.ac.ir

Esfahani, M.R.
Corresponding Author, Associate Professor, Department of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, IRAN, e-mail: Esfahani@ferdowsi.um.ac.ir

Abrishami, J.
Associate Professor, Department of Civil Engineering, Ferdowsi University of Mashhad, Mashhad, IRAN. e-mail: Abrishami@ferdowsi.um.ac.ir

INTRODUCTION

Cracks are among the most common flaws in many practical civil engineering structures. In Concrete dams the cracks are caused by various factors such as volumetric change, load application, inadequate design and construction. Therefore, assuming that no existing dam is completely without cracks, the question of whether the safety of such dam is guaranteed appears to justify.

Most of the existing dams were designed on the basis of the classical beam analysis (σ =P/A $\pm$ MC/I); such an equation only valid for "shallow beams" cannot be blindly applied to a dam without certain shear correction, and it does not recognize the singular nature of the stress at the crack tip [1-5].

In response to the challenge of evaluating older dams, recently fracture mechanics has been strongly advocated in journals as an alternative means to assess dam safety and crack stability in dams [1-6]. Further more, this approach has also been recognized as a valid approach and one that should be investigated prior to major rehabilitation of cracked massive concrete structures [1-3].

Facture Mechanics Concepts have been successfully applied to study the cracking phenomena in dams [1-6]. 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 is reported regarding the cracks at the other places such as crest of dam, corners, around the inspection galleries etc [6].

In this study six different initial cracks were placed at the region of tensile stresses during five different load cases in an existing concrete gravity dam. Then, an incremented analysis based on Linear Elastic Fracture Mechanics was performed to determine crack stability and crack trajectory. The recently developed software "FRANC2D" was used to calculate stress Intensity factor and maximum circumferential stress to compute crack stability and kinking angle of cracks. The results of this study would be useful to assess dam safety and prevent instability of concrete gravity dams.

Keywords: concrete dam, crack propagation, fracture mechanics, stress intensity factor

DAM DESCRIPTION

The ZAVIN Concrete Gravity Dam (Figure 1) is located in the northeast of Iran and was completed in 2002. The main geometric data of the ZAVIN Dam listed in Table 1 [8].

Tab. 1. Geometry of ZAVIN Dam. [8]

Dam height	51.2 m
Crest length	142 m
Crest thickness	5 m
Base thickness	53 m

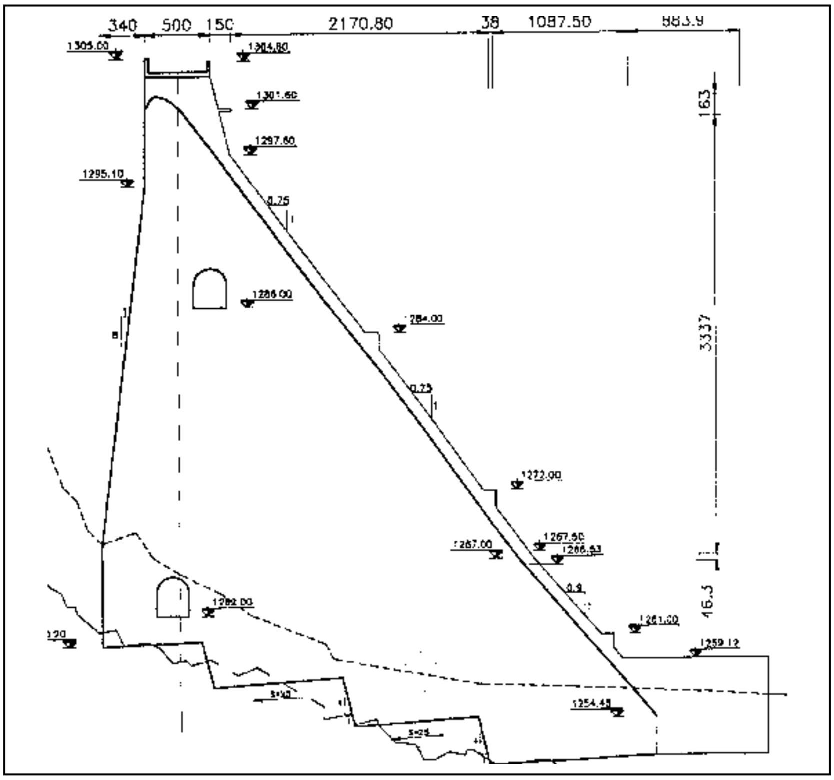

Fig. 1. Central Cross Section of ZAVIN Dam [8]

Two different kinds of finite element models were developed, one coarse discretized model and a model with finer discretization in the regions where stress concentration will occur. The finite element mesh for the dam and a sufficient portion of the foundation developed on the basis of quadratic isoparametric 8 node and Triangular 6 node elements as Table 2. A fully fixed boundary condition was assumed around the perimeter of F.E. model.

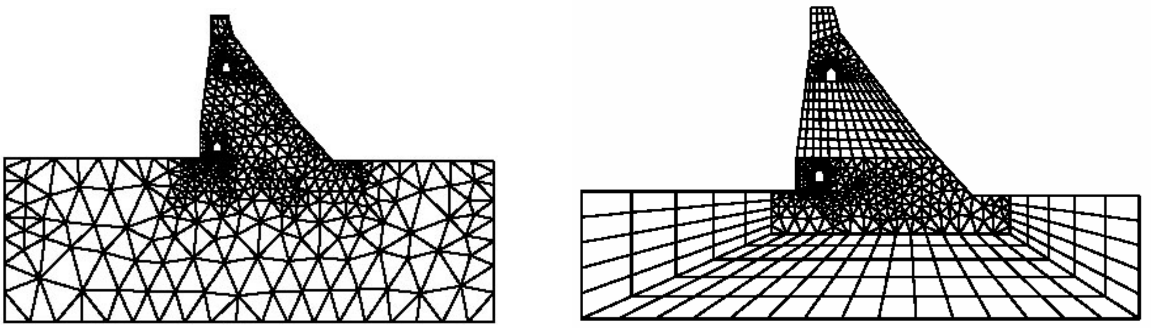

Fig. 2.F.E. Meshes for ZAVIN Dam

Tab. 2. FE Mesh discretization

F.E. Mesh	Nodes	Elements
Coarse Mesh	2100	935
Fine Mesh	2215	1042

MATERIAL PROPERTIES

The material properties adopted in the analysis are shown in Table 3. The values of parameters are obtained from the material tests at the dam site [8], except fracture toughness. Since there is no experimental data available for the fracture toughness of ZAVIN Dam, three estimated values assumed based on the other data in the literature [2, 3, 9, 10].

Tab. 3. Material properties

Material properties	Elastic Modulus (MPa)	Poisson ratio	Density (kg/m^3)	Fracture toughness (MPa $\sqrt{m}$)
Concrete	2100 [8]	0.17 [8]	2400 [8]	1.05 [3,5] 2.3 [2]
Rock	4200 [8]	0.2 [8]	-	0.81 [9,10]
Interface	2100 [4]	-	-	0.3 [10] 0 [3] 2.3 [2]

For the rock foundation and dam concrete, an isotropic and homogeneous behavior was assumed. The rock was assumed as massless during analysis steps and contact elements used in the interface between dam and foundation.

LOAD APPLICATION

For this model five different loading situations were analyzed to assess the dam safety. Load combinations were considered according to the USBR (1976)[1] and MOPU (1967)[2] as follow [2,11]:

Tab. 4. Load Cases

Load Combinations	Load cases
Usual Load Combination	Self-weight + Hydrostatic Pressure at normal water level + Uplift Pressure (USBR Method)+ Internal Crack Pressure
Unusual Load Combination	Self-weight + Hydrostatic Pressure at maximum water level + Uplift Pressure (USBR Method)+ Internal Crack Pressure
Extraordinary Maximum Water Level	Self Weight + Hydrostatic Pressure at 5% more than crest level+ Uplift Pressure (USBR Method)+ Internal Crack Pressure
Earthquake Load Combination (Full reservoir)	Self-weight + Hydrostatic Pressure at normal water level + Uplift Pressure (USBR Method) + Inertial Forces induced by Earthquake (Pseudo-static Method) + Hydrodynamic Pressure
Earthquake Load Combination (empty reservoir)	Self-weight + Inertial Forces induced by Earthquake (Pseudo-static Method)

ANALYSIS

The analysis was performed with a finite element special purpose software, (FRANC2D) in 2D plain strain Condition [9, 12]. The model was analyzed by dynamic relaxation solver, because of using contact element in rock/concrete interface, which was the only source of nonlinearity [12]. So, a linear elastic material model coupled to a linear elastic discrete fracture model was used in this analysis.

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[1] United states Bureau of Reclamation
[2] Spanish Instruction for Large Dams

Although for crack propagation in quasi-brittle material Nonlinear Fracture Mechanics, (NLFM) should be used in large structures, such as dams, because of the smaller size of fracture process zone at the crack tip with respect to the structure size, limited errors should occur under the assumption of linear elastic fracture Mechanics [1,2,3,6,7].
In order to study the dam stability and simulate crack growth, initial non-cohesive cracks were placed at the regions where the critical stresses would occur (Figure 3).
Having specified the location of cracks, FRANC2D was able to automatically propagate the cracks and remesh around the cracks after each step [12]. The code computes stress Intensity factor (SIF) as crack propagation criteria on the base of LEFM and the kinking angle of the crack based on the maximum circumferential stress criteria. Prior to performing the analysis, it was necessary to specify the magnitude of crack increment and also the number of steps over which the crack would propagate. Finally, the SIF history versus crack length was plotted and crack stability was known comparing SIF with fracture toughness.

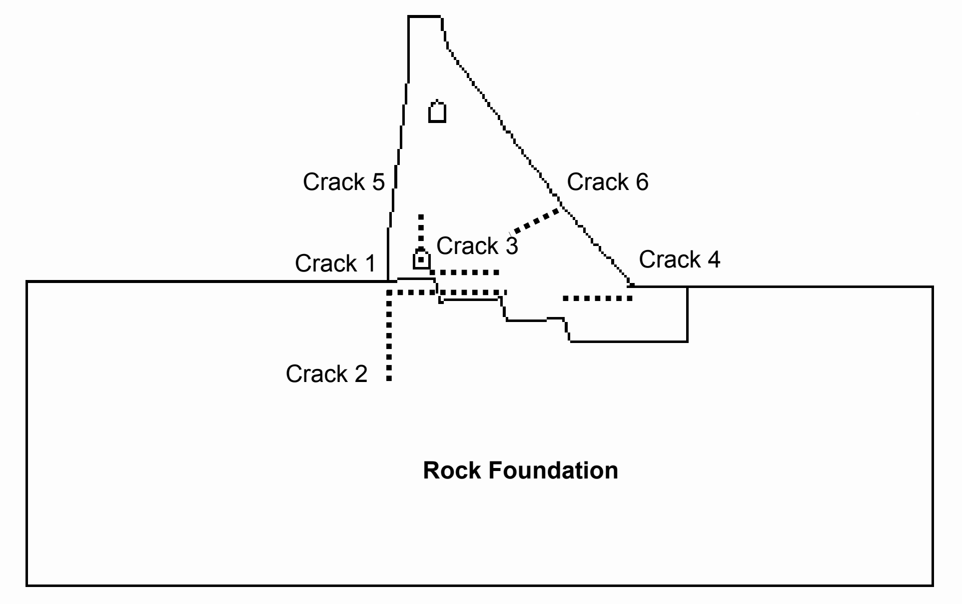

Fig. 3. Initial cracks in the dam body and foundation

PRIMARY RESULTS

First Load Combination (usual load)

Crack No.1 was placed at the upstream boundary of the dam/foundation interface. The crack growth was simulated over 10 steps of increment where each increment was 2 meters as suggested in Ref. [12]. Figure 4 shows the propagated crack No.1 and variation of KI with crack length, respectively.

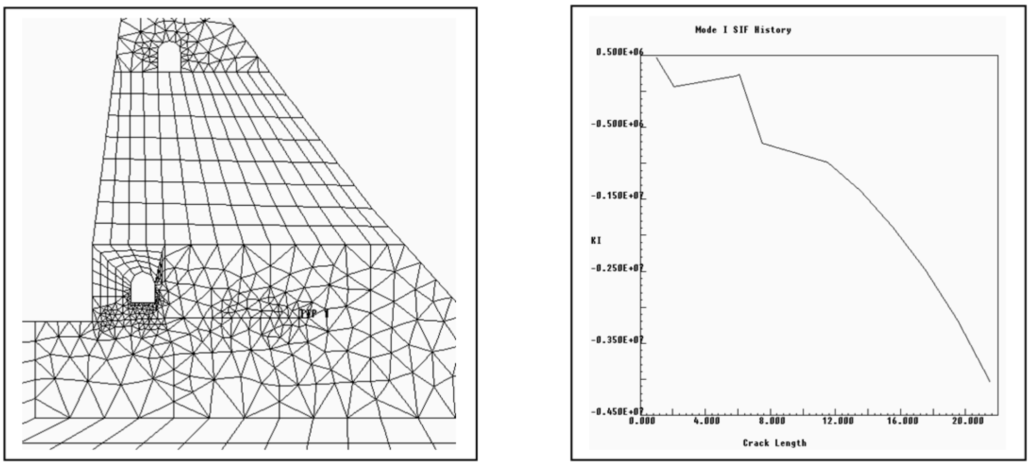

Fig. 4. Propagation of crack No.1 and its SIF history (usual load)

Table 4 shows the predicted final length of crack No.1 using the traditional criterion that crack propagation is in unstable manner when the KI reaches its critical value (KIc). So crack No.1 will propagate just 15% of the dam width.

Tab. 5. Final length of crack No.1 (usual load)

Fracture Toughness of Interface	Final length of Crack No.1
KIc=0.3E6 $Pa\sqrt{m}$	1.8m
KIc=0	6.2m
KIc=2.3E6 $Pa\sqrt{m}$	Not Propagated

Crack No.2 which was placed at the upstream heel, propagated over 10 steps by 2 meters increment toward the rock foundation. Figure 6 shows the propagated crack No.2 and SIF history, respectively. This crack will propagate 14.8m toward the rock foundation.

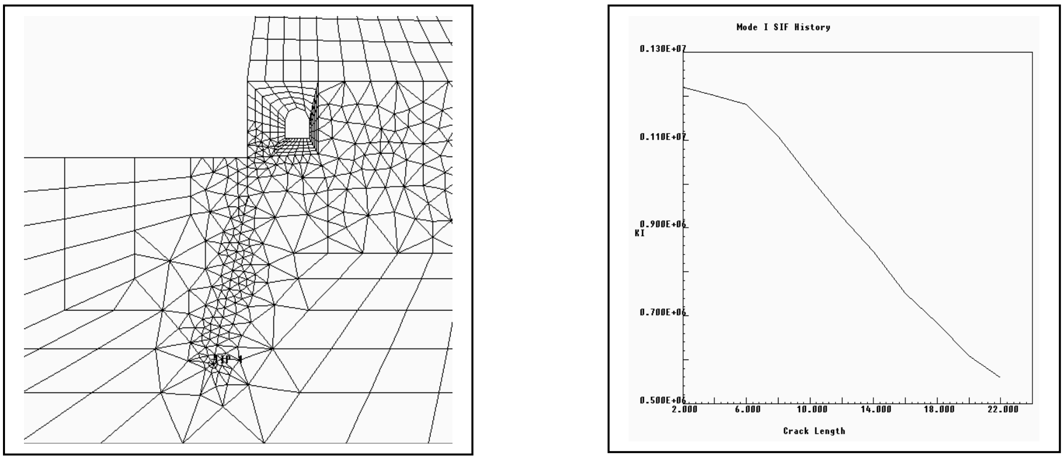

Fig. 5. Propagation of crack No.2 and its SIF history (usual load)

Second Load Combination (unusual load)

In this situation crack No.1 predicted to propagate 20% of the dam width if the lowest fracture toughness is used as shown in Table 6.

Tab. 6. Final length of crack No.1 (unusual load)

Fracture Toughness of Interface	Final length of Crack No.1
KIc=0.3E6 $Pa\sqrt{m}$	6.8m
KIc=0	8m
KIc=2.3E6 $Pa\sqrt{m}$	Not Propagated

Crack No.2 propagated 16.5 meters toward the foundation. It was seen that the higher water level in reservoir causes more kinking of this crack.

Third Load Combination (Extraordinary load)

This load case is similar to the two latest load cases. Cracks No.1 propagated as mentioned in Table 7 and crack No.2 propagated 19.6 meters toward the rock foundation.

Tab. 7. Final length of crack No.1 (Extraordinary load)

Fracture Toughness of Interface	Final length of Crack No.1
KIc=0.3E6 $Pa\sqrt{m}$	11.6m
KIc=0	14.5m
KIc=2.3E6 $Pa\sqrt{m}$	Not Propagated

Forth Load Combination (Earthquake[1] in full reservoir)

In this load case, three expected initial cracks were studied. Crack No.1 at the upstream heel propagated as shown in Table 8. Table 8 indicated that crack No.1 was extended more than 2/3 of the base width. So, ZAVIN Dam will be unstable in this load case.

Tab. 8. Final length of crack No.1 (Earthquake load in full reservoir)

Fracture Toughness of Interface	Final length of Crack No.1	
	Acceleration 0.2g	Acceleration 0.3g
KIc=0.3E6 $Pa\sqrt{m}$	More than 25 meters	More than 25 meters
KIc=2.3E6 $Pa\sqrt{m}$	More than 25 meters	More than 25 meters
KIc=0 $Pa\sqrt{m}$	More than 25 meters	More than 25 meters

Crack No.2 at the upstream was propagated toward the foundation and its final length would be more than 22 meters. Finally, crack No.3, which was placed at the bottom of the lower inspection gallery, propagated over 4 steps of 2 meters increment. Figure 9 illustrated the final profile of the crack and Table 9 shows the final length of this crack.

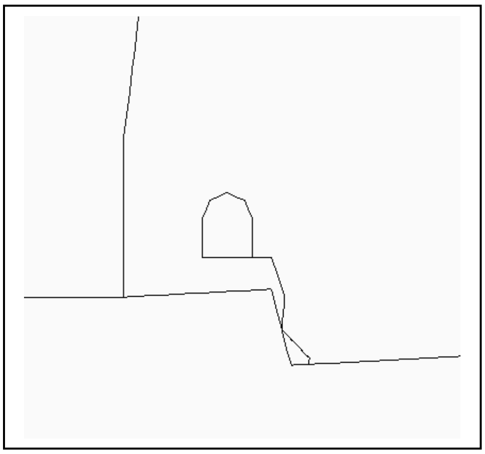

Fig. 6. Propagation of crack No.3 (Earthquake load in full reservoir)

Tab. 9. Final length of crack No.3 (Earthquake load in full reservoir)

Fracture Toughness of Concrete	Final length of Crack No.3	
	Acceleration 0.2g	Acceleration 0.3g
KIc=1.05E6 $Pa\sqrt{m}$	Not propagated	Not propagated
KIc=2.3E6 $Pa\sqrt{m}$	Not propagated	Not propagated

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[1] Magnitue of earth acceleration in the region of dam constructed was assumed according to the Iranian Earthquake Code (2800, Rev.2) [13]

Fifth Load Combination (Earthquake in empty reservoir)

In this case, regarding the critical direction of earthquake, three expected initial cracks were propagated.
Crack No.4 which was placed at the downstream toe of dam, propagated over 4 steps. Figure 7 illustrated the final profile of the crack and Table 10 shows its final length.
Crack No.5 was placed at the downstream face of the dam, where the body slops changed. This crack propagated over 9 steps as show in Figure 8 and the final length of this crack is shown in Table 11.
Crack No.6 was placed at the roof of the upper inspection gallery and propagated over 5 steps as shown in Figure 9. Results indicated that SIF for this crack is lower than the concrete fracture toughness, so this crack is stable and would not propagate.

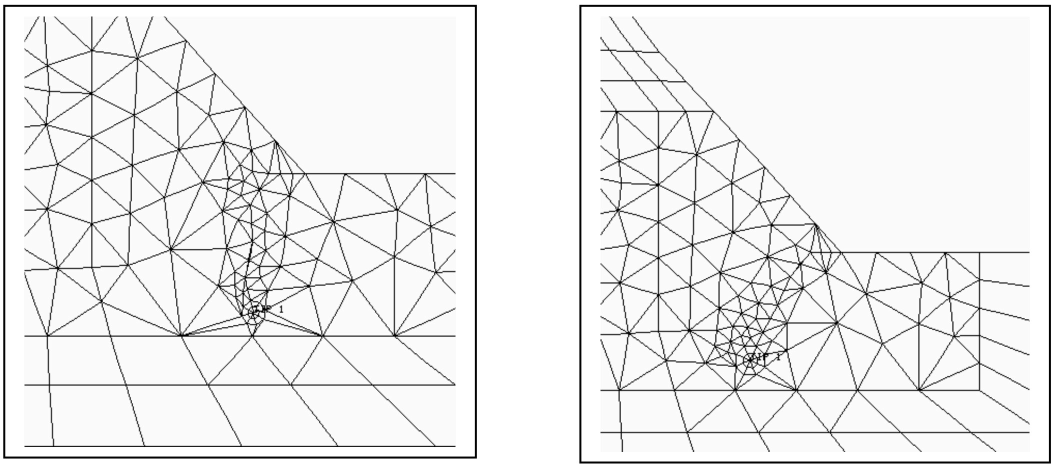

Fig. 7. Propagation of crack No.4 by earth acceleration 0.2g (left one) and acceleration 0.3g (right one), for earthquake load in empty reservoir

Tab. 10. Final length of crack No.4 (Earthquake load in empty reservoir)

Fracture Toughness of Concrete	Final length of Crack No.4	
	Acceleration 0.2g	Acceleration 0.3g
KIc=1.05E6 $Pa\sqrt{m}$	Not propagated	Not propagated
KIc=2.3E6 $Pa\sqrt{m}$	Not propagated	Not propagated

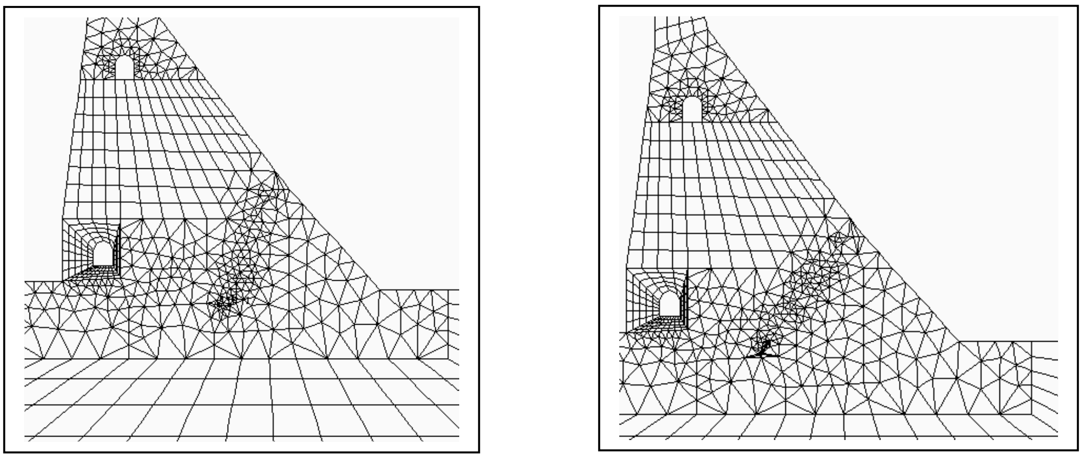

Fig. 8. Propagation of crack No.5 by earth acceleration 0.2g (left one) and acceleration 0.3g (right one), for earthquake load in empty reservoir

Tab. 11. Final length of crack No.5 (Earthquake load in empty reservoir)

Fracture Toughness of Concrete	Final length of Crack No.5	
	Acceleration 0.2g	Acceleration 0.3g
KIc=1.05E6 $Pa\sqrt{m}$	Not propagated	6m Crack Will Propagate to 14m
KIc=2.3E6 $Pa\sqrt{m}$	Not propagated	Not propagated

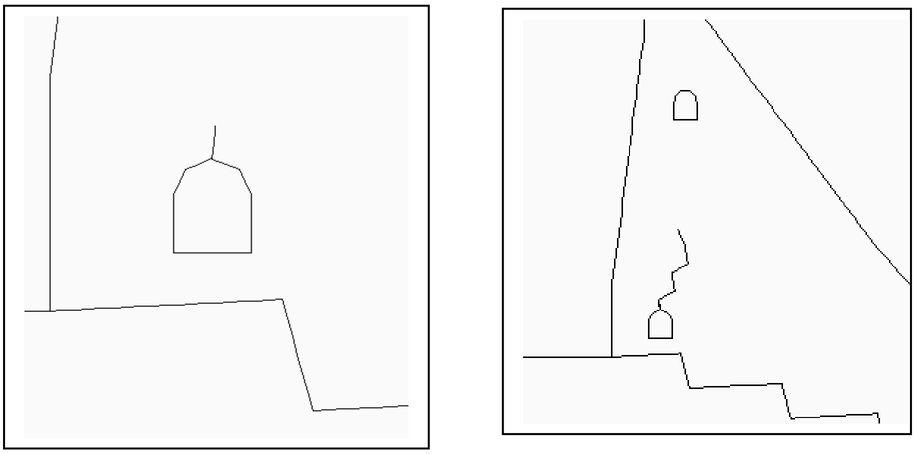

Fig. 9. Propagation of crack No.6 (earthquake load in empty reservoir)

CONCLUSION

An attempt was made to study the behavior of six predicted initial cracks lying at several places in the dam body and foundation of an existing concrete gravity dam "ZAVIN", using the concept of Linear Elastic Fracture Mechanics. The dam was analyzed by FRANC2D software under five load conditions and the following observations could be drawn:

1. In usual, unusual and extraordinary load combinations, the horizontal crack at the heel of dam will propagate 15%, 20% and 33% of the dam width, respectively.
2. In extreme load combination (empty reservoir), the initial cracks will not propagate. Therefore, ZAVIN dam is stable for this condition.
3. In extreme load combination (full reservoir), the initial heel crack will propagate more than 2/3 of the dam width, leading to complete separation of the dam base.
4. In extraordinary and extreme load combination (full reservoir), the initial vertical crack will propagate more than 25 meters toward the foundation. This major crack increases seepage from the reservoir and causes sliding instability.

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