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Seismic Stability Analysis of the Cracked Concrete Gravity Dams

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ABSTRACT

In recent decades, the issue of seismic safety of concrete dams has attracted a lot of attention. One reason for this is that the plans have become economic and also the life span of the existing dams is increased. Thus in the engineering community there is a great interest in developing and applying a powerful process for nonlinear analysis and as much as possible close to reality of concrete dams under different loads especially dynamic loads generated by earthquakes. In the present article Zavin Dam is modeled and nonlinear dynamic analysis of concrete gravity dams is conducted with regard to interaction between dam, lake and foundation. Also the smeared crack model is applied for the nonlinear analysis of concrete gravity dams and analyzing the position and direction of cracks is used. In this study the nonlinear dynamic analysis of the effects of three different earthquakes with the same PGA of about 0.5g and different frequency content is performed and the dynamic interaction between the dam-lake is modeled by the rust method. For nonlinear modeling of concrete in nonlinear dynamic analysis the Drucker- Prager failure criterion has been used. After performing dynamic analysis on Zavin Dam in the presence of crack the vertical and horizontal displacement values of the crest, the main tensile stress at the end of the crack and the values of plastic strain are obtained along x and y. The results show that the concrete tensile cracking is an important nonlinear factor in dam behavior. Reducing the amount of frequency in nonlinear dynamic response of the dam after cracking indicates that as a result of plasticity of some elements the dam hardness is reduced and its displacement increases.
KEYWORDS: concrete gravity dam, displacement, tensile stress, crack progress, nonlinear dynamic analysis.

INTRODUCTION

Dam Building industry has started with modern methods using dams with large scales about three decades ago in Iran. Study and design of large dams started around the year 1948 and their construction began in late 1950s and entered a new era with the advent of the Iranian Islamic revolution and the country's water industry has been aimed at being self-efficient in this ground. The most important factor in reducing the useful life of a concrete dam is water settlement and one of the major causes of water settlement is cracking of concrete. As a result, it is necessary to attempt to prevent cracks in parts of the structures that are exposed to water pressure and consider the risk of cracks. Therefore, when preparing the concrete mix design the construction and operation of the dam and during the construction and development, usually conventional cracks in the concrete dams and methods of prevention of such cracks in such structures are discussed. One of the most important risks that threaten the stability of a concrete dam and may also lead to the failure of the dam and endanger many lives is the cracks in the concrete dam body and its development in various directions. These cracks cause by water infiltration into the dam body and through creating additional pressure within the body lead to the growth of the cracks downwards and will finally lead to the slipping of the isolated parts of the dam. To familiarize with the cracks it should be noted that the physical and mechanical properties of concrete and its composition and behavior play a very important role at the time of cracking, the type of cracks and how it is spread.

REVIEW OF THE LITERATURE

Research conducted to predict the cracks' expansion in concrete gravity dams is restricted to the cracks at the junction of the dam to foundation. In the concrete gravity dams for the crack considered at the dam to the foundation area there is linear elastic failure mechanical conditions (LEFM) because the length of the damaged area of the tip of crack will be small compared to the dimension of the structure and it will be negligible. With concrete dams' aging and the progress in human societies, the need for safety analysis of the dams is felt more than before. In this regard in recent years great efforts are made in modeling the nonlinear behavior particularly under seismic loads and several models are provided for the non-linear behavior and using them the non-linear behavior of the concrete dams is evaluated under the static and seismic loads. Modeling the cracks' profiles in concrete dams under static and heat loads has attracted the attention of some investigators. In the field of the non-

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linear behavior of dams during earthquakes it is possible to refer to USCOLD publications [1]. In the study of seismic behavior and predicting cracks in dams it is possible to indicate the work of Chopra et al (1972) as the first step in which using the linear elastic analysis the situations in which cracks may appear are specified. In this study gravity dams of Koyna in India and Pine flat In the United States are studied regardless of the effect of interaction between the lake and foundation under the Koyna earthquake (1967). The first nonlinear FEM analysis was performed by Pal on concrete gravity dams. In this study Koyna Dam is analyzed regardless of the lake and assuming a solid foundation using the expanded crack model to simulate the progress of the crack with the fracture resistance of materials criterion. Some researchers have applied a combination of continuous, CCPM and discrete models for the seismic analysis of gravity dams [3]. In this study the equivalent tensile strength measure is used for the onset and expansion of cracks in which the crack expands on a plate perpendicular to the main tensile stress. Among the studies in which the discrete crack model is used include the work presented by Tinawi and Guizani (1994) in which the hydrodynamic pressure inside cracks has been investigated on the seismic response of concrete dams.

Smeared crack model for static and dynamic analysis of concrete dams in two dimensional space

Smeared crack model is one of the models that is widely used for two-dimensional static and seismic analysis of concrete gravity dams because the use of this model is simpler than other methods and is associated with fewer problems. Smeared crack model is also used for nonlinear analysis of concrete gravity dams and analyzing the position and orientation of cracks. In all nonlinear models and analyses presented in this study the strain tensile stresses and strains are numerically positive. The stress and strain relationship in materials is generally similar to equation (1). In this relationship [D] is the elastic modulus matrix, {σ} is the stress components' vector and {ε} is the strain components' vector.

$$\{\sigma\} = [D]\ \{\varepsilon\} \qquad (1)$$

Given the planar stress and isotropic linear behavior cracking matrix [D] will be based on the equation (2). Where: E is the modulus of elasticity and υ is dam's concrete's Poisson's ratio.

$$[D] = \frac{E}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \qquad (2)$$

In the Smeared crack model energy criterion is a proper criterion for the diagnosis of the onset of failure process. In the energy criterion the area under the uniaxial stress - strain curve according to equation (3) to the concrete peak strength is considered as the index for the crack initiation. In this equation $\sigma_i$is the apparent tensile strength. The concept of apparent tensile strength is presented in Figure (1-a).($\sigma_1$and ε_1 respectively stress and strain, main element.)

$$U_0 = \int_0^{\varepsilon_t} \sigma\, d\varepsilon = \frac{\sigma_0 \varepsilon_0}{2} \qquad (3)$$

In the nonlinear analyses it is assumed that cracking starts when the strain energy density $\frac{\sigma_1 \varepsilon_1}{2}$ is equal or higher than the parameter U_0 based on the equation (4):

$$\frac{\sigma_1 \varepsilon_1}{2} = U_0 = \frac{\sigma_i^2}{2E} \text{ ؛ } (\sigma_1 > 0) \qquad (4)$$

Under seismic loads parameter U_0 with a constant dynamic gain coefficient DMF_e (Dynamic Magnification Factor) is as follows:

$$U_0' = \frac{\sigma_i'^2}{2E} = DMF_e^2\, U_0 \qquad (5)$$

Where: the parameters with Prim indicate the dynamic parameters. Under seismic loads the parameter U_0 in equation (5) is replaced with the corresponding dynamic value of $U_0^{'}$. Similarly, under dynamic loads the main tensile stress σ_1 and strain ε_1 are replaced by $\sigma_0^{'}$and $\varepsilon_0^{'}$ as presented in Figure (1- b). In this study, the soft stress - strain curve section of the concrete is considered as linear. In order to fulfill the principle of failure energy conservation the softening slope of the curve is set in such a way that the dissipated energy remains constant per unit area [13].

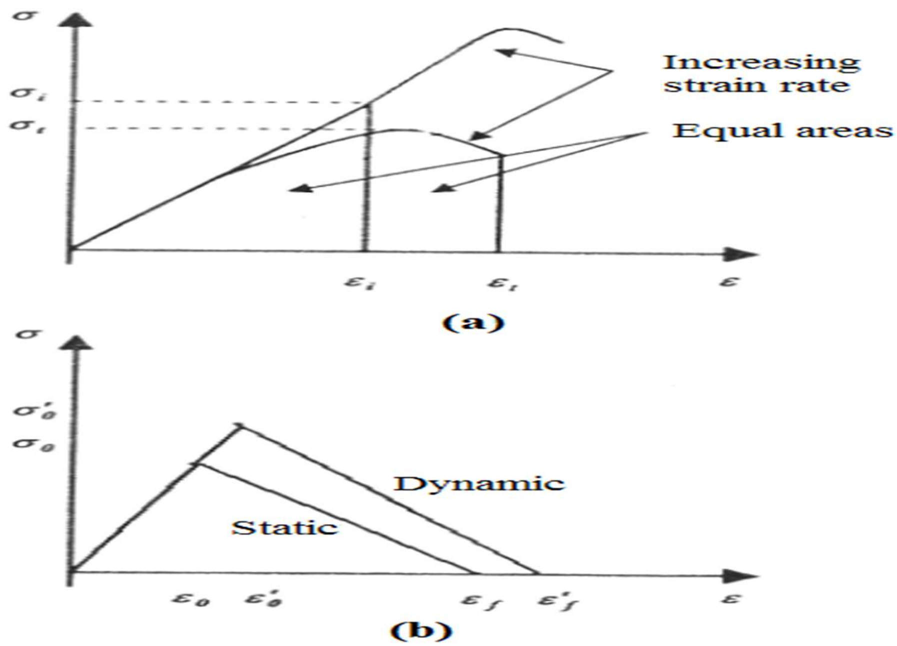

Figure (1): Non-linear stress-strain relationship near the peak stress and dynamic loading effect on various parameters [13]

Zavin Kalat concrete gravity dam

The dam is located at 95 kilometers northeast of the city of Mashhad and Kalat and 1.5 kilometers from the Olia village at a place called Doabi on a River called Zavin as one of the main streams of the Qarah Tikan border river. The dam has a height of 51.2 meters from the foundation and the crest length of 132 meters. Lavin Dam lake capacity in maximum level is 3000000 cubic meters and 2690000 cubic meters at normal level. The dam is capable of setting more than three million cubic meters of water for agricultural purposes. The regulated water is capable of irrigating more than 440 hectares of up and down Lavin village lands. This river is a permanent river and its runoff is 8.1 million cubic meters annually. Zavin dam on this river is designed to save the river to supply water for agricultural lands near water, coastal villages, drinking water and industrial estate [11]. Figure (2) presents Zavin concrete gravity dam in the city of Kalat.

Figure (2): The image of Zavin concrete gravity dam in the city of Kalat

The basic applied numerical methods

In this study predicting the life span of the cracks and the two-dimensional modeling of the crack growth is done by the Abaqus using the finite element methods. Abaqus software is a set of engineering simulation software programs based on the finite element method which is able to solve a wide range of engineering problems from the simple linear to the complex nonlinear simulations. Abaqus has an extensive library of different types of elements as well as a wide collection of models of different materials for modeling most common engineering materials. This software is capable of performing the structural analyses (stress/displacement) as well as thermal, electric soil mechanics, and mass transfer and the interaction analyses such as structure-fluid interaction. In the nonlinear analyses Abaqus has automatically selected loading and convergence tolerance and sets them continuously so that a detailed response is obtained.

MATERIAL AND METHODS

In the present study Abaqus program is used for modeling and analysis of concrete gravity dam. In this study the analyses are conducted on Zavin Dam. This dam is a concrete gravity dam. Table (1) shows the elastic properties of concrete used in dam construction:

Table (1): The elastic properties of concrete used in body and dam foundation [11]

Concrete specific weight	**2400($\frac{kg}{m^3}$)**
Concrete compressive strength	200($\frac{kg}{cm^2}$)
Modulus of elasticity of concrete	15100($\frac{kg}{cm^2}$)
Tensile strength of concrete	2.1e5($\frac{kg}{cm^2}$)
Poisson's ratio	0.17
Concrete failure energy	100($\frac{N}{m}$)
Saturated specific weight of bedrock	2660($\frac{kg}{m^3}$)
Modulus of elasticity of the bedrock	4.2e5($\frac{kg}{cm^2}$)
Poisson's ratio of the bedrock	0.2

The loads applied on the structure in modeling Zavin dam include the gravity load of the body, hydrostatic water pressure in normal mode (normal level) and flood (maximum level), sediments pressure, uplift pressure, hydrodynamic pressure and seismic forces on the dam body. To perform the body and dam foundation loading the specific weight presented in Table (1) is used. In this loading the weight of the peripheral equipment such as valves is ignored. The total mass of the dam body at the depth unit is 2812800 kg and the total mass of dam foundation at the depth unit is1, 634,676.4 kg. According to the Water normal level (1302 m) the hydrostatic pressure of each point at the upstream is calculated according to its height. For loading the earthquake in the dynamic analysis of the dam the horizontal component (longitudinal) of three earthquakes is used. Japan's Kobe earthquake with PGA = 0.503, USA's Loma earthquake with PGA =0.501 and Aryzkan Turkey's earthquake with PGA = 0.496; Zavin dam is dynamically analyzed under these earthquakes.

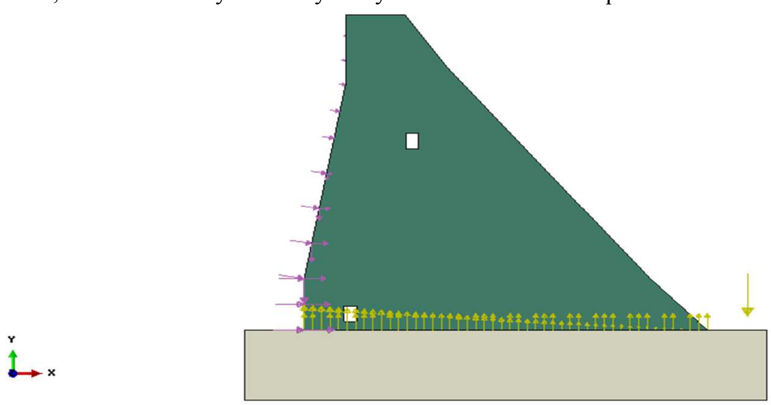

Figure (3): Different loading mode of Zavin concrete gravity dam

Finite element model

Abaqus is general software based on Finite element method (FEM) and it is one of the most powerful software programs in general areas. The static and dynamic analyses of the materials are done by this software in Zavin dam. The correct meshing and choosing the right elements are the most important steps in finite element analysis. The dimensions and type of meshing depend on the type of analysis, modeling and the accuracy of the output results. For example the size of the elements in the nonlinear analysis is usually much smaller than linear analysis. In finite element analysis usually by reducing the size of the elements the accuracy of the results is increased but this increases the number of elements and their analysis time exponentially. In order to model the body and the foundation of the dam Abaqus Software and for meshing the body and foundation the SOLID 4node CPS4R element is used. In the area near the contact area of the dam and foundation, where there is the possibility of cracking and cracking is considered, the smaller element is used to both prevent the cracking of the element and after cracking its stress distribution to the adjacent elements is managed properly.

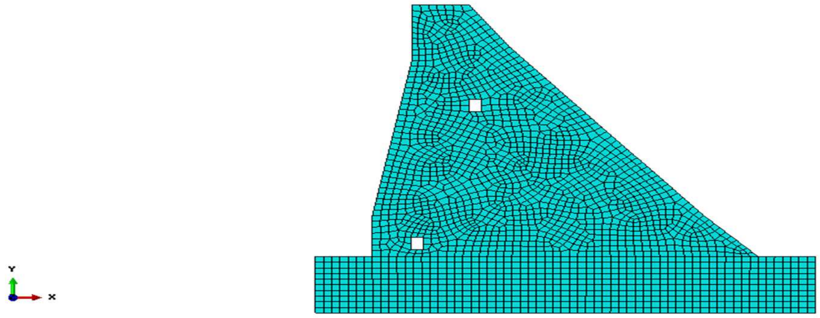

Figure (4): Meshing by finite element analysis of Zavin concrete gravity dam

The method of modeling the effect of lake's hydrodynamic pressure on the dam response to the earthquake
Vibrations caused by earthquakes can cause tremors and movement in the dam and its foundation towards the reservoir and the water in it is applies its additional pressure by its inertia against this motion. The exact determination of the hydrodynamic pressure distribution curve and its value is difficult for various reasons and then usually the simple methods are used to estimate the hydrodynamic pressure, the resultant force and the moment cause by it. Different studies such as Zangar (1975) show that the hydrodynamic pressure distribution caused by earthquake on the dam is almost parabolic (semi-parabolic semi-elliptical) Figure (5) and the following equation can be used to find the pressure intensity level used for each section to a depth z [12]:

$$P_{ez} = C_e \alpha_h \gamma_w . h \qquad (6)$$

Where: α_h is the horizontal earthquake acceleration coefficient to the gravity acceleration, h is the water level at the section under study (from the bottom to the water level), γ_w water specific weight and $C_e$is dimensionless coefficient which depends on the water height, upstream slope of the dam body and the Z value which is obtained by the following equation:

$$= \frac{c_m}{2}\left[\frac{z}{h}\left(2-\frac{z}{h}\right)+\sqrt{\frac{z}{h}\left(2-\frac{z}{h}\right)}\right] \qquad (7\ )C_e$$

Where: c_m is the maximum C_e obtained as follows:

$$c_m = 0.735\left(\frac{90-\emptyset}{90}\right) \qquad (8)$$

$\emptyset$ is the angle between the upstream side and the vertical line. According to the above equations the hydrodynamics force is calculated at each point.

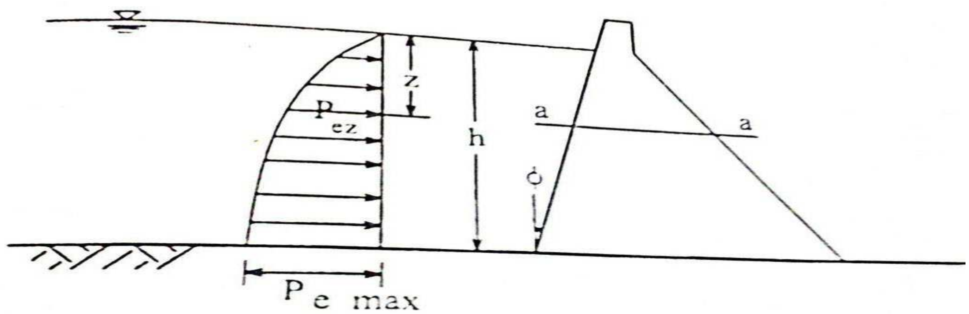

Figure (5): Distribution of hydrodynamic pressure on Dam [12]

Table (2): The values of hydrostatic and hydrodynamic pressures at different levels

Level	Hydrostatic pressure (pa)	hydrodynamic pressure (pa)
51.2	0	0
50	11772	975.6
45	60822	4946.36
40	109872	6269.76
35	158922	7218.72
30	207972	8000.88
25	257022	8677.44
20	306072	9278.88
15	355122	9846.40
10	404172	10365.92
5	453222	10847.76
0	502272	11304.96

***Hydrodynamic pressure is obtained by the rust formula.**

DISCUSSION

In designing the concrete dams usually the tensile strength of concrete is ignored except in specific areas of the dam that limited tensile stresses can be accepted according to the designer. If the tensile strength exceeds the allowable tensile strength, the concrete cracks and the crack continues to the point that the tensile strength is equal with the allowable tensile strength. In this study the tensile strength of concrete used is considered as the crack initiation criterion. If the static loads are increased the maximum stress appears in the dam bottom and there is the possibility of cracking here. Usually modal analysis is the starting point of dynamic analysis for determining the structural response against dynamic loads in which the natural frequencies and vibration modal form of the system are determined. In this study before performing the dynamic analyses the modal analysis and parameters are considered to determine the attenuation coefficients.

RESULTS

The progress of crack in the downstream dam body

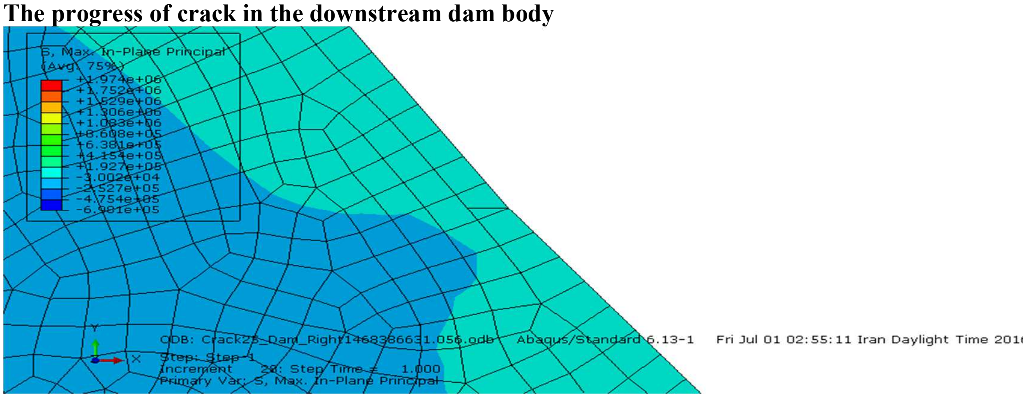

Figure (6): stress distribution around the cracks in the downstream dam body with the length of 25 cm

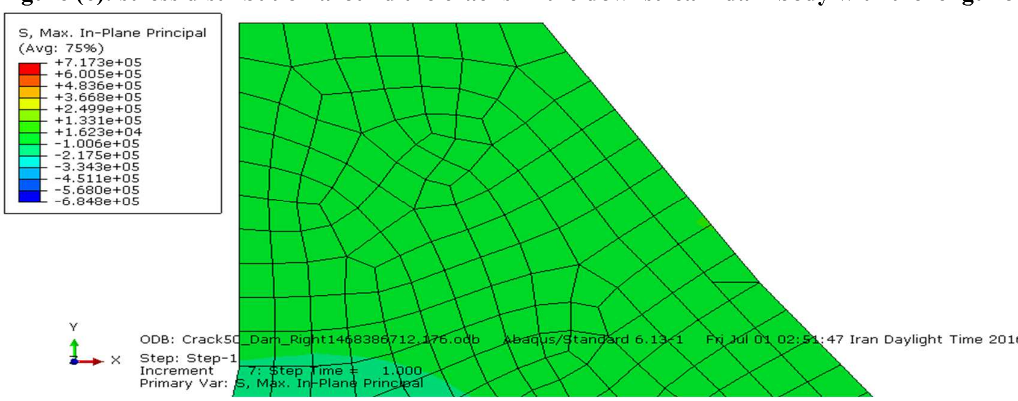

Figure (7): stress distribution around the cracks in the downstream dam body with the length of 50 cm

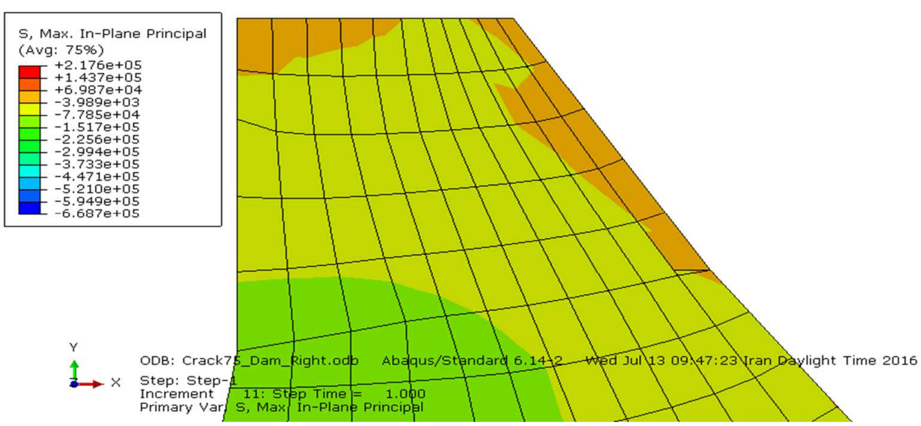

Figure (8): stress distribution around the cracks in the downstream dam body with the length of 75 cm

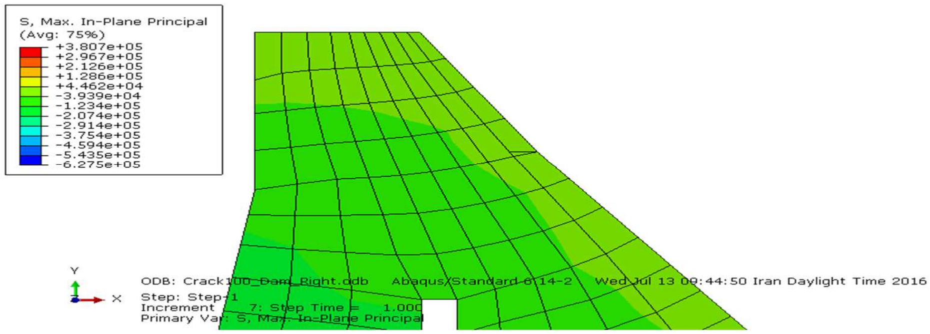

Figure (9): stress distribution around the cracks in the downstream dam body with the length of 100 cm

According to the stress distribution in the downstream the length of the crack is considered as 1m.

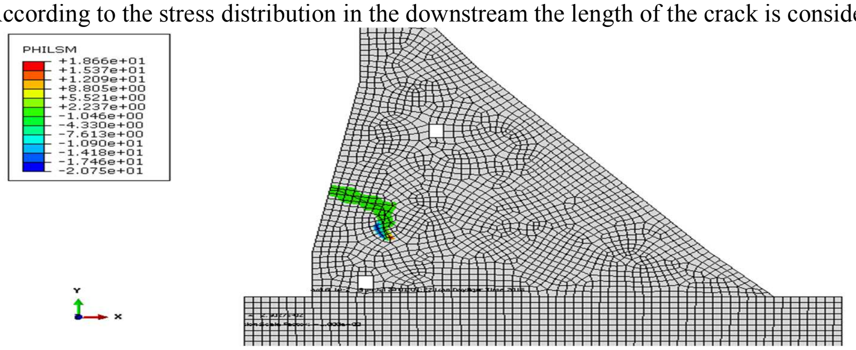

Figure (10): Final development of cracks in the upper body of the dam under Aryzkan earthquake

Modal analysis

Table (3): The results of modal finite element analysis of Zavin dam with and without cracks

Frequency without crack ($\frac{cycles}{time}$)	9.4795	18.126	20.637	27.794
Frequency with crack ($\frac{cycles}{time}$)	9.3894	18.004	20.373	27.349

Modal analysis of concrete gravity dam with crack

The results of modal analysis of Zavin concrete gravity dam are as follows:

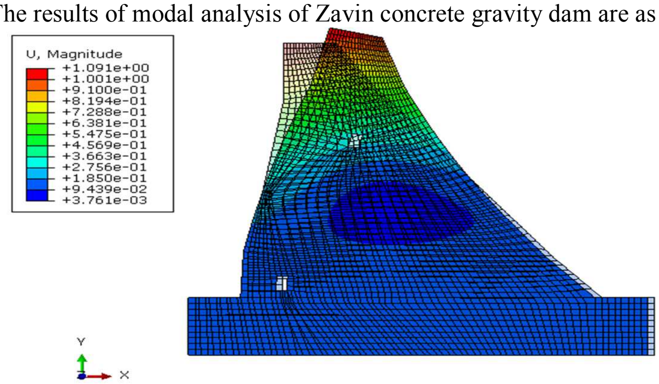

Figure (11): The first mode shape with the Frequency 9.3894 HZ and period 0.1065 (sec)

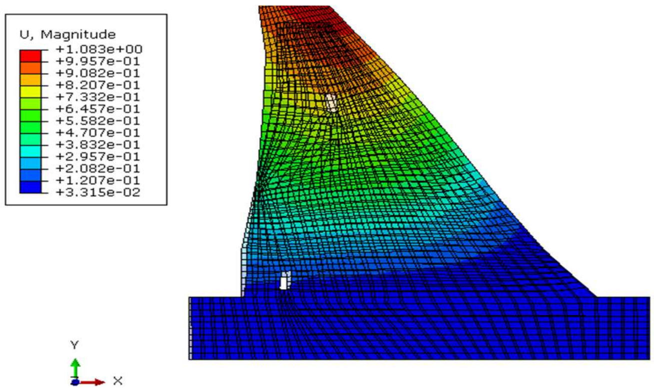

Figure (12): The Second mode shape with the Frequency 18.004 HZ and period 0.0555 (sec)

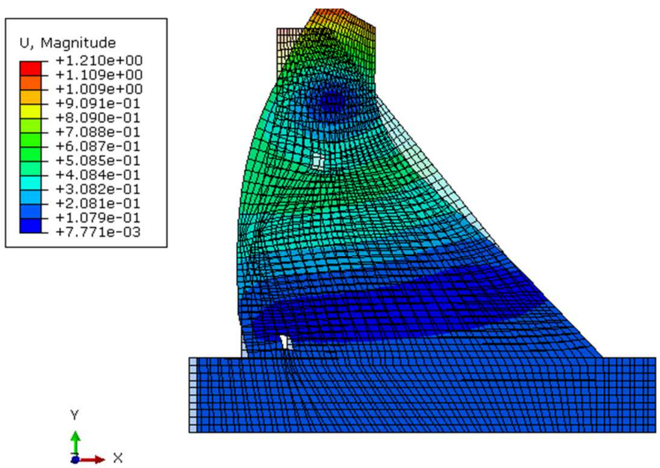

Figure (13): The Third mode shape with the Frequency 20.373 HZ and period 0.0491 (sec)

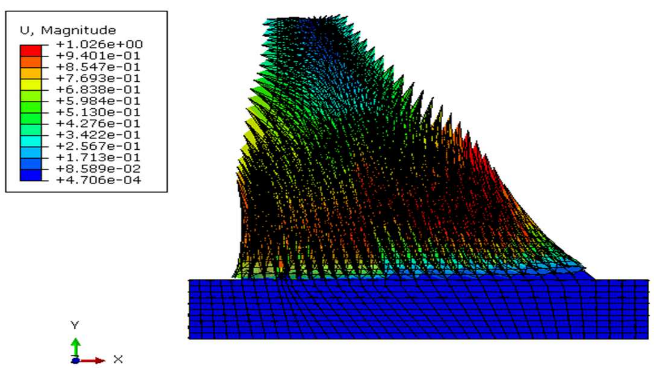

Figure (14): The Fourth mode shape with the Frequency 27.349 HZ and the period 0.0366 (sec)

Nonlinear Dynamic Analysis

For loading the earthquake in the dynamic analysis of the dam the horizontal component (longitudinal) of three earthquakes is used. Japan’s Kobe earthquake with PGA = 0.503, USA’s Loma earthquake with PGA =0.501 and Aryzkan Turkey's earthquake with PGA = 0.496.

The results of nonlinear dynamic analysis of Zavin dam with crack under the effects of the earthquakes are listed as follows:

Table (4): Maximum main tensile stress at the end of crack in non-linear response of Zavin dam under different earthquakes

Effective earthquakes	The maximum tensile stress at the end of crack in the nonlinear response (Mpa)
Kobe Earthquake	4.4663
Loma earthquake	2.7416
Aryzkan Earthquake	2.0153

Table (5): The results of nonlinear dynamic analysis of Zavin dam under Kobe earthquake

Kobe earthquake	Non-linear response of the dam without crack	Non-linear response of the dam with crack
The maximum horizontal displacement of dam crest (m)	0.3937	0.0225
The maximum vertical displacement of dam crest (m)	0.1125	0.0238
Maximum plastic strain in the direction of x at the tip of the crack	------------------------	0.0326
Maximum plastic strain in the direction of y at the tip of the crack	-------------------------	0.1391

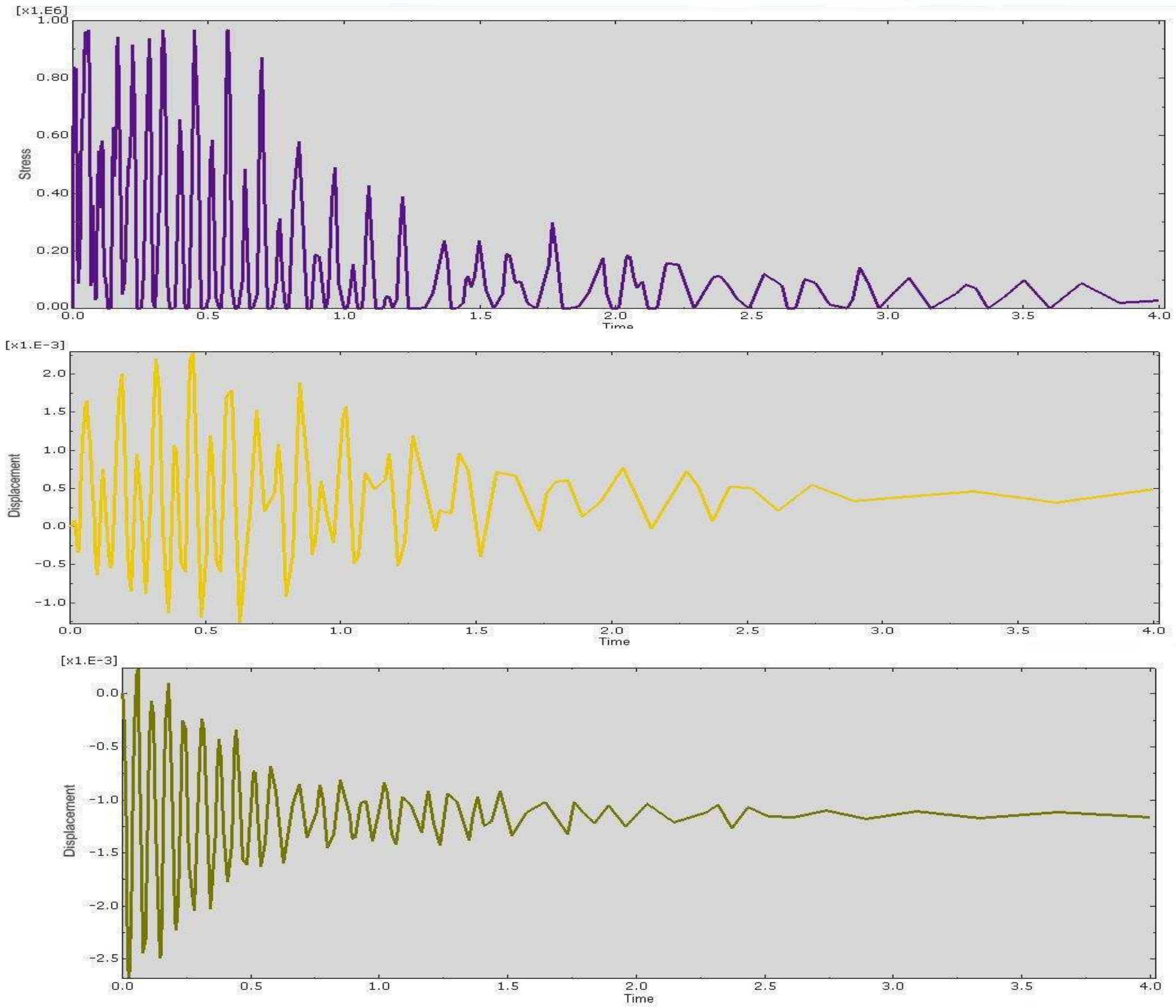

Figure (15): The time history of stress in dam heel, horizontal and vertical crest displacement under Kobe earthquake

CONCLUSION

In this study the nonlinear dynamic analysis of Zavin dam is done under three different earthquakes with PGA of about 0.5g using Drucker- Prager failure criterion for nonlinear modeling of concrete and the rust method is used to model the dynamic interaction between the dam and reservoir. The results of this study may be summarized as follows:

1. Reservoir sediments have a huge impact on earthquake energy absorption and dynamic response of the system through the absorption of hydrodynamic compressive waves' energy absorption and response reduction of the system under the vertical ground acceleration and this is also important for the ground horizontal acceleration.
2. The reservoir depth has a significant impact on dam system response and this response is higher in the response to the vertical component than the response to the horizontal component.
3. Reducing the frequency of dynamic response in nonlinear mode with cracking indicates that as the result of plasticity of some elements the dam hardness is reduced and their displacement is increased.
4. In nonlinear dynamic analysis of concrete gravity dam with cracks the horizontal and vertical displacements of the dam crest are much less than the horizontal and vertical displacements of the dam crest in nonlinear dynamic analysis of concrete gravity dam without cracks and this indicates that in the cracked state a part of energy is absorbed by the crack and this leads to the displacement.

Acknowledgments
Hereby the contributions of Khorasan Razavi Water Distribution Co. and Pooy Water Consulting Engineers in roviding the information on Zavin concrete gravity dam are appreciated.

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