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Safety Analysis and Seismic Behavior of Concrete Arch Dams (V&U-shaped Dams)

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ABSTRACT

Investigation of seismic safety evaluation of concrete dams has been the focus of many researchers due to the importance of dam safety during an earthquake. Because the destruction of these structures due to an earthquake can have negative economic and social effects. In the present study, the nonlinear dynamic analysis of gravity concrete dams has been done considering the effect of dam-reservoir interaction. In fact, the minimum and maximum principal stresses of the U-shaped dam and reservoir have been measured via ANSYS. The results show that the static analysis with non-linear behavior in the rock mass with medium and weak layers has more stability compared to the weak homogeneous system. But it is more possible to concentrate plastic strains in weak layers. Other results of this study showed that the compressive stresses in the safety check of the dam were not critical and the maximum tensile arc stresses were obtained mainly in the upper levels of the middle blocks.

Keywords: V-shaped dam, U-shaped dam, seismic behavior, concrete arch dam, ANSYS

1. INTRODUCTION

Among the types of built dams, arch dams have a special position. In addition to the simple materials that are used to fill the valley in dams, the shape of this type of dams reflects the modern knowledge in the interaction between the structure and the environment around the dam. Their main shapes, along with aesthetic issues and apparent strength, basically justify the performance of dams in terms of materials, which are necessary to control very large forces caused by the accumulation of water. A very important point is the issues that arise in high arched dams (more than 200m height). In this case, very large forces caused by the water pressure of the tank are applied to a thin wall and controlled by it. Therefore, the safety of the dam in the mentioned conditions is an important issue that has been taken into consideration in the current study. It should be noted that so far no concrete dam has failed due to earthquake stimulation, but the analysis, design and evaluation of dams can be considered an important part of earthquake engineering. In fact, the only report of the complete failure of concrete dams is due to the failure of the stone support of the foundation. On the other hand, three important cases of damage to concrete dams have occurred, which can be referred to as the Hsinfengkiang concrete buttress dam in China under a magnitude 6.5 earthquake in 1962, the Koyna gravity concrete dam in India under a magnitude 6.5 earthquake in 1967, and Sefidroud concrete buttress dam in Iran under earthquake with magnitude 7.6 in 1992 [1-4]. Predicting the dynamic response of concrete arch dams during an earthquake is one of the complex issues in the dynamics of structures and depends on several factors such as the interaction of the dam with the foundation and the reservoir, the hydrodynamic pressure caused by the reservoir, the effects of the heterogeneous foundation, the presence of functional joints in the dam body, concrete cracking, and the non-linear inelastic behavior of concrete materials [5-8]. With the advent of the finite element method, the analysis methods of concrete arch dams were affected by that method. For the first time, this method was used at the late 1950s for the analysis of arch dams. At the beginning, the analyzes were linear elastic, and with the progress in this field, the nonlinear analysis of concrete arch dams was also performed using this method. With the invention of new methods of structural analysis, the use of these methods for evaluating the seismic performance of structures has been considered [9]. Concrete dams are one of the most important engineering structures. This type of structure can cause irreparable financial and human losses due to an earthquake. Therefore, safety analysis and evaluation of seismic behavior of concrete dams is of special importance.

Kazemi and Bagheri [10] in 2004 investigated the reliability in the design process of anchor rehabilitation of gravity concrete dams. In their study, a comparison has been made between the safety balance created by the allowable stress method and the reliability method. In fact, the behavior of a gravity concrete dam under static loads and quasi-static seismic loads has been investigated. In order to determine the safety coefficient and reliability index, the largest block of Pine Flat dam has been studied. The results show that the analysis based on the reliability of gravity concrete dams provides high safety conditions in the stability analysis of the structure. In 2017, Wang et al. [11] investigated the reliability of tensile stresses in the foundation of gravity concrete dam. In their study, the limit state function equation is presented in order to analyze the tensile reliability at the foundation level. Furthermore, nonlinear finite element analysis has been used to obtain the crack length at the foundation level in order to calculate the reliability. Also, Longtan roller concrete gravity dam is used as a case study. The results of this research show that the mentioned method will be reliable. In 1981, Chopra et al. [12] analyzed the reliability using the non-linear finite element method in gravel dams. In order to check the reliability of the concrete slab in a gravel dam, it was carried out with the help of ANSYS software and under static loads.

In 1983, Gregory et al. [13] proposed a method to estimate the probability of failure due to sliding in gravity concrete dams. Dam safety based on risk analysis is a method to express risk quantitatively in the reservoir dam system. In their study, probabilities which are quantitative evaluating the conditional probability of system response for a concentrated load event on a gravity concrete dam. The purpose of this method is to improve the conditional probability of the reservoir dam system response based on numerical simulation techniques, along with reliability techniques and Monte Carlo simulation. In 2016, Norouzi et al. [14] analyzed the dynamic behavior of gravity concrete dam under explosive load inside the tank. The complete conformity of the results has been obtained. Then the analysis of the dam-reservoir-foundation system during different scenarios was done in the software by explicit dynamic analysis. The results showed that the displacements of different points of the dam body are more in the horizontal direction than the vertical direction and considering the non-linear behavior increases the displacements. In addition, the comparison of the height changes of the explosive charge showed that placing the explosive charge in the middle part of the tank creates a higher acceleration rate. The distribution of the stress wave in the dam body begins with the explosion in front of the location of the explosive charge in the dam body, and these stresses are higher in the outer shell of the downstream face of the dam than in the upstream face near the explosion point. Also, considering the non-linear behavior compared to the linear behavior does not cause a noticeable change in the stress distribution. Souri and Mirzabozorg [15] investigated the effect of stress-dependent damping in nonlinear seismic analysis of gravity concrete dams. In this study, the damping coefficient for each element depends on its main stress and is calculated based on the EDEDA (Element Development Energy Dissipation Algorithm). The analysis of Pine Flat gravity concrete dam shows that the proposed algorithm is able to model the linear and non-linear behavior of the dam body well and provide more reliable and logical results. Khiavi et al. [16] investigated the effect of near and far earthquakes on the seismic response of gravity concrete dams. The results of their study indicate the criticality of the dynamic behavior of the dam against the records of the near field compared to the records of the far field. Despite the significant amount of studies conducted on concrete dams, it is observed that none of the studies have been conducted on the evaluation of seismic behavior and safety analysis of U& V-shaped concrete dams.

2. METHODOLOGY

Using a suitable geometric model is very important in the design of the shape of concrete arch dams. In the process of designing the shape of the concrete arch dams, the horizontal and vertical sections should be selected in a way that is appropriate to the dam structural behavior. In other words, the geometric design should be conforming with the stress of the arch dam, which will result in the optimal usage of the structural potential and the reasonable use of the materials resistance. On the other hand, in order to facilitate the construction and simplicity of implementation, the geometric model should not be too complicated to be applicable in practical projects [17]. The border side of the structure (where the supports and the body of the dam meet) can change according to the topography of the area. Therefore, at different heights, the alignment lines should be specified and the meeting place of the dam body and the supports should be obtained with mathematical equations. In this study, the shape of the valley is divided into 10 layers along the height and the intersection of the healthy rock level lines on both sides is expressed with broken lines, whose nodal coordinates are the main input data [18]. The horizontal coordinates of point C (the crown of the dam located on the upstream face of the dam in the central vertical section) are as follows (Figure 1):

$$x_c = x_1 \qquad y_c = y_1 \tag{1}$$

Where xc and yc are reference coordinates. The angle between the radial plane of the central vertical section and the yoz plane can also be represented by X3. X1, X2 and X3 are three design variables that determine the position of the dam axis. To determine the shape of an arch dam, first the central core is determined,then the shape of the horizontal sections at different levels are determined [19].

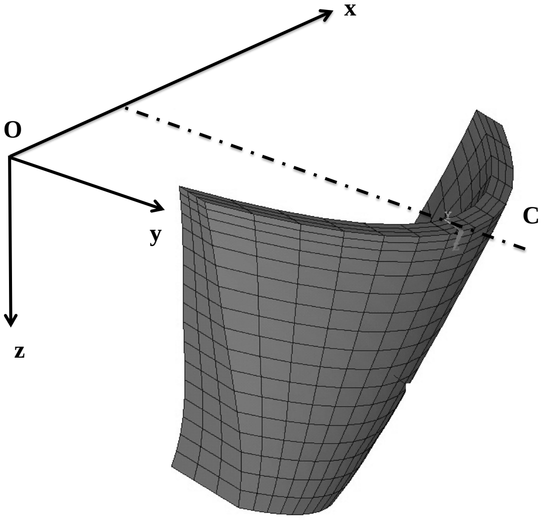

Figure1. Position of dam axis

The design parameters change with the coordinates and are written with the z coordinate (height coordinates from the top of the crown to the bottom) as polynomials of z in the following form [20]:

$$f(z)=k_0+k_1z+k_2z^2+\ldots+k_mz^m \tag{2}$$

where f(z) is the design parameter, z is the vertical coordinate and k0, k1, k2, ... km are its coefficients. The number of design parameters depends on the pattern of the arch shape of the body and the f(z) function can also be considered as a Spline function. Assuming z=0, z1, z2, ..., zm in the above relation, the system of equations is obtained in the form of relation (3):

$$\begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 1 & z_1 & z_1^2 & \cdots & z_1^m \\ 1 & z_2 & z_2^2 & \cdots & z_2^m \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 1 & z_m & z_m^2 & \cdots & z_m^m \end{bmatrix} \begin{Bmatrix} k_0 \\ k_1 \\ k_2 \\ \vdots \\ k_m \end{Bmatrix} = \begin{Bmatrix} f_0 \\ f_1 \\ f_2 \\ \vdots \\ f_m \end{Bmatrix} \tag{3}$$

where f=f(z) and by solving the above coefficients k0, k1, k2, ... km will be determined by the design parameters f0, f1, f2...fm, which are used in the optimization process as variables and called design variables. One of the advantages of this method is that all these design variables have physical meanings. Therefore, there are a total of m design variables to define the dam, which are X1, X2... Xm, where the three variables X1, X2, X3 determine the position of the dam and X4, X5... Xm determine the shape of the dam. For a single-curvature arch dam, the upstream face of the central core is generally a straight line and only a polynomial of m is needed to determine the thickness, and for the curve of the central core of a double-curvature arch dam, a polynomial of order m (usually 2, 3 or m) is required for determining the upstream face (centerline of the section) and another polynomial is required to determine the thickness of the section. These equations will be presented as follows [14].

2.1. Dam body modelling

2.1.1. The upstream curve of the central core in height

A 2nd order polynomial has been used in the design of the upstream curve of the central core:

$$y_{cc}=x_4z+\frac{x_4}{2x_5H}z^2 \tag{4}$$

where H is the height of the central core and X4 and X5 are two design variables that satisfy the following conditions:

$$\frac{dy_{cc}}{dz}=\begin{cases} x_4 & z=0 \\ 0 & z=x_5H \end{cases} \tag{5}$$

2.1.2. 3rd order polynomial to determine the thickness of the central core in height

$$T_C=x_7+(\alpha_3x_7+\alpha_4x_8+\alpha_5x_9+\alpha_6x_{10})\left(\frac{z}{H}\right)+(\beta_3x_7+\beta_4x_8+\beta_5x_9+\beta_6x_{10})\left(\frac{z}{H}\right)^2+(\gamma_3x_7+\gamma_4x_8+\gamma_5x_9+\gamma_6x_{10})\left(\frac{z}{H}\right)^3 \tag{6}$$

where, X7, X8, X9 and X10 are the thickness of the central core at z/H=0, z/H=b, z/H=c and z/H=1, respectively, and the values of b and c are obtained from the variable design. The αi, βi and γi parameters are obtained based on the order considered for the functions determining the design parameters. The dimensions of the initial design of the central core are determined in the SI system according to the arch dam design guide provided by USBR. Based on this method, which is based on a statistical study on the shape of concrete arch dams in the world, the thickness of the central core is obtained from the following relationships at different levels.

$$\begin{aligned} T_{crest} &= 0.1\times(H+1.2L_1) \\ T_{base} &= \sqrt[3]{0.001HL_1L_2\left(\frac{H}{122}\right)^{\left(\frac{H}{122}\right)}} \\ T_{0.45H} &= 0.95T_{base} \end{aligned} \qquad (7)$$

where L1 is the direct distance of two supports at the crown level and L2 is the direct distance of two supports at a distance of 0.15 height from the river bottom. The shape of the arch dam sections may be one of the sheets of single-centered arch, multi-centered arch (3,2 or multi-centered), parabolic arch, elliptical arch, hyperbolic arch and logarithmic spiral arch. In the present study, parabolic arch is used to model the horizontal sections of the dam body. By determining the thickness of the body along the arc at any given level, the shape of the horizontal sections is determined. The axis between the webs of the horizontal section of the parabolic dam and the body thickness along the horizontal arcs are calculated for the right and left sides of the body from relations (8) to (18) [21]. (Figure 2).

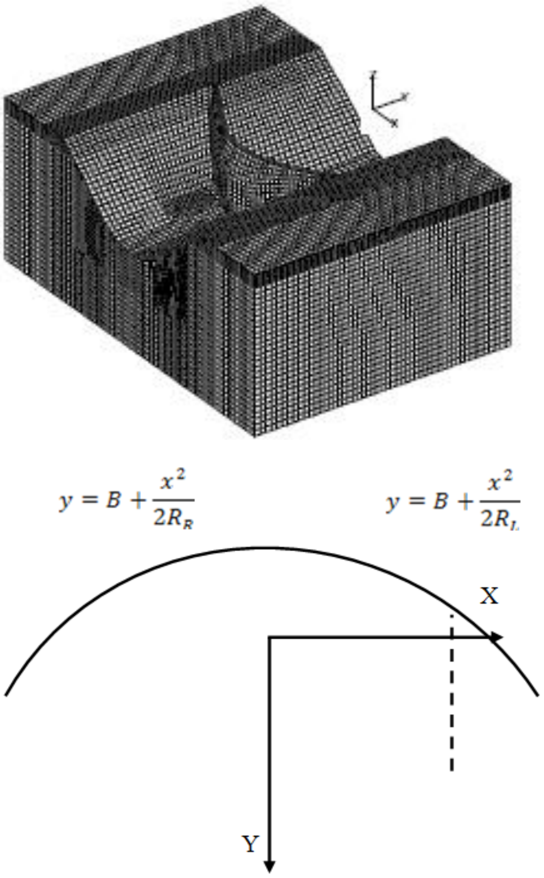

Figure 2. The parabolic shape of the dam body

For the right half of the body:

$$T_S = T_C + (T_{AR} - T_C)\frac{S^2}{S_{AR}^2} \qquad (8)$$

For the left half of the body:

$$T_S = T_C + (T_{AL} - T_C)\frac{S^2}{S_{AL}^2} \qquad (9)$$

where B is the transverse coordinate of the crown of the middle horizontal arc, and RR and RL are the right and left centerline radius of the horizontal arc at X=0, respectively. The values of these parameters are calculated in different levels of the body using third-order functions. Also, TC, TAR, and TAL are the thickness of the horizontal arc in the crown, right support, and left support, respectively. Also, S is the length of the arc from the crown of the horizontal arc and SAR and SAL are from point C to the left and right supports. The equation of the arc length of a parabolic arch dam from the crown of the horizontal arch is obtained as follows:

$$S = \frac{x}{2R}\sqrt{R^2 + x^2} + \frac{R}{2}\ln\left(\frac{x + \sqrt{R^2 + x^2}}{R}\right) \qquad (10)$$

Finally, the shape of the horizontal sections is completely determined by 6 design parameters TAL, TAR, RL, RR, TC and B:

$$\begin{aligned} R_R = {} & X_{11} + (\alpha_3 X_{11} + \alpha_4 X_{13} + \alpha_5 X_{13} + \alpha_6 X_{14})(\frac{z}{H}) \\ & +(\beta_3 X_{11} + \beta_4 X_{12} + \beta_5 X_{13} + \beta_6 X_{14})(\frac{z}{H})^2 \\ & +(\gamma_3 X_{11} + \gamma_4 X_{12} + \gamma_5 X_{13} + \gamma_6 X_{14})(\frac{z}{H})^3 \end{aligned} \qquad (11)$$

$$\begin{aligned} R_L = {} & X_{15} + (\alpha_3 X_{15} + \alpha_4 X_{16} + \alpha_5 X_{17} + \alpha_6 X_{18})(\frac{z}{H}) \\ & +(\beta_3 X_{15} + \beta_4 X_{16} + \beta_5 X_{17} + \beta_6 X_{18})(\frac{z}{H})^2 \\ & +(\gamma_3 X_{15} + \gamma_4 X_{16} + \gamma_5 X_{17} + \gamma_6 X_{18})(\frac{z}{H})^3 \end{aligned} \qquad (12)$$

In the above relations, X11, X12, X13 and X14 are R1 values in z/H =0, z/H =b, z/H =c and z/H =1 respectively. Also, X15, X16, X17 and X18 are RL values in z/H =0, z/H =b, z/H =c and z/H =1 respectively.

$$\begin{aligned} T_{AR} = {} & t_1 + (\alpha_3 t_1 + \alpha_4 X_{19} + \alpha_5 X_{20} + \alpha_6 t_2)(\frac{z}{H}) \\ & +(\beta_3 t_1 + \beta_4 X_{19} + \beta_5 X_{20} + \beta_6 X_{18})(\frac{z}{H})^2 \\ & +(\gamma_3 t_1 + \gamma_4 X_{19} + \gamma_5 X_{20} + \gamma_6 t_2)(\frac{z}{H})^3 \end{aligned} \qquad (13)$$

Where X20, X19, t1 and t2 are the TAR values at z/H=0, z/H=b, z/H=c and z/H=1 respectively. Also, TAL by inserting the values of t3, X22, X21, and t4 which are respectively the values of TAL at z/H=0, z/H=b, z/H=c and z/H=1 is obtained. In practice, the thickness of the horizontal arch at the level of the crown of the dam and the level of the base is almost constant and therefore:

$$t_1 = s_1 X_7$$
$$t_2 = s_2 X_{10} \quad (14)$$

The αi, βi and γi coefficients can be calculated from the following relations:

$$\alpha_3 = -\alpha_4 - \alpha_5 - \alpha_6, \quad \alpha_4 = \frac{c^2(1-c)}{D}, \alpha_5 = \frac{b^2(b-1)}{D}, \alpha_6 = \frac{b^2 c^2 (c-b)}{D} \quad (15)$$

$$\beta_3 = -\beta_4 - \beta_5 - \beta_6, \quad \beta_4 = \frac{c^2(1-c)}{D}, \beta_5 = \frac{b^2(1-b^2)}{D}, \beta_6 = \frac{b^2 c^2 (b^2-c^2)}{D} \quad (16)$$

$$\gamma_3 = -\gamma_4 - \gamma_5 - \gamma_6, \quad \gamma_4 = \frac{c(1-c)}{D}, \gamma_5 = \frac{b(1-b^2)}{D}, \gamma_6 = \frac{b\,c(b^2-c^2)}{D} \quad (17)$$

$$D = b^2c^3 - b^3c^2 + b^3c - bc^3 + bc^2 - b^2c \quad (18)$$

Where b and c are design parameters. In this research, the coordinates and geometry of the dam along with the equation of fluid behavior in the Ansys modeling software environment and the minimum and maximum main stresses for the dam and reservoir have been calculated with time history analysis. It should be noted that the stimulation is applied to the floor of the model separately in each direction. To generate acceleration time histories, time histories consistent with the response spectrum of the target earthquake are generated for each of the Harichandran and Hindy coherence models.

2.2. Geometric properties of the dam structure

In this study, for the design of the dam body, parabolic arches were used along the horizontal levels and other parameters related to the design of the horizontal arcs as well as the central core were calculated. The concrete arch dam is modeled on two U-shaped and V-shaped valleys and for two heights of 150 meters and 250 meters. In the model with a body height of 250 meters, the arc length at the crown level is 750 meters for both geometric shapes. The arched concrete dam is modeled on two U-shaped and V-shaped valleys and for two heights of 150 meters and 250 meters. In the model with a body height of 250 meters, the arc length at the crown level is 750 meters for both geometric shapes. For the dam modeled in the U-shaped and V-shaped valley, the length of the body at the bottom is 350 and 150 meters respectively. In the dam with a height of 150 meters, the length of the arch at the crown level in both body shapes is 450 meters, and the length at the bottom level is 270 meters for the U-shaped and 90 meters for the V-shaped model respectively. Other geometric properties of the modeled dams are presented in Tables 1 and 2.

Table1. Geometric properties of 250m height dam

Geometric properties of dam	U-shaped valley	V-shaped valley
Height	250m	250m
Crown length	750m	750m
Length at base level	350m	150m
Valley slope at lateral supports	0.8	1.2
Body thickness at crown level	12m	12m
Body thickness at base level	69m	58m
Thickness at 0.3 height from crown	39m	34m
Thickness at 0.6 height from crown	66m	55m
Body shape	Symmetric	Symmetric

Table 2. Geometric properties of 150m height dam

Geometric properties of dam	U-shaped valley	V-shaped valley
Height	150m	150m
Crown length	450m	450m
Length at base level	270m	90m
Valley slope at lateral supports	0.6	1.2
Body thickness at crown level	7m	7m
Body thickness at base level	30m	23m
Thickness at 0.3 height from crown	18m	15m
Thickness at 0.6 height from crown	29m	22m
Body shape	Symmetric	Symmetric

2.3. Finite Element Model

Modeling and static and seismic analyzes of the dam have been done in ANSYS software. The length of the reservoir in the used finite element model is considered equal to the length of the footing, and the dimensions of the support are considered to be about 3 times the height of the body on each side due to the low ratio of the modulus of elasticity of the support to the body. Also, the support continues to the top of the valley walls. For the meshing of the body and the foundation, the 8-node cubic element SOLID185 is used, which has three degrees of transitional freedom in each node of the element, and the number of elements along the thickness of the body is two layers. For the fluid, FLUID30 has been used, which has three transitional and one pressure degrees of freedom in each node, and the number of elements along the river is 8 rows. The number of elements in the dam body, support and the lake are considered as 640, 11520 and 2560 elements respectively. The pressure of the reservoir at the free surface is assumed to be zero and the boundary conditions of the far end of the reservoir are taken into account for complete absorption of the hydrodynamic wave. To model semi-infinite conditions, the lateral walls of the far end of the support and the foundation of the body are closed in the X and Y directions, and the base is closed in all three directions of X, Y and Z. It is worth noting that positive X is taken in the direction of the width of the river to the left, positive Y in the downstream direction and positive Z in the vertical and downward direction (Figure 3-5).

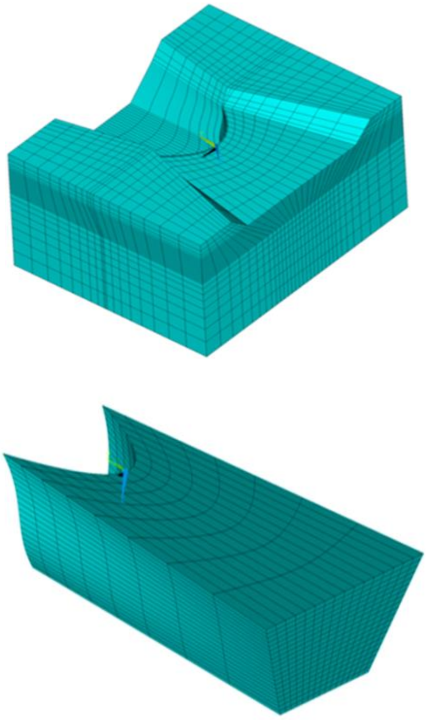

Figure3. Finite element model of dam-foundation-lake

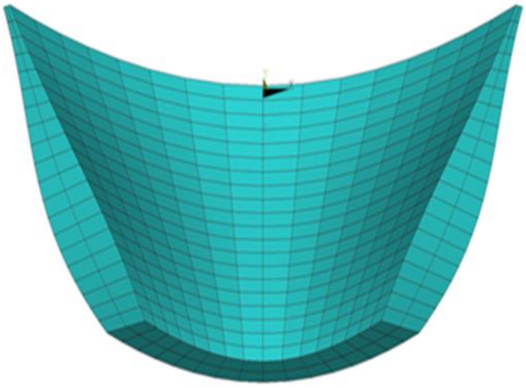

Figure4. Finite element model of U-shaped body

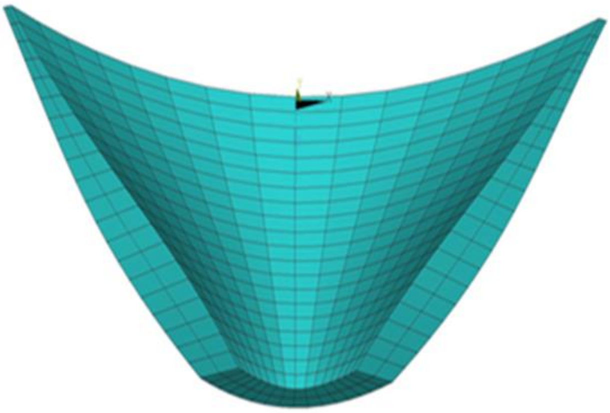

Figure5. Finite element model of V-shaped body

2.4. Material properties and load combinations

The modulus of elasticity of bulk concrete, Poisson's ratio of concrete and its specific weight are considered as 30 GPa, 0.2 and 2400 kg/m3 respectively. Also, for the support, the deformation modulus is 11.5 GPa, Poisson's ratio is 0.25 and its specific weight is 2000 kg/m3. The specific weight of the fluid is 1000 kg/m3, the speed of sound in water is 1436 m/s and the wave absorption coefficient for the tank wall and bottom is 0.8 considered. The damping of body materials is 5% due to the presence of contraction joints, and for foundation materials, integrated stone is considered with the damping of 2%. Static analysis has been done for the main loads, i.e. body weight and hydrostatic load. In order to simulate the real conditions in the body and the foundation, the static analysis was performed in such a way that the foundation was first modeled and analyzed under its weight, and the stresses and displacements resulting from this analysis were obtained and the resulting displacements were set to zero. Then, the body of the dam is modeled and analyzed, and again its internal stresses are maintained and the displacements caused by the body of the dam are set to zero, and after that the lake is modeled. The water level of the lake is considered in normal conditions and it has been applied after applying the weight load. The hydrostatic load is applied to the upstream surface of the body as well as the walls and the bed of the reservoir. In the time history method, the dam-foundation-lake system is stimulated using earthquake records. The foundation is stimulated uniformly and non-uniformly by considering two directions for the propagation of seismic waves (upstream-downstream and transverse) and for both coherence models investigated in this study. Excitation is applied to the base of the model separately in each direction. To generate acceleration time histories, time histories consistent with the response spectrum of the target earthquake are generated for each of the Harichandran and Hindy coherence models (Figure 6).

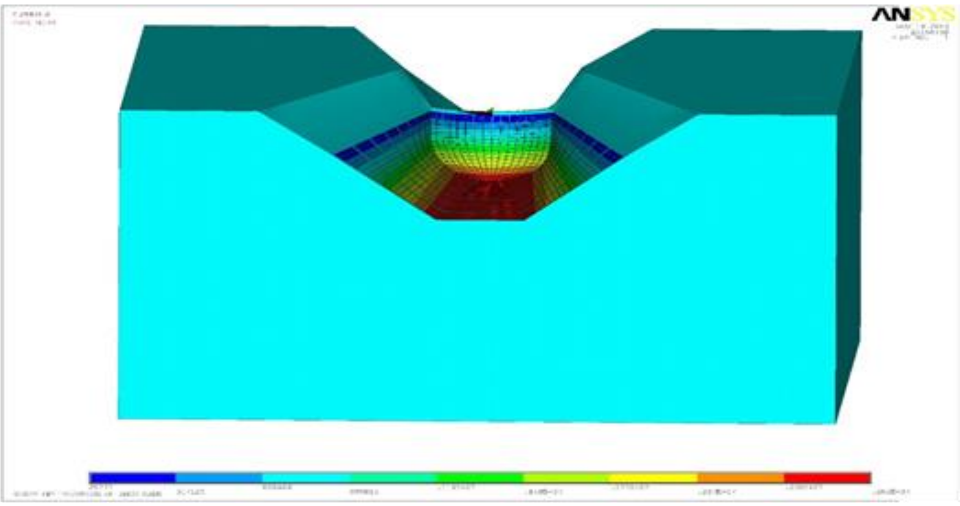

Figure 6. Upstream body and reservoir under the effect of hydrostatic load in normal conditions of the lake

3. RESULTS AND DISCUSSION

At this section, the results of seismic analysis of concrete arch dams in two cases of dam with heights of 250 and 150 meters have been shown and the results of the minimum and maximum stresses applied to the upstream and downstream of the lake and dam have been given. The results show that the static analysis with non-linear behavior in the rock mass with medium and weak layers has more stability compared to the weak homogeneous system. But it is more possible to concentrate plastic strains in weak layers. Other results of this study showed that the compressive stresses in the safety check of the dam were not critical and the maximum tensile arc stresses were obtained mainly in the upper levels of the middle blocks and also in the vicinity of the contact surface with the side supports.

- **250m concrete arch dam**

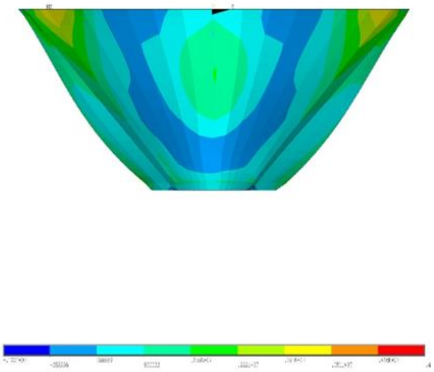

Figure 7. The maximum principal stress of the upstream surface

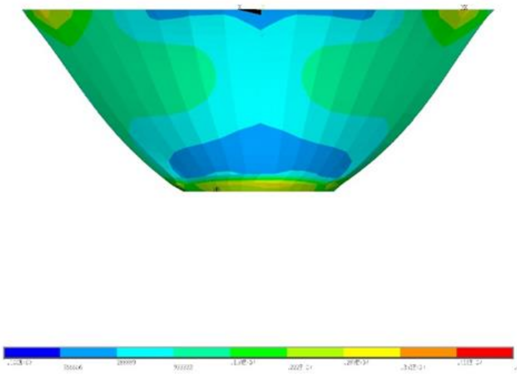

Figure 8. The maximum principal stress of the downstream surface

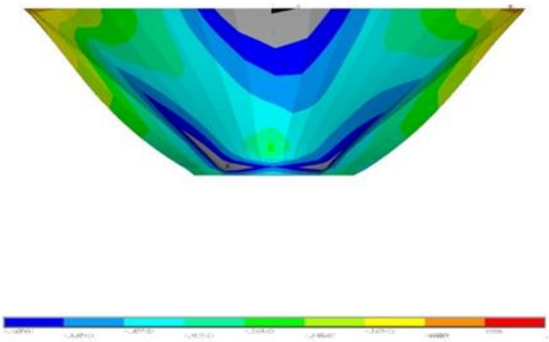

Figure 9. The minimum principal stress of the upstream surface

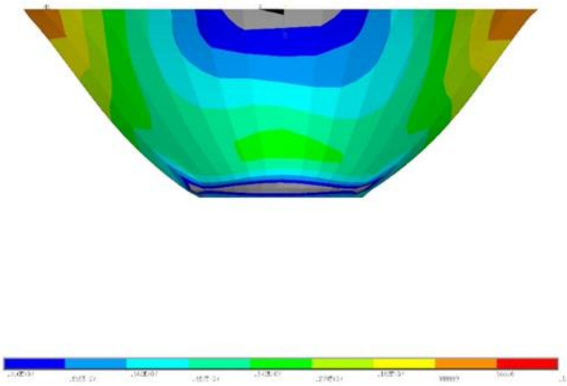

Figure 10. The minimum principal stress of the downstream surface

- **B-150m concrete arch dam**

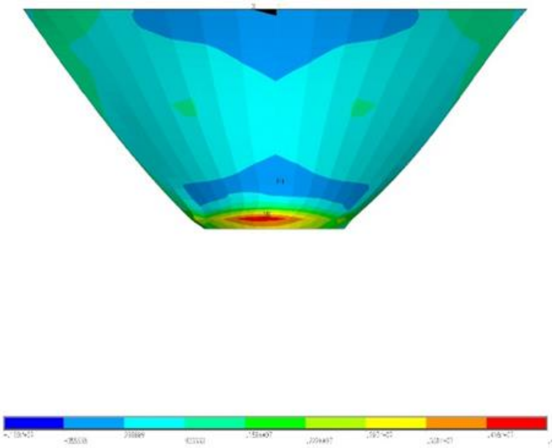

Figure11. The maximum principal stress of the upstream surface

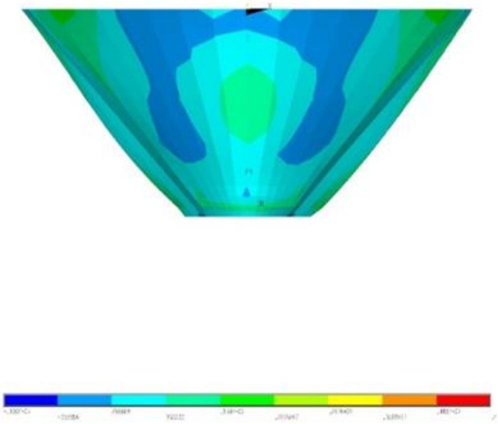

Figure12. The maximum principal stress of the downstream surface

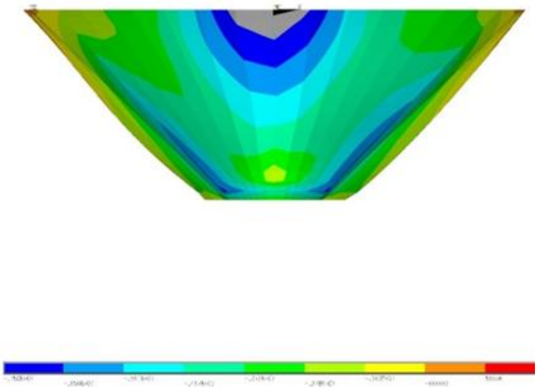

Figure13. The minimum principal stress of the upstream surface

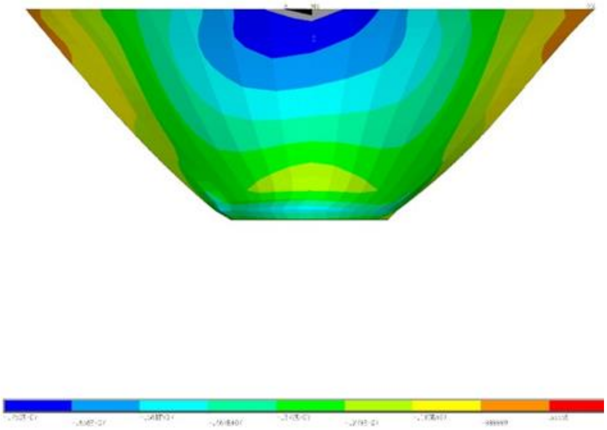

Figure14. The minimum principal stress of the downstream surface

Figures 7–14 show the minimum and maximum principal stresses of the upstream and downstream surfaces of the dam. In general, it can be resulted that the overall stability of the dam is not seriously threatened due to the low tensile stresses in the contact surface of the lateral supports and the foundation, but there is a possibility of relatively severe damage in the form of vertical opening in the upper levels of the central blocks and cracking and horizontal opening in the intermediate levels blocks of the dam. The severity of these damages in winter loading conditions is insignificant and not serious, but it is noticeable in summer loading conditions. For this purpose, it is suggested that in case of severe earthquakes, especially during summer and when the reservoir is full, the water level in the dam reservoir should be lowered. If severe cracks are observed, especially in the middle levels and also in the contact surface of the foundation, this reduction is more important. To further investigate the stability of these blocks, it is necessary to perform nonlinear analysis.

According to the topics presented, the following points should be considered in seismic analysis of arch dams:

- It is necessary to perform a time history analysis to investigate time periods and fluctuations of high tensions. The high tension alone is not the reason for damage, and knowing how they change over time can greatly help to interpret the results.
- It is necessary to perform nonlinear analysis along with linear analysis to help interpretation, when there is a possibility of severe damage.
- It is important to consider the time delay caused by the effect of air temperature on water temperature and internal concrete temperature in case of lack of access to temperature measurement data.
- It is necessary to consider earthquake records from different accelerometers with the same soil type of the location of the accelerometer and the location of the dam in order to investigate the effect of earthquake frequency.
- A specific criterion cannot be considered as the limit for the safety and seismic stability of a dam. Engineering judgment and interpretation of results should be used to achieve this goal.
- It was observed in the static analysis that if the support is homogeneous, the critical stress areas

occur in the foundation of the dam, which indicates the significant effect of the core effect compared to the arch effect of the dam.

- Linear and non-linear static analysis indicates the presence of a tension zone in the upstream part of the dam at a short distance from the dam body.
- Static analysis with non-linear behavior in the rock mass with medium and weak layers showed that there is more stability than the weak homogeneous system. But it is more possible to concentrate plastic strains in weak layers.
- In dynamic analysis, the presence of fixed boundaries causes excessive acceleration in different areas of the dam, and it is necessary to always use energy absorbing boundaries.
- Acceleration difference in linear and non-linear analyzes leads to the creation of plastic and irreversible strain in the elements, which itself leads to the production of more displacement.
- Linear analysis can be used conservatively to investigate the phenomenon of increasing acceleration, and if the change of location and stability of the support is desired, it is necessary to perform a non-linear analysis.

4. CONCLUSION

- According to the location of the dam and preliminary design of the body and its analysis, the general results of the analysis of the concrete arch dam are as follows:
- The distribution pattern of tensile and compressive stresses in the body and supports is appropriate.
- The values of the maximum compressive and tensile stresses in the primary body are appropriate.
- The maximum tensile and compressive stress values created in the base of the body and in the bedrock are appropriate and reasonable.
- The behavior of the body in the construction is almost symmetrical as expected.
- large displacements are a sign of high tensions, so the critical time period for high tensions can be predicted from the time period in which there are large displacements.
- The failures caused by arch stresses are more than those caused by core stresses.
- Compressive stresses are not critical in dam safety.
- The maximum tensile arch stresses are observed mainly in the upper levels of the middle blocks and also in the vicinity of the contact surface with the side supports. In the downstream surface, the amount and range of these stresses in summer loading conditions are more than winter ones. In the upstream surface, the range of these stresses in summer conditions is reduced compared to winter, but their intensity is more.
- The amount of tensile stresses in the upstream surface is more than the downstream one in most cases.
- The amount of maximum tensile stress is relatively low mainly in the blocks placed between the middle section and the lateral support due to the tensile strength of the horizontal joints. In summer loading conditions, the amount of stresses is more than in winter ones. Also, in summer conditions, the amount of stresses in the upstream surface is more than the downstream one. This is the opposite in winter conditions.
- The maximum compressive stresses are mainly observed in the upper levels of the middle blocks and also in the vicinity of the side supports in the middle levels. The amount of stresses in summer loading conditions is more than winter ones. Also, in most cases, their amount is higher in the upstream surface than in the downstream.
- In the vicinity of the contact surface with the side supports and the foundation, there is an expectation of partial opening of the joints. Also, it is expected that the operation of the overflow valves will not face serious problems due to the low stress values in that area.
- In the reviewed models, the analysis of double-arched dams was omitted due to limitations, and the earthquake record was applied to the model in only one direction. Therefore, for future studies, it is recommended to analyze double-arched dams in three longitudinal, transverse, and vertical directions.

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