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Dynamic Analysis of the Arch Concrete Dam under Earthquake Force with ABAQUS

M.A. Lotfollahi Yaghin and M.A. Hesari
Faculty of Civil Engineering, University of Tabriz, Islamic Republic of Iran

Abstract: In this study, the dynamical behavior of arch concrete dams has been analyzed by finite element method. The case study is Karoon-1 (shahid Abbaspoor), double curvature arch dam with the height of 200 m. This dam is considered as one of the most complex dams because of different external and internal radius and angles, also, asymmetrical center of external and internal archs in different levels. So, by geometrical dimensions of the mentioned dam from related designing maps and also its mechanical and physical properties, dam without supports and dam with rock supports are modeled by ABAQUS finite element software. According to dynamical analysis results, have been calculated the time history of main stress, displacement of the dam in crest and river bed level and also, their maximum values in earthquake time duration have been compared and investigated.

Key words: Arch concrete dam, finite element, dynamic analysis, earthquake, ABAQUS

INTRODUCTION

Water with good quality and in sufficient quantity is a basic requirement for humanity. Reservoirs and concrete dams that create those reservoirs provide a means to balance the fluctuation of natural water flow. Multipurpose reservoirs can serve for drinking water, irrigation in agriculture, production of clean and renewable energy, recreation and flood protection. So, the concrete arch dam and study of its stability under variable loading especially earthquake forces play a vital role in the infrastructure of many states for the provision of water resource and saving money.

Finite Element Method (FFM) is a numerical method that can be used to solve different kinds of engineering problems in the stable, transient, linear or nonlinear cases (Bathe, 1996). Among finite element method software's, ABAQUS is known as one of the most precise and practicable software in industry and university researches. It is used for dynamic analysis such as earthquake and water wave loading on structures (ABAQUS Analysis User's Manual, 2006).

Providing the safety of concrete dam in accordance with dynamic forces as a result of earthquake has been noticed by many researchers and engineering science experts in recent years. By noting that one of the important parameters in dam construction projects is the earthquake and on the other hand Iran plateau is a folded shell that is consisted of many fractures and faults and there are a lot of earthquake on it every year. For these, to protect of human losing or economical damages it is necessary to have an analysis from this massive structure.

For this, by having the geometric properties of the Karoon-1 dam from its design sections, physical and mechanical properties of that is modeled in two cases by using ABAQUS. First dam body without supports and second dam body with rock supports. Support conditions and physical specifications for both cases are same. All the work that has been done is:

- Creating the geometric model of dam
- Creating the geometric model of dam and rock supports
- Applying the boundary conditions
- Applying the relevant forces
- Mesh generating
- Analyze type selection, parameters adjustments and running
- Conclusion

RELEVANT RESEARCH HISTORY

National Information Service for Earthquake Engineering (NISEE) in Berkley University is one of the most reliable scientific centers that has a lot of researched reports in relationship with the discussed subject. In any case the studies of the dynamic response Behavior of a dam are limited but from recent studies that can point to the researches which has been done by Christopoulous *et al*. (2003), about the seismic sliding response analysis of gravity dams including vertical acceleration. Also, Léger and Alliard (2008) discussed the Earthquake safety evaluation of gravity dams considering aftershocks and reduced drainage efficiency. In addition,

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Corresponding Author: Dr. M.A. Lotfollahi Yaghin, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran
Tel: +98 914 418 6490 Fax: +98 411 3344287

there are some other researches which discussed the effect of earthquakes on concrete dams such as: Léger and Leclerc (1996), Ghaemian and Ghobarah (1999), Zhou *et al.* (2000), Leclerc *et al.* (2003), Javanmardi *et al.* (2005), Nwankwo and Akoshile (2005), Ftima and Léger (2006), Léger and Javanmardi (2006), Lotfi and Omidi (2007), Samii and Lotfi (2007) and among others. Almost all previous mentioned studies are about stability of concrete dam or seismic analysis. Instead, this paper considers the dynamical analysis of an arch concrete dam under earthquake.

MODELING OF DAM BY ABAQUS SOFTWARE

For modeling we need a proper case study to have a real simulated model. It is clear that creating the geometry and analyzing a real model is difficult and complicated but on the other hand the results would be precise and similar to real condition. Also by evaluation of dam modeling and by predicting the behavior of the structure it is possible to find the weak point in accordance with loading and we can do the best to repair it or remove the defect. For this we gathered the Karoon-1 information and made a real model of it by noting its real design sections. Karoon-1 is double curvature arched dam with 200 m height. Additional information is represented in Table 1. In this dam internal and external radiuses and also internal and external angles in various levels are different. Also internal and external arches of the dam are not concentric and the dam is not symmetric to the axis that crosses from the centers of arches. So, this dam has almost all intricacies that a one could have (Fig. 1, 2).

The main characteristics of dam body are given in Table 1. To have analogy between the geometry of dam and model, 20 nodes, 3-dimensional elements (C3D20RH) with 2 degree curvature are used in ABAQUS6.6 (Fig. 3).

Fig. 1: Downstream view of Karoon-1 dam

Table 1: Geometrical specification of Karoon-1 dam

Dam type	Double curvature arch dam
Length of crest	372 m
Height from foundation	200 m
Thickness at base	33.5 m
Thickness at crest	6 m
Normal water level	177.5 m
Concrete povason coefficient	0.2
Concrete density	2400 kg m^{-3}

Fig. 2: Upstream view of Karoon-1 dam

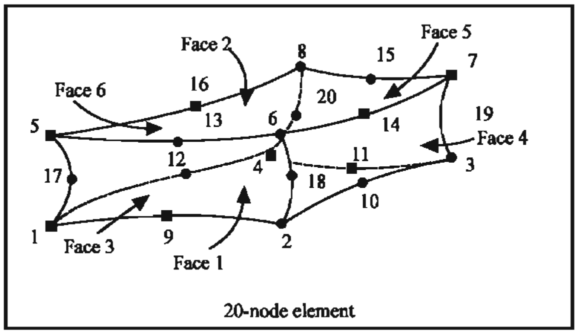

Fig. 3: 20 nodes 3 dimensional element (C3D20RH)

DAM APPLIED RECORDS

Applied records on dam were the horizontal and vertical components of the Koyina earthquake (one of the intensive reported records in the world). The acceleration of this earthquake was 0.5 g (is a high acceleration) and it should be classified as a Design Basis Earthquake (DBE) with happening probability of 20% and 200 years return period. It could be expected that this earthquake can cause damage on dam body. Vertical and horizontal acceleration of the earthquake have been given in Fig. 4 and 5.

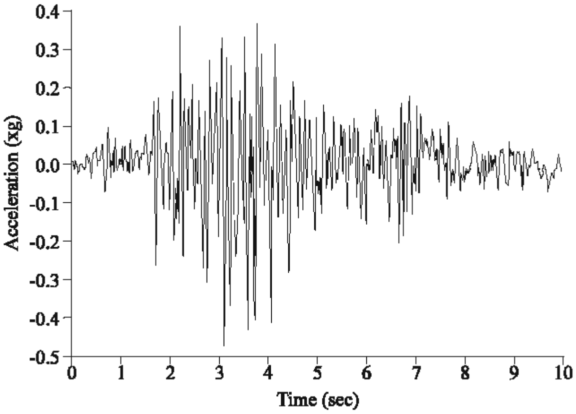

Fig. 4: Vertical acceleration of the earthquake

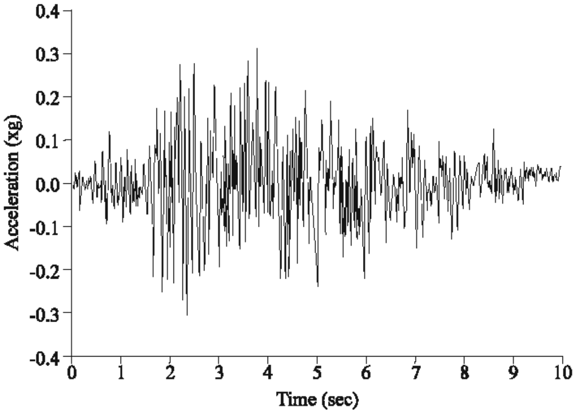

Fig. 5: Horizontal acceleration of the earthquake

SUPPORTS MODELING IN ABAQUS

Supports modeling is done by considering the ratio of elasticity modulus of bed rock to the elasticity modulus of dam body concrete (E_r/E_c). The large ratio, on the other hand, the stiffer bedrock will result to need low height in modeling of the supports. It means that with less bed rock stiffness, to have precise interaction between foundation and dam, we need more height in modeling of abutments. In this study and for this dam the ratio was between 1 and 2.

MODAL ANALYSIS AND DAM VIBRATION MODE FREQUENCIES WITH AND WITHOUT SUPPORTS

For inspecting the dynamical behavior of dam, to calculate the damping coefficient primarily vibration frequencies modes should be calculated. In this case, the dam is modeled without Supports and for this case, to have no movement in abutments; movements in abutments nodes were restricted in all directions. First 7th modes frequencies resulted from modal analysis are represented in Table 2.

Table 2: First 7th modes frequencies

Dam with supports		Dam without supports	
Mode	Frequency	Mode	Frequency
1	1.76799	1	1.6311
2	2.14547	2	1.7142
3	2.9860	3	1.7372
4	3.3423	4	1.7574
5	3.7177	5	1.7855
6	4.2332	6	1.7910
7	4.2991	7	1.8828

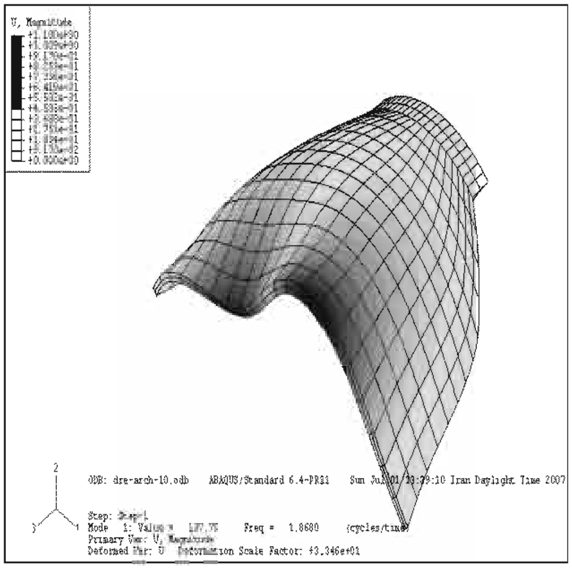

Fig. 6: Total displacement according modal analysis (first mode)

Damping coefficient is calculated by means of Riley method. Damping coefficient can be founded by means of linear combination of mass matrix and stiffness matrix. Coefficients of these linear components are calculated from modes frequencies of dam.

$$C = \alpha M + \beta K \tag{1}$$

α and β are Riley linear combining coefficients and calculated from Eq. 2 and 3:

$$\alpha = 2\xi\omega_i.\omega_j/(\omega_i+\omega_j) \tag{2}$$

$$\beta = 2\xi/(\omega_i+\omega_j) \tag{3}$$

In these formulas ξ is the damping ratio and in dynamical analysis it assumed 5%, ω_i and ω_j are two angular frequencies of vibration modes.

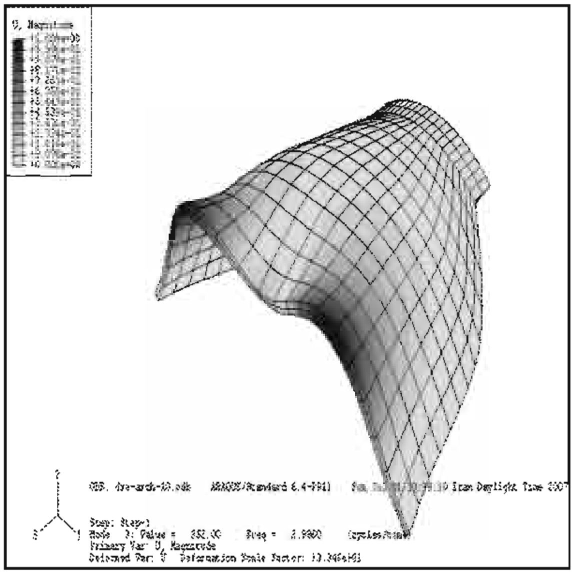

Fig. 7: Total displacement according modal analysis (third mode)

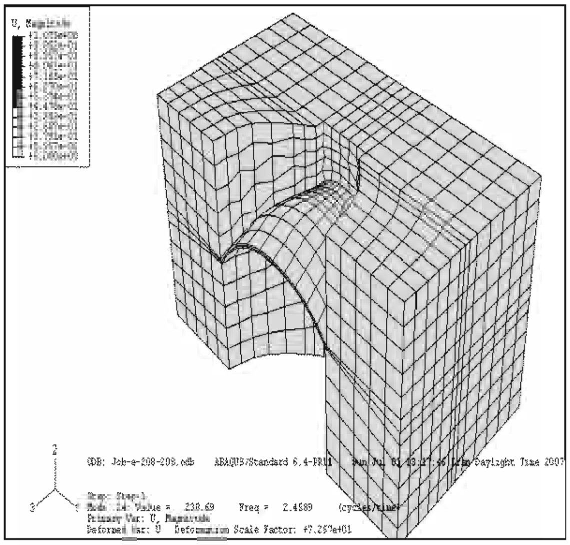

Fig. 8: Total displacement according modal analysis (first mode)

In Karoon-1 dam dynamic analysis Riley damping coefficient are calculated from first and third dam vibrating modes and critical damping ratio which was 5%: $\alpha = 0.1149$, $\beta = 0.0206$.

First and third vibrating modes are shown in Fig. 6 and 7, respectively.

In this, part dam and its rock supports were modeled in ABAQUS software according to designed section and then modal analysis was completed (Table 1).

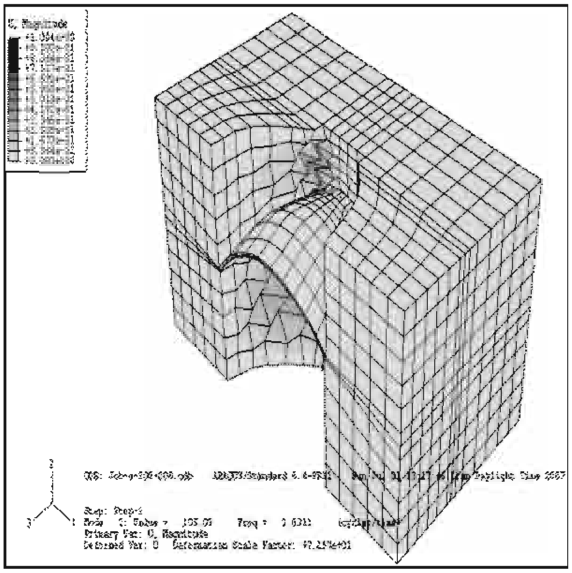

Fig. 9: Total displacement according modal analysis (third mode)

In Karoon-1 dam dynamic analysis modeling with supports Riley damping coefficient are calculated from first and third dam vibrating modes and critical damping ratio which was 5%: $\alpha = 0.0841$, $\beta = 0.0296$.

First and third vibrating modes are illustrated in Fig. 8 and 9, respectively.

DYNAMIC ANALYSIS OF CONCRETE ARCH DAM WITH EMPTY RESERVOIR

The most important step in Finite Element method structural analysis is creating a mathematical model composed of separated elements which simulate the real continuous structures.

The purpose of this modeling is having a system with limited degree of freedom instead of a system with infinite degree of freedom. Virtual work principal is used to derive dynamic equilibrium equations of structural elements. Whenever an elastic structure is deformed under dynamic loads it can be assumed in every moment. Virtual displacement of Δu should be added to the displacement of U. These small displacements result in virtual relative displacements of $\Delta \varepsilon$. Therefore, in every moment energy of virtual relative deformation (Δu) can be calculated for any stress condition in the structure. With these conditions external virtual work includes volume and surface forces, inertia and damping. In this section, dynamic analysis of dam-reservoir system is considered in time domain and also dam foundation is assumed rigid. The dynamic displacement equation of dam structure with n degree of freedom can be followed as Eq. 4.

$$M\ddot{U}+C\ddot{U}+KU = F(t) \tag{4}$$

If the displacement of U_g (t) is occurred in foundation with empty reservoir then the dynamic displacement of dam can be written as Eq. 5.

$$M\ddot{U} + C\dot{r} + Kr = O \tag{5}$$

Absolute and relative displacements of dam nods have relationship as shown in Eq. 6.

$$U = r + j.U_g\,(t) \tag{6}$$

The elements of vectors u, r, U_g (t) and j matrix are represented as following:

$$U = \begin{bmatrix} U_1 \\ V_1 \\ U_2 \\ V_2 \\ \\ \\ U_2 \\ V_n \end{bmatrix}, r = \begin{bmatrix} r_{1x} \\ r_{1y} \\ r_{2x} \\ \\ \\ \\ r_{ny} \end{bmatrix}, \; U_g(t) = \begin{bmatrix} U_{gx} \\ U_{gy} \end{bmatrix}, j = \begin{bmatrix} 10 \\ 01 \\ 10 \\ 01 \\ \\ \\ 10 \\ 01 \end{bmatrix} \tag{7}$$

Substitution of 6 in 5 resulted in:

$$M\ddot{r} + C\dot{r} + Kr = -M.j.\ddot{U}_g(t) \tag{8}$$

M, C and K are mass, damping and stiffness matrixes, respectively and ^{r} are the applied earthquake acceleration and r is the relative displacements of the nods (Zienkiewicz and Taylor, 2000).

DYNAMIC ANALYSIS OF CONCRETE DAM WITH FULL RESERVOIR

Dam displacement equation for the empty reservoir condition was calculated from Eq. 8. When dam reservoir is full, hydrodynamic force term should be added to mentioned equation. That is, the amount of (Q.P) (hydrodynamic force) should be added to the right side of 8. P is nodal unknown matrix (pressure in each point) and Q is hydrodynamic pressure to applied forces conversion matrix at the upstream.

In the previous section finite element form of Helmholtz equation is achieved as follow:

$$E\ddot{P} + A\dot{P} + HR = R \tag{9}$$

$$R = \rho\int_{S_1} Na_n dS \tag{10}$$

Now, the Q matrix which converts the hydrodynamic pressure to force in the interface of reservoir and dam should be extracted.

This can be achieved from 10 that illustrate the boundary condition in the interface of reservoir and dam. In that, equation dam α_n is acceleration in perpendicular direction to common interface S_1. As, it represented in dam displacement equation this acceleration is absolute and this is the Sumiton of dam acceleration related to the earth $(\ddot{r})$ and earth acceleration, related to stagnant viewer ($\ddot{U}_g$ (t)), for this we will have:

$$a_n = na_s = n(N^T.\ddot{U}) \tag{11}$$

$$\ddot{U} = \ddot{r} + \underline{j}.\ddot{U}g(t) \tag{12}$$

In which n is a normal to the surface, Ü is absolute earth acceleration related to stagnant viewer and N is reservoir elements shape function matrix.

Substitution of 11 in 10 results in:

$$R = \rho\left[\int_{S_1} N^T.nN.ds\right].\ddot{U} \tag{13}$$

In which the integral in the bracket is Q^T. Now, by substitution Ü from above and by substitution the integral in the bracket with Q^T will have the following equation:

$$R = \rho Q^T\ddot{r} + \rho Q^T.j.\ddot{U}g(t) \tag{14}$$

By substitution of R in finite element form of Helmholtz equation, 14 can be derived on the base of unknown nodal pressure (P) and dam body acceleration $(\ddot{r})$, then we will have:

$$E\ddot{P} + A\dot{P} + HP = \rho Q^T\ddot{R} + \rho Q^T.\underline{j}.\ddot{U}_g(t) \tag{15}$$

As mentioned earlier dam displacement equation by adding Q.P to the right side 8 is followed as:

$$M\ddot{r} + C\dot{r} + Kr = -M.\underline{j}.\ddot{U}_g(t) + Q.P \tag{16}$$

In this equation r and p are unknown. Then differential equation system is formed with two unknown parameters (r and p) as:

$$M\ddot{r} + C\dot{r} + Kr - Q.P = -M.\underline{j}.\ddot{U}_g(t) \tag{17}$$

$$-\rho Q^T.\ddot{r} + E\dot{P} + H.P = \rho Q^T.\underline{j}.\ddot{U}_g(t) \tag{18}$$

Matrix form of this differential equation system that is also known as movement couple equation is as Eq. 19:

$$\begin{bmatrix} M & 0 \\ PQ^T & E \end{bmatrix} \begin{Bmatrix} \ddot{r} \\ \ddot{P} \end{Bmatrix} + \begin{bmatrix} \dot{C} \\ \dot{A} \end{bmatrix} \begin{Bmatrix} \dot{r} \\ \dot{P} \end{Bmatrix} + \begin{bmatrix} K & -Q \\ 0 & H \end{bmatrix} \begin{Bmatrix} r \\ P \end{Bmatrix} = \begin{bmatrix} -M.j\ddot{U}_g(t) \\ -PQ^T.j\ddot{U}_g(t) \end{bmatrix} \quad (19)$$

By solving this differential equation system unknown parameters r and p (dam nods displacements and pressure) can be calculated in different of reservoir. As is can be seen, the coefficient matrix of this system is not symmetric or well compose and simultaneously solving of these equations are time consuming. Therefore, it can be used repeated method to avoid simultaneously solving of these equations (Zienkiewicz and Taylor, 2000).

DYNAMIC ANALYSIS OF DAM AND DEFINING THE MAXIMUM STRESS AND DISPLACEMENT IN THE STUDY POINTS

According to International Committee on Large Dams (ICOLD) for choosing the earthquake parameters, dam should be resisting against applied credible earthquake and resulted vibration from reservoir. These vibrations should be in linear elastic response domain and any damages are not allowed. Some damages are allowed in limited areas for maximum design earthquake. These damages should be in a way that dam could keep its reservoir water. Therefore, to evaluate the design and construction of arch dam it is essential to have dynamic analysis of that system. For this, by using Riley coefficients that were calculated earlier (modal analysis) and vertical and horizontal component on Koyina earthquake and also by using hydrodynamic force (calculated from Westergard added-mass method), dynamic analysis is done on Karoon-1. Two examples, resulted from dynamic analysis are illustrated in Fig. 10 and 11. Figure 10 shows the total displacement of dam under dynamic analysis. Figure 11 gives the maximum principal stress under dynamic analysis during the time when the earthquake forces are applied. In this study all of the studied points are selected in the upstream of dam.

The Fig. 10 and 11 show the general form of dam and show the amount of stresses and displacements in all parts of it in a specific time. When it's needed to determine the stress and displacement or any other parameters in a special point during the time that loads are applying, such as earthquake loads we can use time history graphs. For space limitation only represented four instances of them below. Figure 12 shown the mid point displacement of dam crest in the longitudinal direction of reservoir (U2) at upstream with the presence of earthquake force in the period. Similarly, Fig. 13 shown the mid point displacement of dam foundation in the longitudinal direction of reservoir (U2) (in river bed level) at upstream with the presence of earthquake force in the period of time. In Fig. 14, is illustrated time history of maximum principal stress of the midpoint of the dam crest and in Fig. 15 time history of principal stress of the midpoint of the dam foundation (in river bed level) under dynamic analysis and in the direction of applied earthquake force is represented.

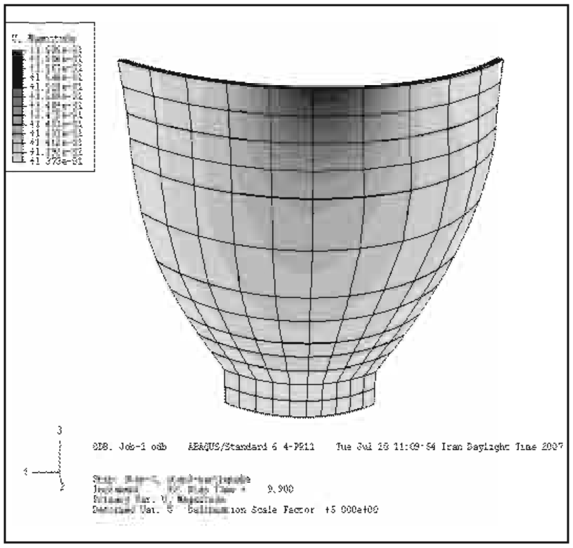

Fig. 10: Total displacement of dam body under dynamic analysis

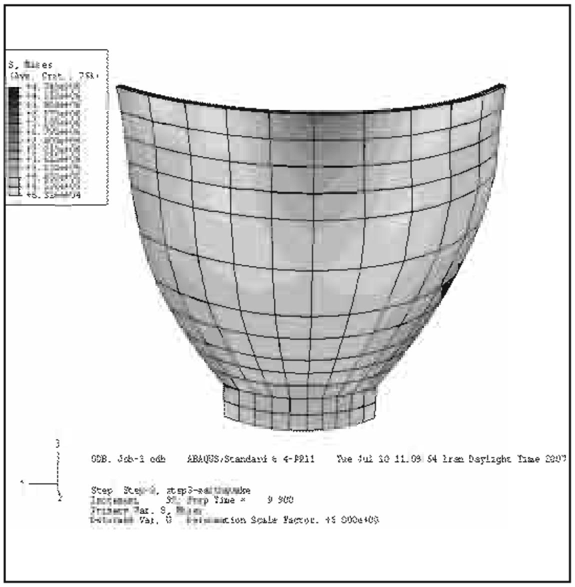

Fig. 11: Maximum principal stress under dynamic analysis

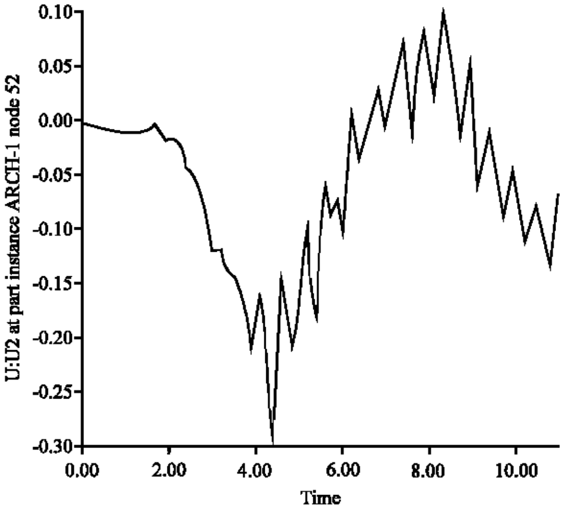

Fig. 12: Time history of mid point displacement of dam crest in the longitudinal direction of reservoir (U2) at upstream

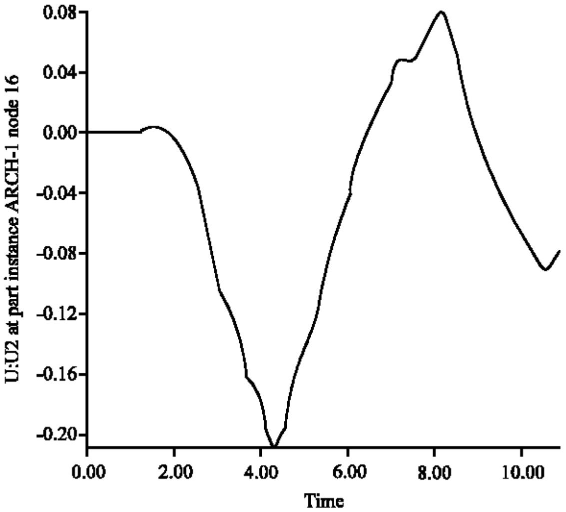

Fig. 13: Time history of the mid point displacement of dam foundation in the longitudinal direction of reservoir (U2) at upstream

According to Fig. 12 and 13, the maximum displacement of the midpoint of crest level center is 30 cm in reservoir water direction and 10 cm in the opposite direction of reservoir water direction. This displacement for the midpoint of the foundation in river bed level in the reservoir water direction is 20 cm and for the opposite direction of reservoir is 8 cm. Likewise from time history graphs maximum principal stresses can be seen in Fig. 14 and 15. The maximum midpoint principal stress of dam crest is 3.5 MPa and this is for the midpoint of foundation level at upstream of dam body is 1.6 MPa.

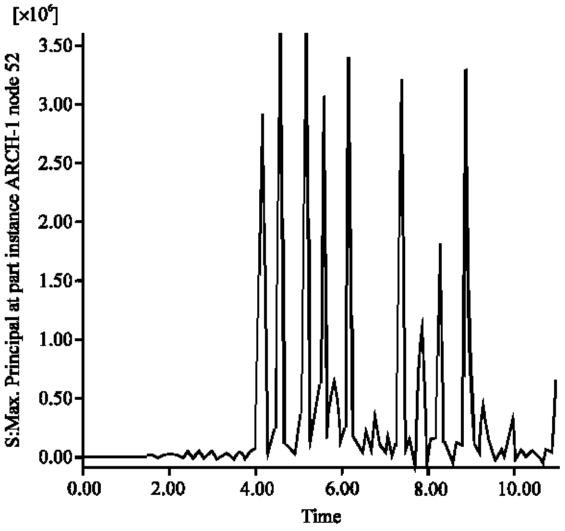

Fig. 14: Time history of maximum principal stress the midpoint of the dam crest under dynamic analysis

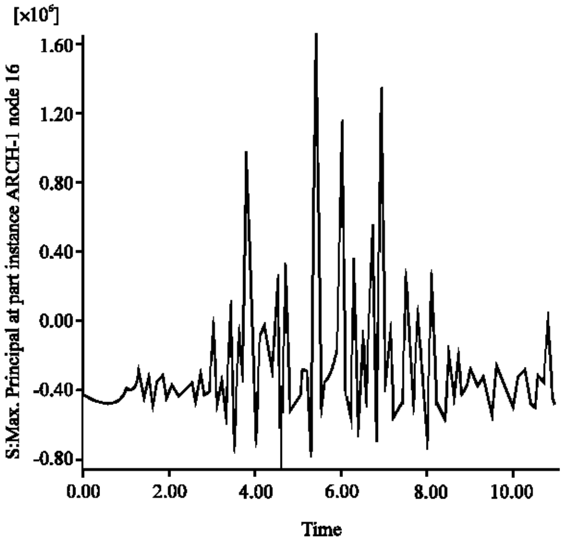

Fig. 15: Time history of maximum principal stress of the midpoint of the dam foundation under dynamic analysis

DYNAMIC ANALYSIS AND DETERMINATION OF MAXIMUM STRESS AND DISPLACEMENT IN STUDIED POINTS OF DAM WITH SUPPORTS

In this section, dam body with rock supports are modeled in ABAQUS in the case of $(1 \le E_r/E_c \le 2)$ according to related sections. By using damping coefficients that are obtained from modal analysis, vertical and horizontal elements of Koyina earthquake acceleration are applied on Karoon-1 dam and its supports. Then, dynamic analysis

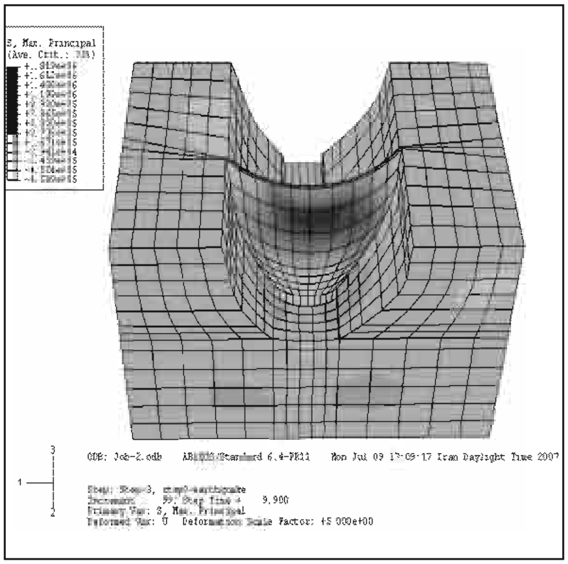

Fig. 16: Total principal stress under dynamic analysis

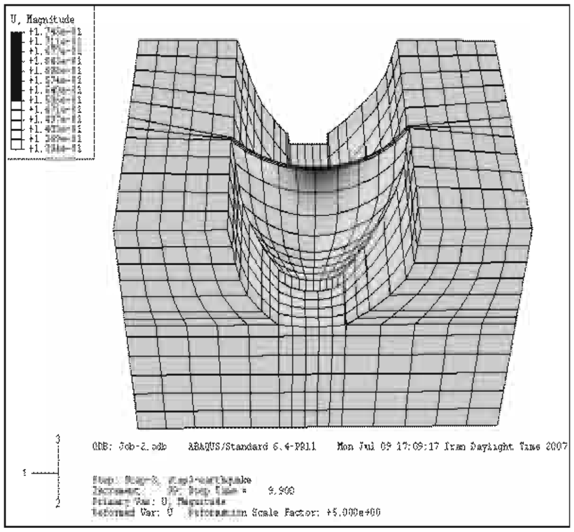

Fig. 17: Total displacement under dynamic analysis

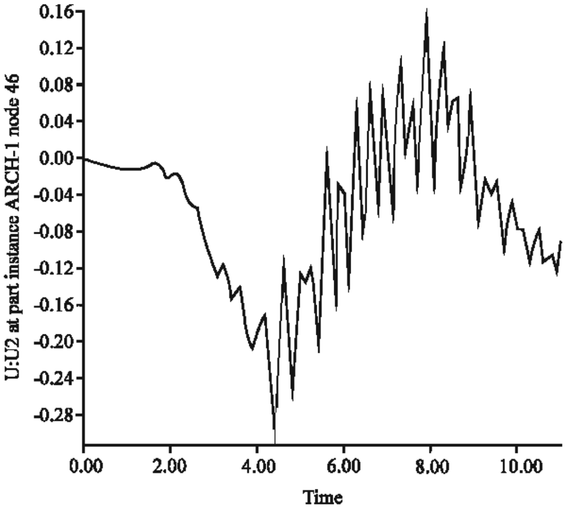

Fig. 18: Midpoint displacement history of dam crest with supports in the longitudinal direction of reservoir (U2) under dynamic analysis

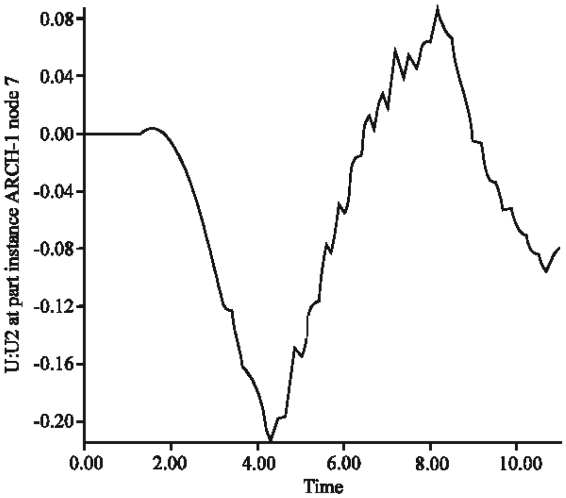

Fig. 19: Midpoint displacement history of dam foundation with supports in the longitudinal direction of reservoir (U2) under dynamic analysis

was done on it. Mass of water behind dam that vibrates with dam is considered in Westergard added mass computational method. Dynamic analysis results are illustrated in Fig. 16 and 17 typically that are total principal stress and displacement under dynamic analysis, respectively.

Similarly, Fig. 18 and 19 show midpoint displacement history of dam crest and foundation with supports in the longitudinal direction of reservoir (U2). According to Fig. 19, the maximum displacement of the midpoint of crest is 29 cm in reservoir water direction and 21 cm for the midpoint under dynamic analysis in the time that earthquake forces are applied. This amount for midpoint of crest in the opposite direction of reservoir water is 16 cm and for foundation midpoint is 8 cm. As same from time history graphs maximum principal stress are presented in Fig. 20 and 21. Maximum principle stress for the midpoint of dam crest with supports is almost 10 MPa and for the midpoint of foundation level at upstream is 6 MPa.

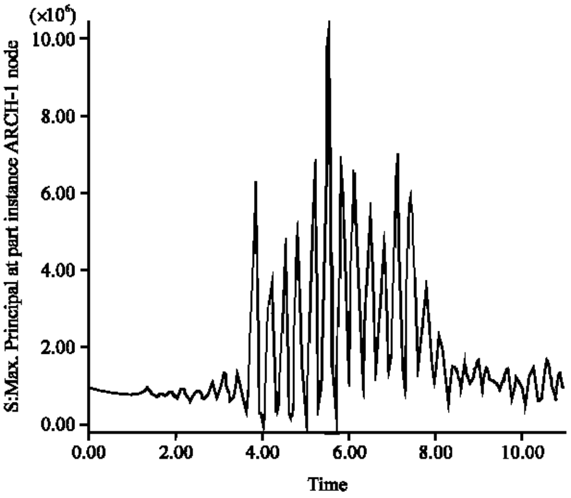

Fig. 20: Time history of maximum principal stress at midpoint o dam crest with supports under dynamic analysis

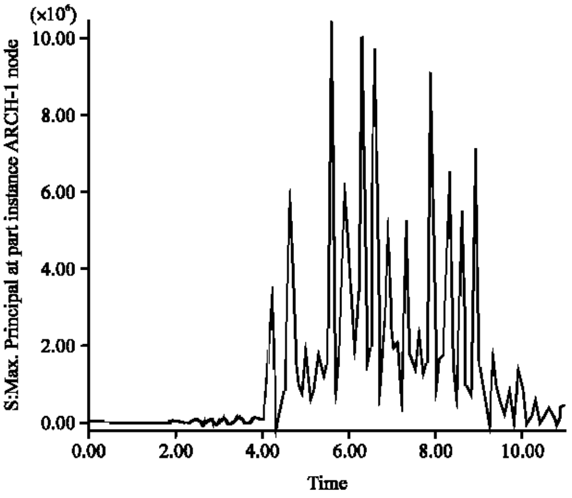

Fig. 21: Time history of maximum principal stress at midpoint o dam foundation with supports under dynamic analysis

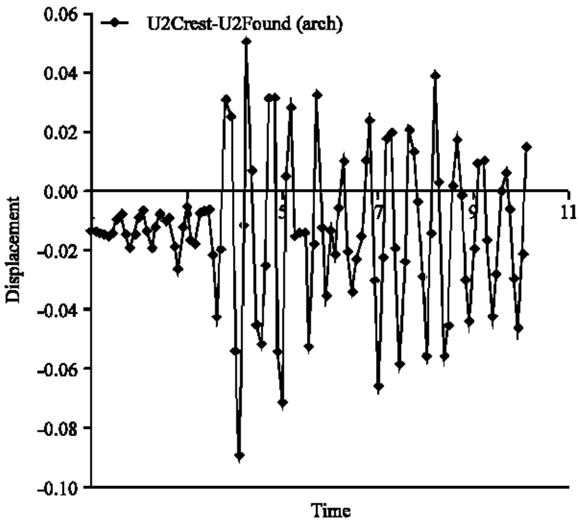

Fig. 22: Dam crests midpoint displacement variation in related to the foundation displacement

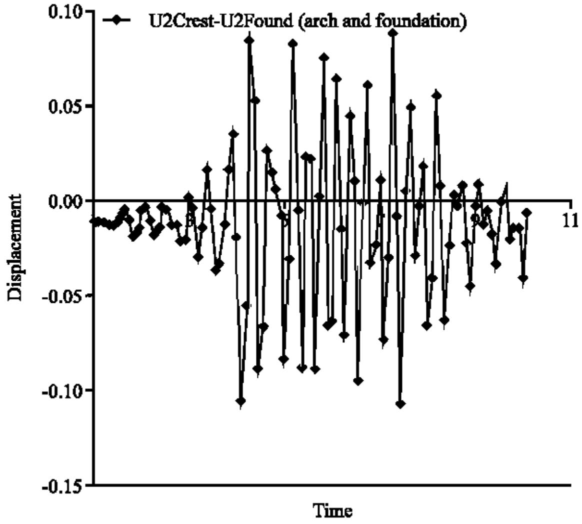

Fig. 23: Displacement variation between midpoint of crest and foundation in reservoir longitudinal direction for the case of dam with supports

As mentioned earlier, earthquake response is for the case that ($1 \leq E_r/E_c \leq 3$). At next step dynamic analysis was done for the case that ($E_r/E_c = 3$) and for the space limitation related, figures were not shown. In this case maximum displacements of the midpoint of crest level center are 29 cm in reservoir water direction and 9 cm in the opposite direction of reservoir water direction (U2). These amounts for the midpoint of the foundation in river bed level in the reservoir water direction are 20 cm and for the opposite direction of reservoir is 8 cm. The maximum midpoint principal stress of dam crest is 4.7 MPa and this is for the midpoint of foundation level at upstream of dam body is 2 MPa. By comparison of these there cases it can be founded for three cases the displacement of the midpoint of foundation (at river bed) is same and the displacement of midpoint of dam crest with supports is more close and for the case of without supports in the opposite direction of reservoir it is to some extent (almost 5 cm) different. Also, there is a regular relationship between resulted maximum principal stresses. It can be seen that maximum principal stresses are increased from case ($E_r/E_c = 3$) to ($1 \leq E_r/E_c \leq 2$), respectively, when there are no supports.

By noting that when in the earthquake forces are applied, total dam body has displacement simultaneously, therefore in next step displacement variation in different points was studied.

For the case without supports these variation are calculated for the midpoint of crest and foundation (Fig. 22).

The maximum amounts were 9 cm for the reservoir water direction and 5 cm for the opposite reservoir water direction. For the case with supports ($1 \leq E_r/E_c \leq 2$) according to Fig. 23 dam crest displacement variations in related to the foundation were 11 cm in reservoir water direction and 9 cm in the opposite reservoir water direction.

CONCLUSION

According to dynamic analysis results and applied earthquake records, for the dam without supports the maximum displacements in the midpoint of the dam crest are 30 cm at the reservoir water direction and 10 cm at the opposite of reservoir water direction (U2). These amounts for the midpoint of dam body foundation are 20 cm at the reservoir water direction and 8 cm at the opposite of reservoir water direction. These displacements are large and they will cause cracks in dam. All of the studied points are selected in the upstream of dam.

According to dynamic analysis of dam without supports, maximum principal stress in the midpoint of crest was 3.6 MPa and this amount for the midpoint of foundation level was 1.6 MPa.

Form dynamic analysis of dam with supports for the case of ($1 \leq E_r/E_c \leq 2$), the maximum displacement of the midpoint of crest is 29 cm in reservoir water direction and 21 cm for the midpoint of dam body foundation under dynamic analysis in the time that earthquake forces are applied. These amounts for midpoint of crest in the opposite direction of reservoir water are 16 cm and for foundation midpoint 8 cm.

Similarly, form dynamic analysis of dam with supports for the case of ($1 \leq E_r/E_c \leq 2$) and from time history graphs, maximum principle stress for the midpoint of dam crest is almost 10 MPa and for the midpoint of foundation level at upstream is 6 MPa.

By comparison of there mentioned cases it can be founded the displacement of the midpoint of foundation (at river bed) is same and the displacement of midpoint of dam crest with supports is more close (1 cm) and for the case of without supports in the opposite direction of reservoir it is to some extent large (almost 5 cm). Also there is a regular relationship between resulted maximum principal stresses. It can be seen that maximum principal stresses are decreased from case ($E_r/E_c = 3$) to ($1 \leq E_r/E_c \leq 2$), respectively, when there are no supports.

By comparison the results from the analysis of dam without with and with supports ($1 \leq E_r/E_c \leq 2$) it can be seen that there are not a lot of difference between displacement graphs and maximum displacement of study points are same. Results showed maximum principal stresses have little differences. For the dam with supports maximum principal stress in the midpoint of the crest has increasing in related to midpoint of foundation.

For the case of dam with supports displacement variation between the midpoint of the crest and maximum displacements are 9 cm for the reservoir water direction and 5 cm for the opposite reservoir water direction. For the case with supports dam crest displacement variations in related to the foundation were 11 cm in reservoir water direction and 9 cm in the opposite reservoir water direction, therefore for the case with supports this variation are increased.

REFERENCES

ABAQUS, 2006. Abaqus Analysis User's Manual. (Ver 6.6) http://www.google.com.pk/ search?hl=en&q=abaqus+analysis+user%27s+manual+2006+%28V6.6%29&meta.

Bathe, K.J., 1996. Finite Element Procedures. 1st Edn., Prentice Hall Inc. Englewood Cliffs, New Jersey, ISBN: 0-13-301458-4, pp: 735.

Christopoulous, C., P. Léger and A. Filiatrault, 2003. Seismic sliding response analysis of gravity dams including vertical accelerations. J. Earthquake Eng. Vibrat., 2: 189-200.

Ftima, M.B. and P. Léger, 2006. Seismic stability of cracked concrete dams using rigid block models. Comput. Struct., 84: 1802-1814.

Ghaemian, M. and A. Ghobarah, 1999. Non-linear seismic response of concrete gravity dams with dam reservoir interactions. J. Eng. Struct., 21: 306-315.

Javanmardi, F., P. Léger and R. Tinawi, 2005. Seismic water pressure in cracked concrete gravity dams: Experimental study and theoretical modeling. J. Struct. Eng., ASCE, 131: 139-150.

Leclerc, M., P. Léger and R. Tinawi, 2003. Computer aided stability analysis of Gravity Dams-CADAM. Int. J. Adv. Eng. Software, 34: 403-420.

Léger, P. and M. Leclerc, 1996. Evaluation of earthquake ground motions to predict cracking response of gravity dams. Eng. Struct., 18: 227-239.

Léger, P. and F. Javanmardi, 2006. Seismic stability of concrete gravity dams strengthened by rock fill buttressing. J. Soil Dynamics Earthquake Eng., 27: 274-290.

Léger, P. and P. Alliard, 2008. Earthquake safety evaluation of gravity dams considering aftershocks and reduced drainage efficiency. J. Eng. Mech., 134: 12-22.

Lotfi, V. and O. Omidi, 2007. Seismic analysis of concrete gravity dams by a decoupled modal approach in time domain. Electron. J. Struct. Eng., 3: 102-116.

Nwankwo, L.I. and C.O. Akoshile, 2005. Monitoring of external background radiation level in Asa Dam Kwara State, Nigeria. J. Applied Sci. Environ. Mgt., 9: 91-94.

Samii, A. and V. Lotfi, 2007. Comparison of coupled and decoupled modal approaches in seismic analysis of concrete gravity dams in time domain. Finite Elements Anal. Design, 43: 1003-1012.

Zhou, J., G. Lin, T. Zhu, A.D. Jefferson and F.W. Williams, 2000. Experimental investigations into seismic failure of high arch dams. J. Struct. Eng., ASCE, 126: 926-935.

Zienkiewicz, O.C. and R.L. Taylor, 2000. The Finite Element Method. 5th Edn. Butterworth-Heinemann, Oxford, UK, ISBN-10: 0340759844, ISBN-13: 978-0340759844 .