Hydro-Thermal Safety Control of Karun-1 Dam under Unusual Reservoir Level Reduction

Mojtaba Labibzadeh [1], Amin Khajehdezfuly [1]

[1.] Department of Civil Engineering, Faculty of Engineering, Shahid Chamran University, Ahvaz, Iran
Labibzadeh_m@scu.ac.ir

Abstract: Karun-1dam safety was examined through carrying over a 3D finite elements analysis. The dam as well as its foundation and abutments have been modeled in a relatively exact manner. Furthermore, the vertical contraction joints were simulated in calculations. Hydrostatic, gravity and thermal effects have been taken into account as the load collections. 10m reduction of reservoir level from normal water level of the dam reservoir was applied in the modeling and the possibility of initiate and development of cracks in dam body was investigated by means of monitoring of principal stresses. The obtained results showed that mentioned possibility existed and the downstream face of the dam in vicinity of the abutments near to crest level probably experiences the tensile cracks. [Journal of American Science. 2010;6(11):179-184]. (ISSN: 1545-1003).

Keywords: Arch dam, Thermal, Contraction joints, Cracks, Dam safety

1. Introduction

Usually, after a service life of several decades, a considerable percentage of existing concrete dams, illustrate some kind of deterioration. Based on the studies performed examining the causes of this phenomenon, the ASR (Alkali-Silica Reaction) and unusual extreme loading such as earthquake excitations and reservoir level fluctuations are the main reasons of this dam stiffness and strength degradation (Swamy and Al-Asali, 1988; Ahmed et.al., 2003; Pedro, 1999). Sometimes mentioned degradation is concomitant with the occurrence of local cracks in dam body which can be a threat for the dam safety. Holding this issue in mind, the main objective of this paper is to investigate the possibility of damage occurrence in Karun-1 arch concrete dam due to unusual reduction in its reservoir level about to 10m from the normal water level. Karun-1 dam is a double curvature concrete dam located in northeastern of Khouzestan province of Iran in vicinity of Masjedsoleiman city which its construction were completed in 1976. The dam height is approximately 200m from the base level, its dam crest thickness is 6m and the thickness of the dam at base level is about 380m.

In this investigation, as well as the hydrostatic pressure of reservoir and dam weight, the thermal loads due to air temperature changes have been assessed in the modeling. Thermal loads has a major effects in arch concrete dam stability analysis (Sheibani and Ghaemian, 2006; Ardito, et. al, 2008; Léger and Leclerc 2007; Léger and Seydou 2009; Labibzadeh and Khajehdezfuly, 2010). Furthermore, for achieving the more and more accurate in analysis, the effect of vertical contraction joints in hydro-thermal simulation of the dam was taken into account. Even though the latter issue was no major challenge for dam engineers in their analyses and designs, this factor can affect the dam safety analysis results significantly (Labibzadeh and Khajehdezfuly, 2010). In the past recent years, the amount of the rainfall has been decreased considerably in Iran specifically in Karun-1 dam water fall domain. Consequently, the reservoir volume of the dam has been reduced gradually. As the water level of the dam was decreasing, the safety control of Karun-1 dam became more highlighted due to the fact that the electrical energy generation of the dam has been increased recently thorough the development of the second phase of its power plant. It is the main reason of doing this research. The proposed study has been done by means of a relatively 3D exact simulation of the geometric, material behavior and boundary conditions of the dam. Principal stress tensors, displacement vectors were selected as stability indexes safety control and examined. It will be shown that under the reservoir level reduction up to 10m the possibility of initiate and development of cracks in downstream face of the dam exists.

2. Material and Methods

As it was mentioned in previous section, the hydrostatic, gravity and thermal loads have been simulated in the proposed model. The governing equation for heat transfer in three-dimensional region is (Reddy and Gartling, 2001):

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(k_{ij}\frac{\partial T}{\partial x_j}\right) + Q \qquad (1)$$

Where ρ = density $\left(\frac{kg}{m^3}\right)$; C = specific heat $\left(\frac{J}{kgK^0}\right)$; T = temperature of medium K^0; t =time (s); k_{ij} = Cartesian components of conductivity tensor $\left(\frac{W}{m^2K^0}\right)$; Q =internal heat generation per unit volume $\left(\frac{W}{m^3}\right)$and ij summation on repeated subscripts (i,j=1,2,3).

The above mentioned equation with the following boundary conditions generates the mathematical model of heat transfer which in turn is the physical model:

$$T = \bar{T} \quad on \quad \Gamma_T \qquad (2a)$$

$$-\left(k_{ij}\frac{\partial T}{\partial x_j}\right)n_i = -q_a + q_c + q_r \quad on \quad \Gamma_q \qquad (2b)$$

Where q_a = applied flux $\left(\frac{W}{m^2}\right)$; q_c = convective flux $\left(\frac{W}{m^2}\right)$; q_r = radiative flux $\left(\frac{W}{m^2}\right)$and n_i = Cartesian component of unit normal boundary vector.

In our problem the $Q, \Gamma_T, \Gamma_q, \bar{T}$ and q_a are illustrative of hydration, concrete-water interface, exposure surface, reservoir temperature and solar radiation flux respectively.

Implementing the thermal transfer equation (1) through the powerful numerical approximate method F.E.M results in:

$$M^e\dot{T} + K^eT = Q^e + q_a - CT + F_{hc} - RT + F_{hc} \qquad (3)$$

Where $\dot{T}$ denotes the rate of change of temperature with time and:

$$M^e = \iiint_{\Omega_e} \rho C \psi \psi^T \, d\Omega \qquad (4)$$

The equivalent thermal mass matrix of an element;

$$K^e = \iiint_{\Omega_e} k\left(\frac{\partial\psi\partial\psi^T}{\partial x^2} + \frac{\partial\psi\partial\psi^T}{\partial y^2} + \frac{\partial\psi\partial\psi^T}{\partial z^2}\right) d\Omega \qquad (5)$$

The equivalent thermal stiffness matrix of an element;

$$Q^e = \iiint_{\Omega_e} \psi Q \, d\Omega \qquad (6)$$

The equivalent internal heat generation vector of an element;

$$q_a = \iint_{eq} \hat{\psi}\, q_a \, ds \qquad (7)$$

The equivalent applied heat flux vector of an element;

$$C = \iint_{eq} \hat{\psi}\, h_c \, ds \qquad (8)$$

The equivalent convectional heat matrix of an element;

$$R = \iint_{eq} \hat{\psi}\, h_r \, ds \qquad (9)$$

The equivalent radiative heat matrix of an element;

$$F_{h_c} = \oint\!\!\int_{eq} \hat{\psi} h_c T_a ds \qquad (10)$$

The equivalent convectional heat vector of an element;

$$F_{h_r} = \oint\!\!\int_{eq} \hat{\psi} h_r T_a ds \qquad (11)$$

The equivalent radiative heat vector of an element;

In above equations:

ψ is defined as the interpolation function in the element domain. The sign ^ indicates the restriction of the interpolation function to an element face and the ds = element surface area. h_c is defined as the convection coefficient $\left(\frac{W}{m^2K^0}\right)$and implemented in definition of the q_c (exchange of the heat by convection as a result of temperature differences between Γ_q and ambient temperature) through the Newton's cooling law:

$$q_c = h_c(T - T_a) \tag{12}$$

Where T = temperature of Γ_q boundaries and T_a = ambient temperature. These two temperatures are measured based on Kelvin degrees. In this paper, T_a is considered as the air temperature and T is the concrete temperature at the external surface of the dam. h_c was calculated in this study by the following relatively accurate formulation (Duffie and Beckman 1980):

$$h_c = 5.7 + 3.8V \tag{13}$$

V = fluid speed (wind speed) (m/s). h_r represents the linearized radiation coefficient $\left(\frac{W}{m^2}\right)$ and used in evaluating of exchange of the heat by the electromagnetic radiation (Stefan-Boltzman law) through the below manner:

$$q_r = eC_s\left(T^4 - T_a^4\right) \tag{14}$$

e =emissivity of surface and C_s = Stefan-Boltzman constant [$5.669\times10^{-8}\left(\frac{W}{m^2}\right)$]. The relation (14) can be rewritten as follows to have a friendlier user form:

$$q_r = h_r(T - T_a) \tag{15}$$

Where h_r is defined as:

$$h_r = eC_s\left(T^2 + T_a^2\right)(T + T_a) \tag{16}$$

q_a identifies the amount of absorbed solar energy by the body of system (in our study the dam) and described by the below equation:

$$q_a = a\bar{H} \tag{17}$$

In which $\bar{H}$ = total amount of solar energy reaching the surface and a = solar absorptivity of the surface.

Rearranging and assembling the equation (3) over the entire domain yields the following tensorial form of the primarily ordinary differential equation (1):

$$M\dot{T} + \hat{K}T = \hat{F} \tag{18}$$

Where

$$\hat{K} = K + C + R \tag{19a}$$

$$\hat{F} = Q + q_a + F_{h_c} + F_{h_r} \tag{19b}$$

Equation (18) presents a system of nonlinear dependent differential equations because the components of tensor $\hat{K}$ depends on the temperature values T and T_a. Since, in our study, the smallest period of considered time in calculation was set to a day (24 hours), so the variation of temperature with respect to time became very small value and therefore the first term of equation (18) was neglected. The sequence of solution has been summarized as in figure 1.

3. Results and Discussions

Following the method described in previous section, the Karun-1 arch concrete dam has been analyzed under the effect of 10m unusual reduction of its reservoir level from normal water level. The most dangerous situation which threatens the dam safety was obtained when the level of the lake came down to 480m from the free sea level. This means that the reservoir level reduces about to 10m from its normal water level. The counters of dam displacements at this level have been shown in figure 2.

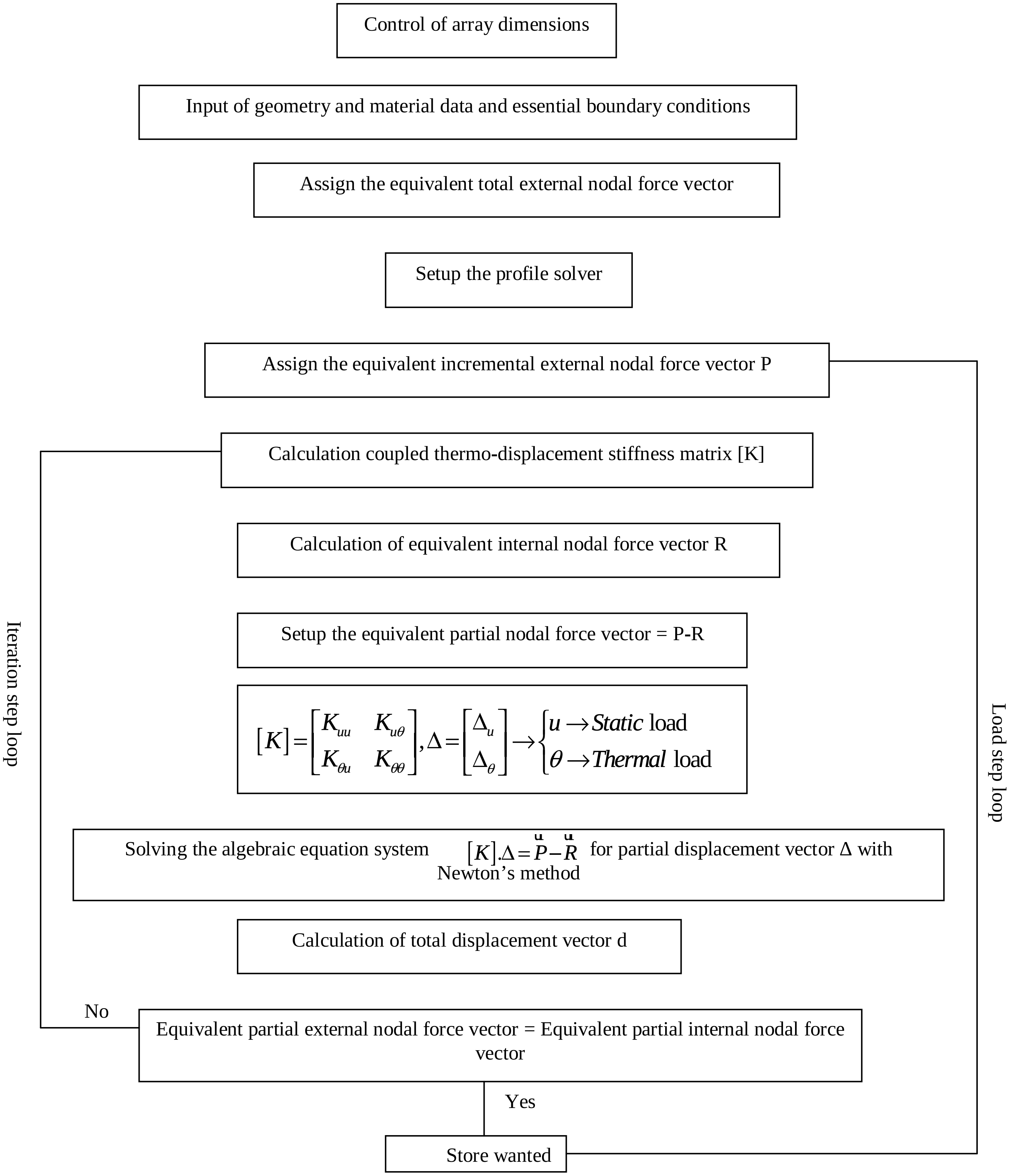

Figure1. The numerical solution of proposed problem

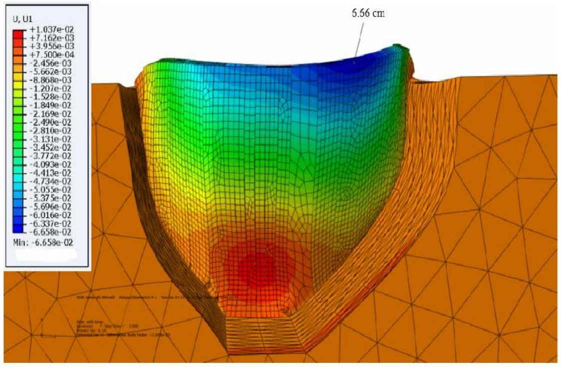

Figure 2. the Karun-1 dam deflections: the reservoir level= 480m

The face which is observed in figure 2 is the upstream face of the dam. As it can be seen from that picture, the largest displacement is about to 6.67 cm at crest level toward the upstream face. This value is not too large for the dam with the mentioned dimensions form the engineering point of view. In figure 3 the pattern of displacements at crest level of the dam was depicted.

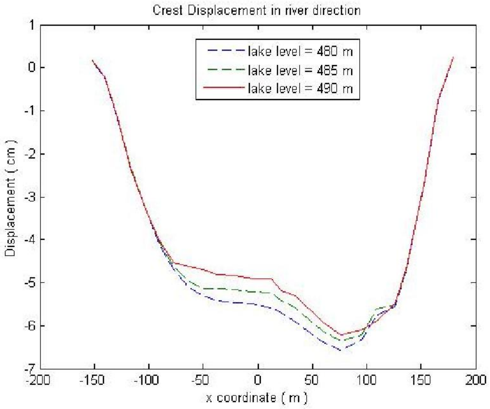

Figure 2. displacements in crown of dam

As it can be seen from figure 2 the displacements are not symmetric with respect to the middle of the crest. This is due to the fact that this arch dam has not the symmetric geometry and was designed with two different arch radius and centers at each level. Moreover, the biggest displacements obtained for the reservoir level equal to 480m. This confirms that the worse situation is occurred when the lake level of the dam decreased about 10m from the normal water level.

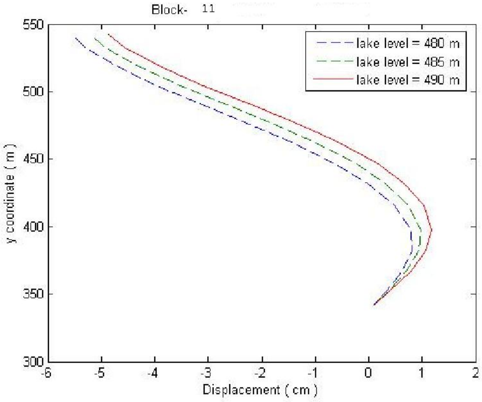

Figure 3. displacements along the height of the dam

The variation of deflections along the height of the block no.11 (the highest block of the dam) has been illustrated in figure 3. This picture verifies that under the reduction of reservoir water level, the lower parts of the dam deflect towards the downstream whereas the upper parts tend to move to upstream direction. This configuration of the dam cannot be captured in two dimensions and so in this study the three dimensional model has been used.

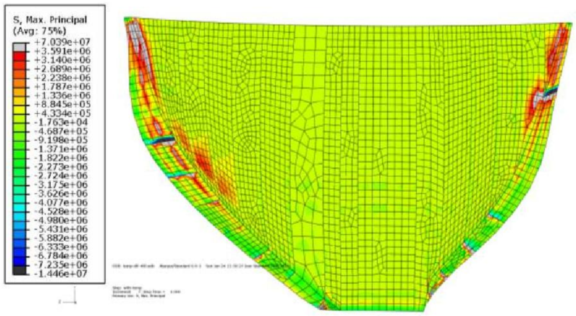

Figure 4. maximum principal stresses, downstream

For assessing the potential of cracking through the unusual reduction of water level, the attention should be focused on maximum and minimum stresses. The maximum stresses can inform us about the cracking due to tensile nature and minimum stresses can tell us about the cracking due to crushing of the concrete. The largest maximum stresses occurred on downstream face of the dam and has been shown in figure 4. From this graph it can be deduced that there are regions on downstream face near the abutments which tensile cracking can be occurred (the red color regions). It is worth to mention that the maximum allowable tensile strength of dam concrete can be considered as 3.5 MPa. So, author of this paper suggests that the operation of the dam should be organized in such a way that this amount of water level reduction is avoided. The minimum principal stresses are depicted in the next figure. As it can be seen from it the crushing of concrete cannot be happen because the stress values are smaller than the compressive strength of mass concrete (40 MPa).

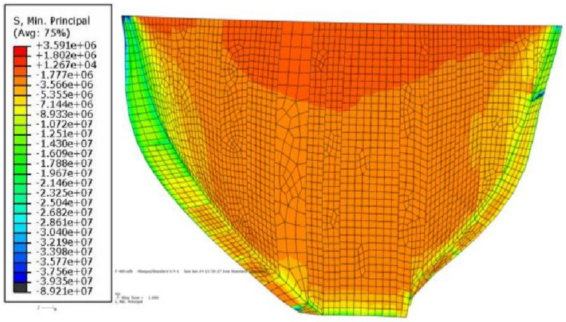

Figure 5. minimum principal stresses, downstream face.

4. Conclusion

After reviewing the results of stress analysis of Karun-1 arch concrete dam it was cleared that the unusual reduction of the reservoir level dam can be the source of cracking on downstream face of the dam in tensile mode and such a reduction should be avoided by proper operation programming.

Acknowledgements:

Author is so grateful to Yaqub Arab and Ebrahim Barati Choobi, the head his assistant in Dam Stability Control Center of Water&Power Authority of Khouzestan Province of Iran.

Corresponding Author:
Dr. Mojtaba Labibzadeh
Head of Civil Department,
Faculty of Engineering, Shahid Chamran University,
Ahvaz, Iran.

E-mail: labibzadeh_m@scu.ac.ir

References

1. Swammy, RN and Al.Asali, MM. Engineering properties of concrete affected by alkali-silica reaction. ACI Material Journal, 1988, 85:367-374.
2. Ahmed, T., Burley, E., Rigden, S., Abu-Tair Al. The effect of alkali reactivity on the mechanical properties of concrete. Construction Building Material, 2003; 17(2):123-144.
3. Pedro, JO, editor. Arch dams, Designing and monitoring for safety. Wien: Springer, 1999.
4. Sheibani, F., and M. Ghaemian. Effects of environmental action on thermal stress of Karaj concrete arch dam. J. Engineering Mechanics, 2006; 132 (5): 532-544.
5. Ardito, R., Maier, G., and G., Massalongo. Diagnostic analysis of concrete dams based on seasonal hydrostatic loading. J. Engineering Structures, 2008; 30:3176-3185.
6. Léger, P., and M., Leclerc. Hydrostatic, temperature, time-displacement model for concrete dams. J. Engineering Mechanics, 2007; 267-278.
7. Léger, P., and S., Seydou. Seasonal thermal displacements of gravity dams located in northern regions. J. Performance of Constructed Facilitis (ASCE), 2009; 23 (3): 166-174.
8. Labibzadeh, M. and A. Khajehdezfuly. Effect of vertical contraction joints thermo-static stability of Karun-1 arch dam. Trends in Applied Sciences Research, 2010; 6(1):31-42.
9. Labibzadeh, M., Sadrnejad, S. A., Khajehdezfuly, A. Thermal assessment of Karun-1 dam. Trends in Applied Sciences Research, 2010; 5(4):251-266.
10. Reddy, J. N. and Gartling, D. K. The finite element method in heat transfer and fluid dynamics. CRC, Boca Raton, Fla., 2001; 5-108.
11.

6/9/2010