Analysis of a System of Dam-Foundation-Reservoir under Full Loading

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Abstract

Types of loadings commonly considered for analysis of a system of arch dam-foundation-reservoir include static loads, thermal loads and seismic loads. Since arch dams are thin concrete structures, thermal loading is of paramount importance for them. During a yearly cycle of temperature change in dam site, there are moments of peak stress distribution, which occur within a certain time range of extremum seasonal temperatures. To account for extreme conditions, simultaneous application of different loadings have been performed in this study. In other words, in moments of peak thermal stresses, seismic and static loads are also applied to the system. In this paper, an arch dam in Iran is selected as the case study. Properties of the dam are previously obtained, using calibration analysis. Four different cases are analyzed under full loadings including, dam under full loading in warm and cold seasons of the year with two cases of empty and full reservoir conditions. Using the results could give insight on extremum condition of loading for a concrete arch dam.

Keywords: concrete arch dam, thermal loading, seismic loading, dam-foundation-reservoir system.

1. INTRODUCTION

Thermal loading has more severe effects on thin concrete structures such as arch dams. When the effects of thermal loading is combined with other influential loadings, such as static and seismic loads, the severity of the effects increases. Therefore superposing the effects of all involving loadings should be correctly considered. Leger et al. (1993) developed a numerical model to calculate the nodal temperatures in a concrete gravity dam. They found that the temperature gradient near surfaces of the dam causesconsiderable tensile stresses, which affect global distribution of stress in the dam body.Sheibany and Ghaemian (2006) investigated the reason of cracking for an arch dam. They concluded that two dimensional modelling of an arch dam leads to underestimation of thermal effects and 3D model is required. They also mentioned that temperature variation within dam body might lead to surface cracking in most cases. Stucky and Derron (1992) proposed a numerical method that, based on ambient temperature, could estimate the nodal temperature in the thickness of the dam. They claimed that their method could yield conforming responses with respect to real data, acquired from an arch dam. Bofang (1997) developed an empirical formulation to estimate reservoir water temperature at desired depth of reservoir on desired day of the year. Their method is based on ambient weather data and conforms well to numerous dams in the world.

Seismic analysis of concrete dams is performed under numerous assumptions. One common method in engineering practice is considering zero mass for foundation of dams in a system of dam-foundation-reservoir. Massless foundation assumption was first proposed by Clough et al. (1985). Later Leger and Boughoufalah(1989) compared this method with other viable options and concluded that although stress magnitudes are overestimated, it still is the easiest way to implement the earthquake in numerical models.

In this paper, a comprehensive analysis of a system of arch dam-foundation-reservoir is performed under thermal, static and seismic loadings. To do so, a series of analyzes are considered in step-by-step format. At the first step, a thermal analysis is conducted to obtain nodal temperatures within body of the dam for a full year. Based on the results, thermoelastic simulation of the system is performed and according to peak values of stresses for cases of empty and full reservoir, two extremum conditions of thermal stresses in one year, including warm and cold seasons of the year, are extracted. In the next step, static loads, including dam's self weight and reservoir's hydrostatic pressure are applied to the system and the results are employed for the final step, which is seismic analysis of the system under all loadings. At the final step, effects of considering seismic loads in different times of the year are investigated. All interactions, including dam-reservoir and foundation-reservoir interactions, are considered in the numerical model.

2. EQUATIONS

To simultaneously consider all loadings involved in the analysis, strain-temperature equations, equilibrium equations and equations of motion are solved, which are described in the following.

2.1 HEAT TRANSFER CONSTITUTIVE LAW

Constitutive equation of thermal conduction is given by Reddy and Gartling(2001):

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

where, ρ is density, c is specific heat, T is temperature of medium, t is time, k_{ij} is conductivity tensor and Q is internal heat generation per unit volume.

The above equation is solved under following boundary conditions:

$$\begin{aligned} T &= T_w && On\ \Gamma_w \\ q = -k \frac{\partial T}{\partial n} &= q_c + q_r - q_a && On\ \Gamma_q \end{aligned} \tag{2}$$

where, q_c is convective flux, q_r is radiative flux, q_a applied fluxand Γ_w and Γ_q are surfaces in contact with water and air respectively.

2.2 SOLID DOMAIN

To generate thermal strain following formulation can be employed:

$$\varepsilon^T = \alpha(\theta)(\theta - \theta^0) - \alpha(\theta^i)(\theta^i - \theta^0) \tag{3}$$

where, θ is current temperature, θ^i is the initial temperature, θ^0 is the reference temperature, and α is the thermal expansion which is a function of temperature. With thermal strain tensor in hand, one can calculate thermal stressesusing Hook's law.

Governing equations of motion for the dam-foundation system are as followed:

$$\mu \nabla^2 u + (\lambda + \mu)\nabla\nabla u + \rho f = \rho \ddot{u} \tag{4}$$

where, ρ is density, μ and $\lambda$are Lame constants and f is body force.Equilibrium equations are obtained by dropping acceleration term in eq. 4.

2.3 FLUID DOMAIN

Hydrodynamic pressure distribution in reservoir is governed by Laplace equation:

$$\nabla^2 p = \frac{1}{c^2} \ddot{p} \tag{5}$$

where, p is hydrodynamic pressure and c is the wave propagation speed in fluid.

2.4 FINITE ELEMENT DISCRETIZZTION

Finite element formulations for the system of dam-foundation-reservoirare obtained as:

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = F_s + F_r + F_e \tag{6}$$

$$[G]\{\ddot{p}\}+[D]\{\dot{p}\}+[E]\{p\}=-\rho[Q]^T\{\ddot{U}\}+F_f \quad (7)$$

where, [M] is mass matrix, [C] is damping matrix, [K] is stiffness matrix, F_s is seismic force vector, F_r is reservoir related force vector, F_e is external force vector, [G] is equivalent mass matrix of reservoir domain, [D] is equivalent damping matrix of reservoir domain, [E] is equivalent stiffness matrix of reservoir domain, [Q] is coupling matrix and F_f is fluid related force vector.

Eqs. 6 and 7 are coupled together and should be solved simultaneously to obtain response of whole system in terms of displacement and pressure.

Boundary conditions of the problem include the zero-pressure surface of the reservoir, non-absorbing far-end of the reservoir and mutual interaction on the interface of solid and fluid regions.

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3. MODEL DESCRIPTION

For case study of the method, ZayandehRud double curvature concrete arch dam was selected. Its tallest monolith is 95.5 m high and has 28.72 m thickness in bottom and 6.5 m thickness at crest level. A view of the dam is shown in Fig. 1.

Figure 1. ZayandehRud arch dam

To develop a numerical model of the dam, a system of dam-foundation-reservoir was considered with reservoir length approximately equal to 5 times of dam height.

Finite element model of the system of dam-foundation-reservoir is represented in Fig. 2. Three layers of quadratic 20-node elements were employed to mesh the dam body. Same type of element were utilized for foundation and reservoir. In numerical model, the effects of galleries and spillways are neglected.

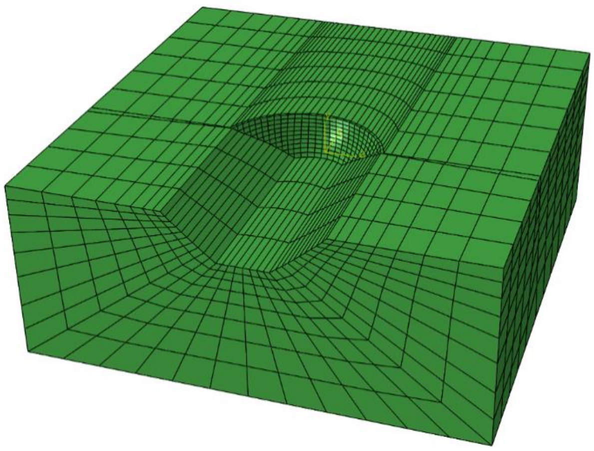

Figure 2. Finite element model of the system

To perform the comprehensive simulation, step-by-step analyzes were considered. At first step a thermal analysis, using the material properties of Table 1, was performed. A sine function to estimate the ambient air temperature at any time of the year was selected, which is reported as follows:

$$T_a(t) = 12.45 - 12.52\cos(\omega(t + 2.02)) \tag{8}$$

where, t is the time of the year in month.

The air temperature sine function and reservoir depth fluctuation are plotted in Fig. 3.

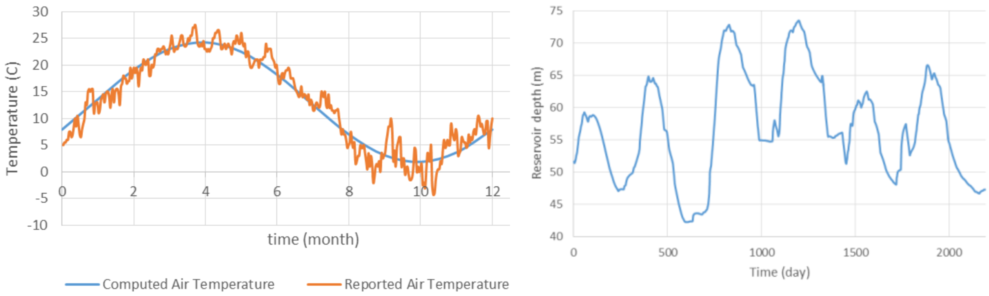

Figure 3. Computed air temperature (left), reservoir depth fluctuation (right)

Using air temperature since function and reservoir depth, Bofang's empirical formulation (Bofang 1997) was employed to obtain water temperature in any desired depth of reservoir at any time of year.

Table 1- Thermal properties

Parameter	Value
Dam's initial temperature (°C)	14
Specific heat (J/Kg°C)	880
Conductivity (J/m.day°C)	176000
Convection coefficient (W/m^2.day°C)	1340000

Using the nodal temperature, acquired in first step, a thermoelastic analysis was conducted to obtain thermal stress distribution. In this step, two separate cases of empty and full reservoir were considered and for each case, the extremum times of the year, which produce maximum values of thermal stresses, were extracted.In the next step, static forces including, dam'sself-weight and reservoir's hydrostatic pressure, are imposed on the system at these peak moments for each case. Mechanical properties of the system are based on Table 2.

Table 2- Mechanical properties

Parameter	Dam	Foundation
Elastic modulus (GPa)	35	13 for left abutment 9 for right abutment
Density (Kg/m^3)	2400	0
Poisson's ratio	0.2	0.25
Expansion coefficient (1/°C)	8e-6	8e-6

Finally, time history analysis of the system under thermal, static and dynamic loads is performed by applying the acceleration of earthquake at the foundation boundaries. To this end, Northridge earthquake was selected for seismic analysis, which has PGAs of 0.4g, 0.4g and 0.25g for longitudinal, transverse and vertical directions respectively. Note that for this step, massless foundation assumption is utilized and 5 percent damping is also considered for the system. Time history of Northridge earthquake record is shown in Fig. 3.

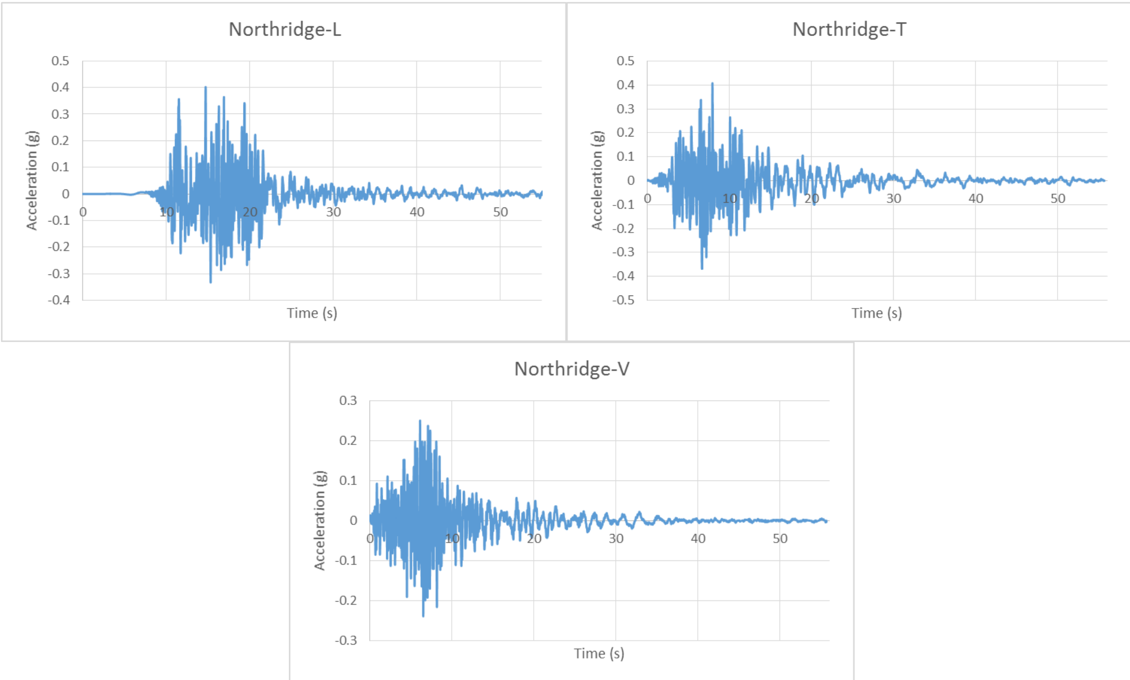

Figure 3. Three components of Northridge earthquake

4. RESULTS

Contour of temperature distribution for crown cantilever is presented in Fig. 4.

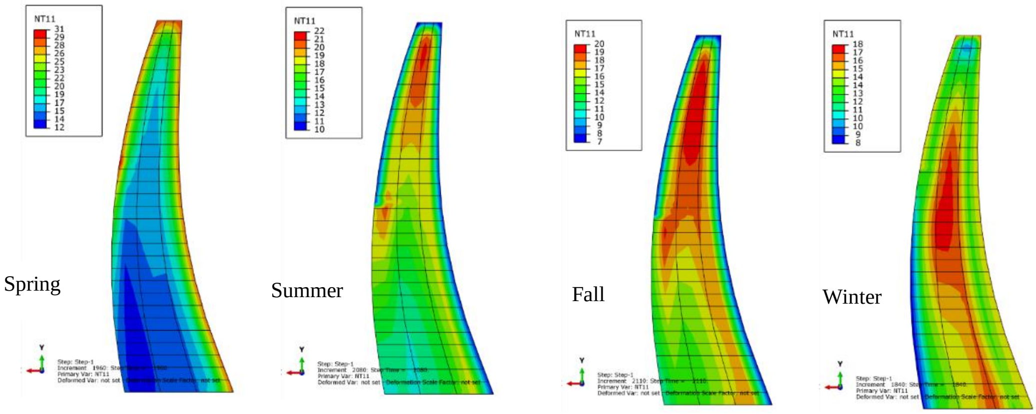

Figure 4. Peak temperature contours in different seasons of the year

Contoursof stress distribution for full loading under empty reservoir assumption are shown in Figs5-8.

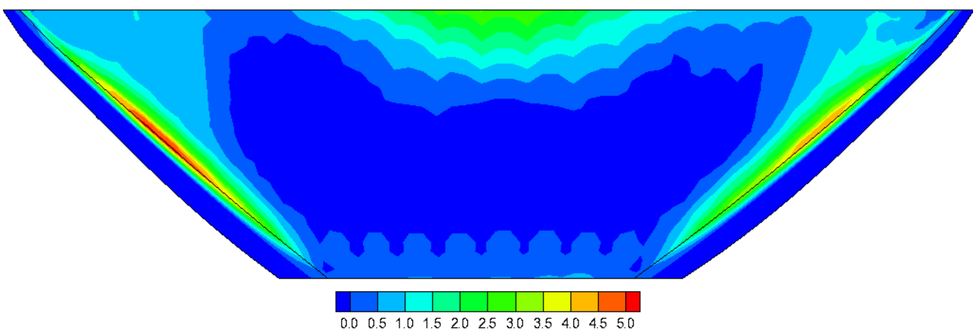

Figure 5. Contour of tensile stress distribution, empty reservoir, warm season, downstream

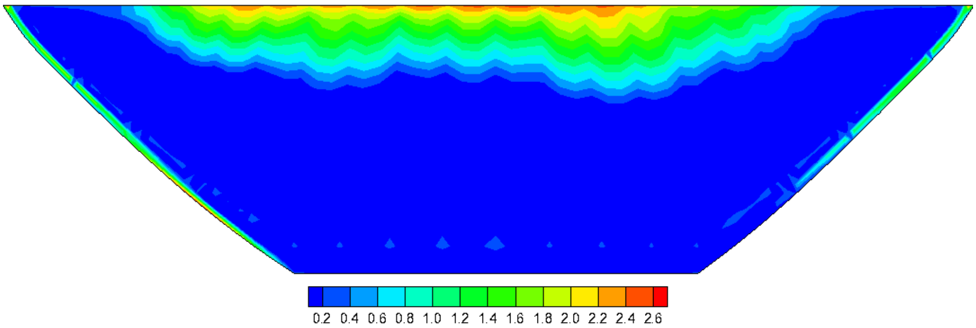

Figure 6. Contour of tensile stress distribution, empty reservoir, warm season, upstream

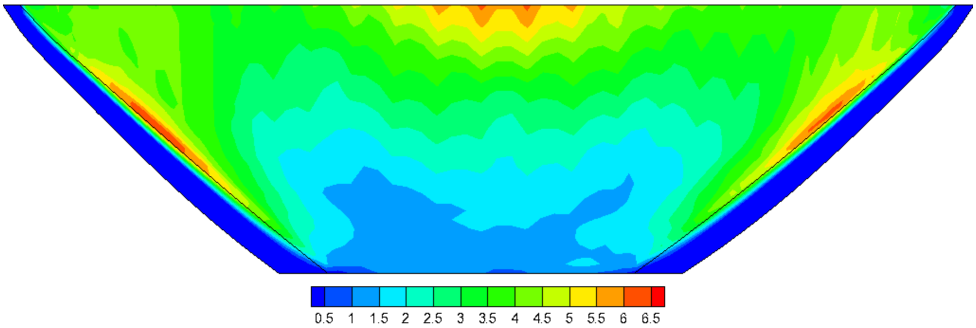

Figure 7. Contour of tensile stress distribution, empty reservoir, cold season, downstream

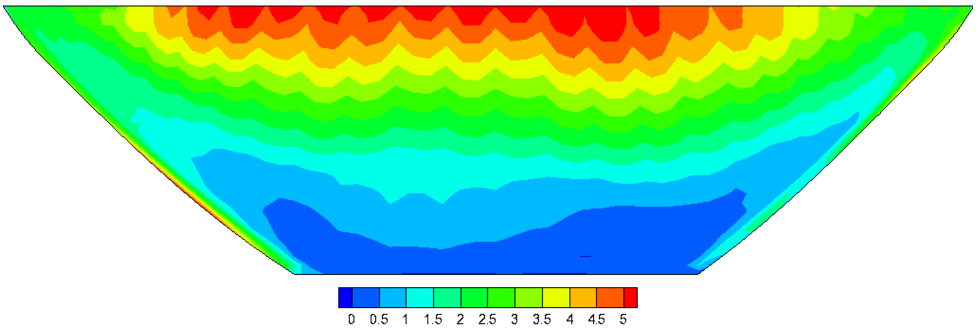

Figure 8. Contour of tensile stress distribution, empty reservoir, cold season, upstream

Contours of stress distribution for full loading under full reservoir assumption are shown in Figs 9-12.

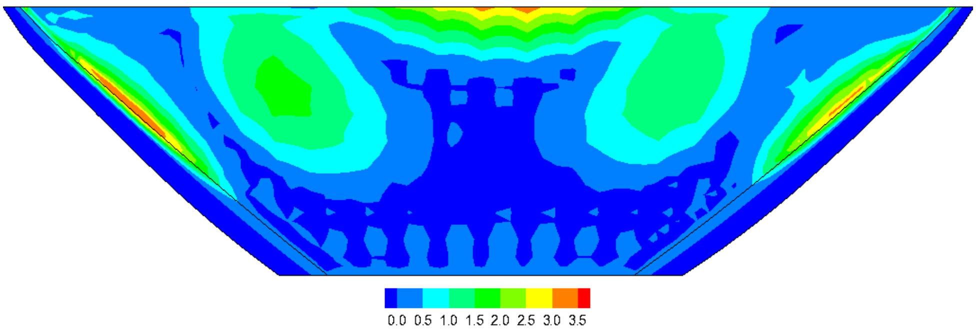

Figure 9. Contour of tensile stress distribution, full reservoir, warm season, downstream

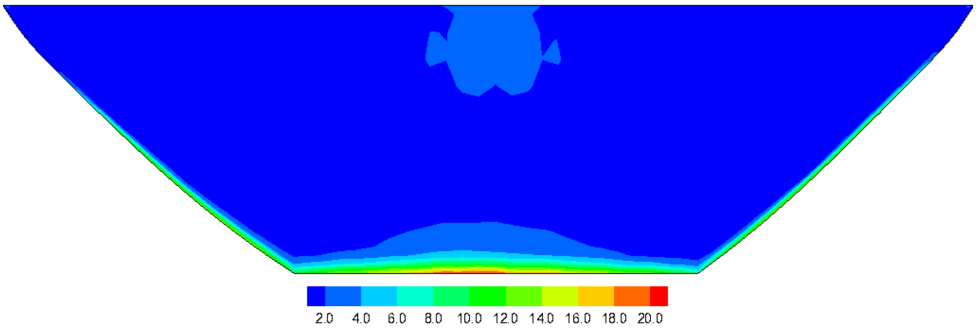

Figure 10. Contour of tensile stress distribution, full reservoir, warm season, upstream

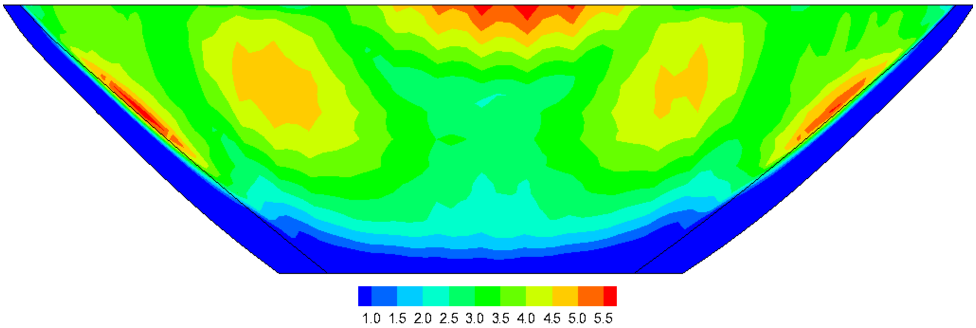

Figure 11. Contour of tensile stress distribution, full reservoir, cold season, downstream

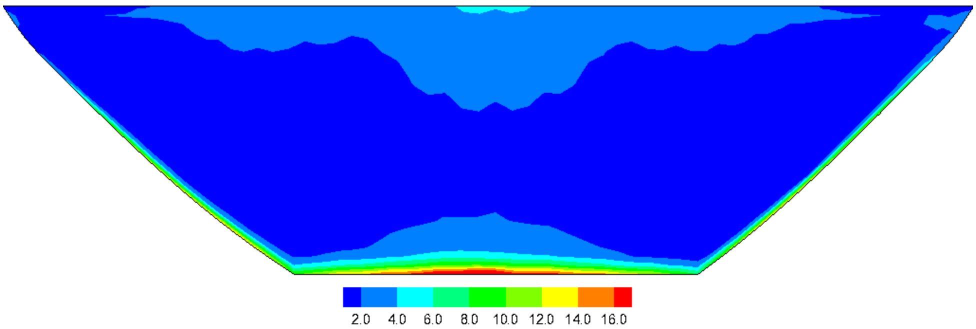

Figure 12. Contour of tensile stress distribution, full reservoir, cold season, upstream

Summary of the results is presented in Table 3.

Table 3- Summary of stress results in MPa

reservoir	Warm season				Cold season			
	Downstream		Upstream		Downstream		Upstream	
	*T	*C	T	C	T	C	T	C
Empty	5.52	11.1	2.71	24.9	6.86	7.87	5.53	22.5
full	3.66	21.8	20.5	22.3	6.1	19.8	20.4	22.4

*T and C refer to Tensile and Compressive stresses respectively

5. CONCLUSIONS

In this study, analysis of a system of arch dam-foundation-reservoir under simultaneous effects of thermal, static and dynamic loads was performed. To consider thermal effects, a separate analysis to obtain nodal temperatures was conducted, based on real data of ambient air temperature and reservoir depth. After obtaining nodal temperatures, a thermoelastic analysis followed by static analysis was performed at peak moments of thermal stresses for cases of empty and full reservoir during a year. At the final step of the study, a comprehensive analysis including thermal, static and seismic loadings, with consideration of all effective interactions, was performed and results were presented.

As can be seen from the results, extreme tensile stresses belong to full reservoir case where the level of stress in war season of the year is almost doubled with respect to empty reservoir case. Regardless of time of the year, in empty reservoir case downstream face of the dam is in critical state while full reservoir case, upstream face of the dam experiences maximum tensile stress. As it is obvious from the results, in different times of the year, which are based on thermal analysis of the system, notable differences in overall stress results can be observed which indicate the importance of considering full loading for comprehensive study of complex systems such as concrete arch dams.

6. REFERENCES

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