Thermal and Mechanical Properties Calibration for Concrete Arch Dams

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Abstract

Concrete arch dams are prone to kinds of loadings that are not usually the case for common structures. Such loadings include thermal and seismic loads as well. To investigate the behavior of arch dams during their lifetime, mechanical properties of the dam and foundation are required. To do so, a calibration analysis is mandatory. With respect to real data, recorded during structure's lifetime, a thermal analysis followed by a mechanical calibration should be carried out. This is very effective approach when there are no valid data available on properties of important structures such as concrete arch dams. In this study, the procedure to calibrate the properties of dam and foundation system is presented for a concrete arch dam in Iran. Obtained results conform well to recorded data and prove the accuracy of the implemented approach to estimate said properties.

Keywords: concrete arch dam, thermal calibration, mechanical calibration, lifetime safety.

1. INTRODUCTION

Thermal loads influence thin plain concrete structures more severely. This condition become more problematic for concrete arch dams, which are subjected to thermal gradient due to different condition on the upstream and downstream faces of dam. Temperature of reservoir has a shift with respect to ambient temperature and this time shift varies with reservoir depth. This leads to different temperature changes in different section of dam body, which would eventually lead to concrete cracking if not considered in design. To be able to account for thermal effects in analysis, one needs correct data on characteristics of the system. By utilizing real data of thermometers and pendulums, thermal and mechanical properties of arch dams can be obtained, using calibration analysis. A good calibration usually leads to numerical responses that conform well with recorded data therefore a correct procedure for this process is necessary.

There are numerous studies regarding thermal analysis of concrete dams. Agullo and Aguado (1995) presented a one-dimensional finite difference model by proposing a simple formulation of thermal behavior. They showed that the mean temperature of the section depends on the ambient temperature, the temperature of reservoir, and solar radiation. Meyer and Mouvet (1995) performed a finite element analysis investigating the temperature variations and the corresponding thermalresponses of an arch dam. Their results showed that thermal expansion coefficient is the most influential parameter in thermal analysis of arch dams in comparison with elastic modulus of the dam. Daoud et al. (1997), included the effects of ambient temperature variation, solar radiation, temperature gradients, and ice development in the reservoir. They also included the effects of conductivity differences due to saturation of parts of the dam.Sheibany and Ghaemian (2006) studied the effects of thermal loads on cracking of concrete arch dams. They utilized a 2D model for their analysis and concluded that a 3D model would be more appropriate in thermal analysis of concrete arch dams. Apart from finite element methods, an empirical method, proposed byStucky and Derron (1992), is also common in dam engineering practice. This simple method is capable of estimating nodal temperatures in thickness of the dam with acceptable accuracy.Bofang (1997) presented an empirical method for estimating water temperature distribution in different depth of reservoir and different times of the year. His method works fine for reservoirs, that are not covered in ice during most part of the year.

In this study, a calibration analysis of Zayandehrud double curvature arch dam is performed, using real data of thermometers and pendulums of the dam. In the first step, thermal properties of concrete are extracted using ambient air data, reservoir water fluctuation and thermometer readings. In this step, Bofang's empirical formulation, to estimate water temperature at desired depth and desired time, is employed. Using nodal temperatures, calculated at the end of previous step, a series of analyzes is performed to acquire mechanical properties of the dam. To do so, relative numerical results are compared with pendulum readings to obtain the best set of properties that produce the closest responses to actual data.

2. EQUATIONS

2.1 HEAT TRANSFER CONSTITUTIVE LAW

Considered in most engineering problems, main sources of heat transfer include conduction, convection, and radiation.Constitutive equation of thermal conduction, as stated by Reddy and Gartling(2001), is given by:

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

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.

Internal heat generation Q, is generally temperature dependent. However, for macroscopic engineering problems, it is customary to assume that Q is independent of temperature. Assuming isotropic conductivity, constant specific heat and temperature independent Q, Eq. 1 is simplified into following equation:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \nabla^2 T + \frac{Q}{k} \tag{2}$$

where, α is defined as:

$$\alpha = \frac{k}{\rho c} \tag{3}$$

The above equation is solved under following boundary conditions:

$$\begin{aligned} T &= T_w && On\ \Gamma_w \\ q = -k\frac{\partial T}{\partial n} &= q_c + q_r - q_a && On\ \Gamma_q \end{aligned} \tag{4}$$

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

Convective heat transfer follows Newton's cooling law, which states that temperature exchange between bodies can be defined as follows:

$$q_c = -h_c (T_a - T) \tag{5}$$

where q_c is convective flux, h_c is convection coefficient and T_a and T are ambient and surface temperatures respectively.

Convection coefficient depends on fluid speed, viscosity, surface shape, etc. There are simplified formulations to calculate convection coefficient, which only depend on fluid speed namely, McAdam's and Watmuff's as follows:

$$h_c = 3.8V + 5.7 \tag{6}$$

$$h_c = 3.0V + 2.8 \tag{7}$$

Thermal radiation resulted by temperature differences between surface of the body and surrounding medium can be defined by Stefan-Boltzman law:

$$q_r = -eC_s(T_a^4 - T^4) \quad (8)$$

where, e is emissivity of surface, C_s is Stefan-Boltzman constant and T_a and T are ambient and surface temperatures respectively. Linear form of the above equation yields:

$$q_r = -h_r(T_a - T) \quad (9)$$

where linearized radiation coefficient h_r is defined by:

$$h_r = eC_s(T_a^2 + T^2)(T_a + T) \quad (10)$$

In this study, radiation consists of absorbed solar energy by the surface and electromagnetic energy emanated from the surface. Total absorbed solar energy or applied flux is given by following equation:

$$q_a = aI_t \quad (11)$$

where, a is solar absorptivity of the surface and I_t is total amount of solar energy.

2.2 AMBIENT TEMPERATURE CALCULATION

Since air temperature fluctuation obeys a sinusoidal behavior in most regions, a sine function can be best fitted to real data to estimate the air temperature in any time of the year. While air temperature is at hand, Bofang's empirical formulation to estimate reservoir water temperature in any time of the year at any depth of water can be employed which has the following form:

$$T(y,t) = T_m(y) + A(y)\cos\omega(t - t_0 - \varepsilon) \quad (12)$$

where, y is depth of water, t is time in month, T(y,t) is water temperature in desired time and depth, $T_m(y)$ is annual average temperature of water, A(y) is the range of annual fluctuation of water temperature, ω is frequency of water temperature change and t_0 and ε are time shifts (for further details refer to Bofang (1997)).

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.

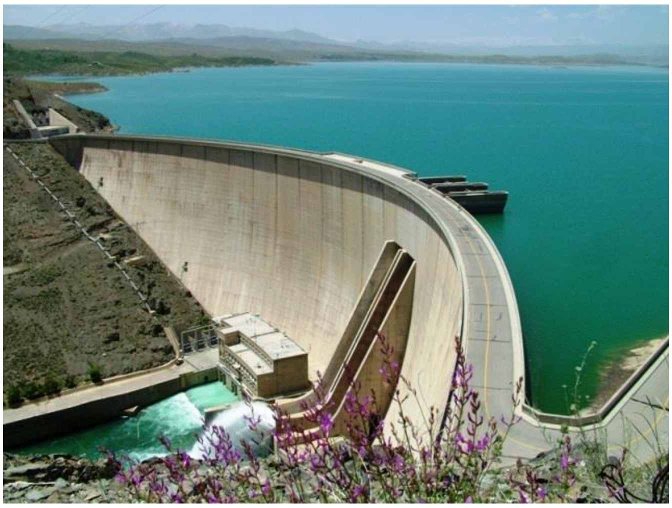

Figure 1. ZayandehRud arch dam

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

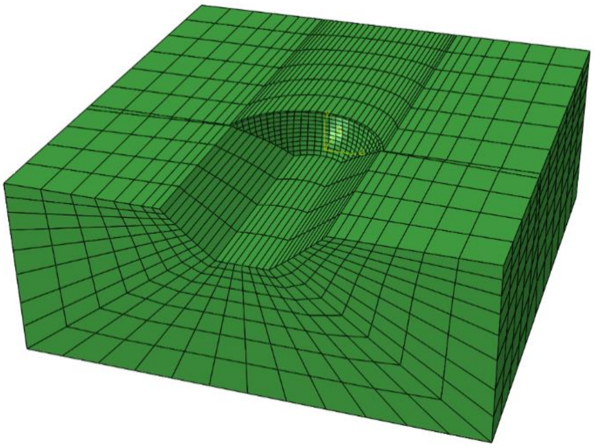

Figure 2. Finite element model of the system

Since six years of temperature data from the dam body and ambient air were available, this data were used to produce the air temperature sine function, which is shown as below:

$$T_a(t) = 12.45 - 12.52\cos(\omega(t + 2.02)) \tag{13}$$

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

The air temperature function is plotted against real data of the last year available in Fig. 3.

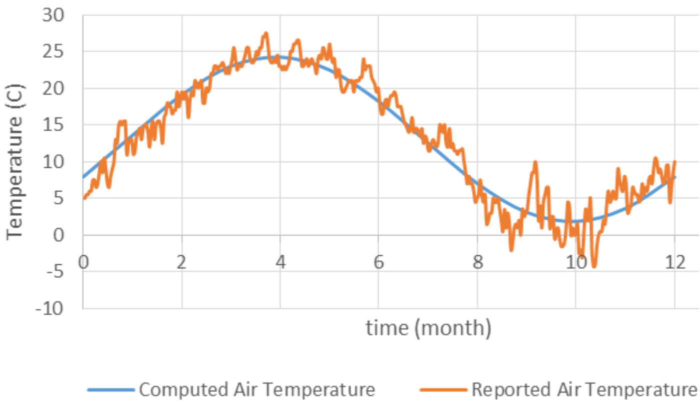

Figure 3. Computed air temperature versus recorded air temperature

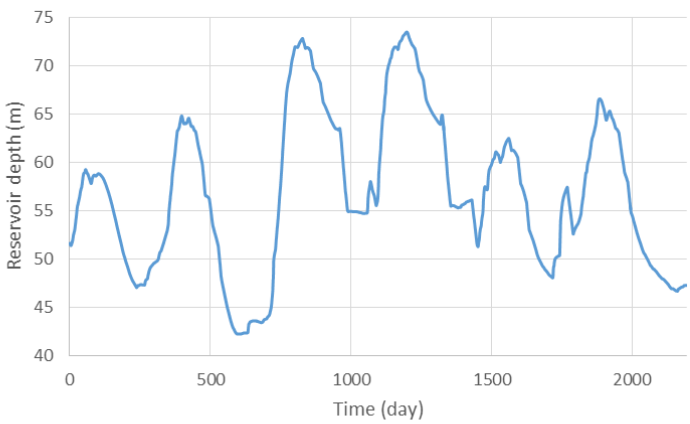

Figure 4. Reservoir depth fluctuation in six years

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

4. CALIBRATION

4.1 THERMAL CALIBRATION

Since calibration analysis is usually performed in cases where no real data is available, an initial estimation of involving parameters should be performed. Acceptance range of these parameters for concrete is reported in Table 1.

Table 1- Acceptable range of thermal parameters for concrete

Parameter	value
Dam's initial temperature (°C)	No specific value
Specific heat (J/Kg°C)	879-1088
Conductivity (J/m.day°C)	160000-300000
Convection coefficient (W/m^2.day°C)	According to wind speed

Using the finite element method, developed earlier, different values for mentioned parameters were employed and compared with real data obtained from installed thermometers in body of the dam (Fig. 5).

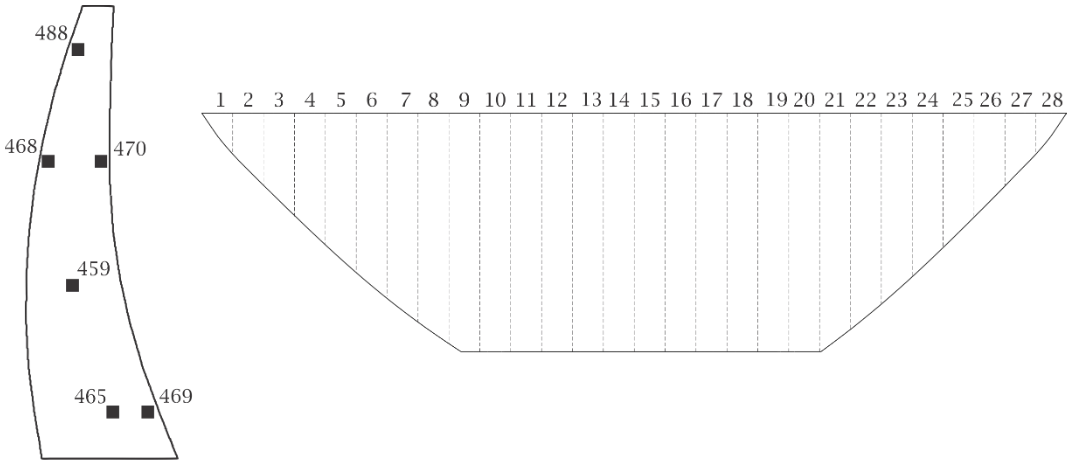

Figure 5. Location of thermometers in crown cantilever (left), blocks of dam body (right)

the calibrated parameters which give the best fit to real data are reported in Table 2.

Table 2- Calibrated values of thermal parameters for dam

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

To be able to see the effectiveness of good calibration, computed temperature at locations of thermometers for some selective cases are plotted against real data in Fig. 6.

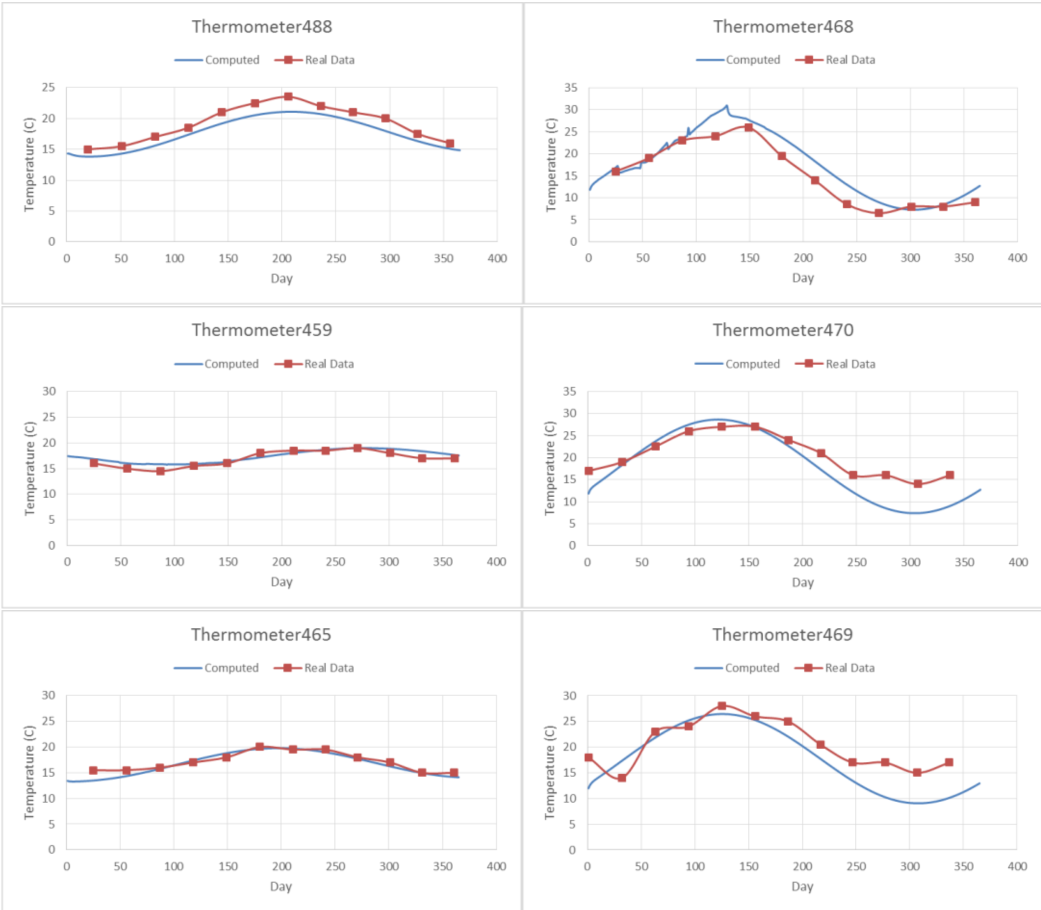

Figure 6. Selective cases comparing recorded and real data

4.2 MECHANICAL CALIBRATION

Other mechanical properties, which participate in calculations of stresses and displacements in static or dynamic analysis, include elastic modulus and thermal expansion coefficient. Since these parameters are involved in displacement calculations, real data acquired from pendulum reading were employed to calibrate them. Using the nodal temperature, obtained from thermal calibration step, nine different cases were considered according to Table 3. All cases were analyzed under hydrostatic, gravity and thermal loading.

Table 3- Nine different cases considered for analysis

Case	Elastic modulus (GPa)	Thermal expansion coefficient (1/°C) x1e-6
1	25	6
2	25	8
3	25	10
4	30	6
5	30	8
6	30	10
7	35	6
8	35	8
9	35	10

Since pendulum readings are not absolute values of displacement, all cases are compared by calculating their relative response with respect to one base reading. Comparing relative displacements, case 8 results are in best agreement with recorded data from pendulums. Results of case 8 for all pendulums installed in dam body are shown in Figs. 7-9.

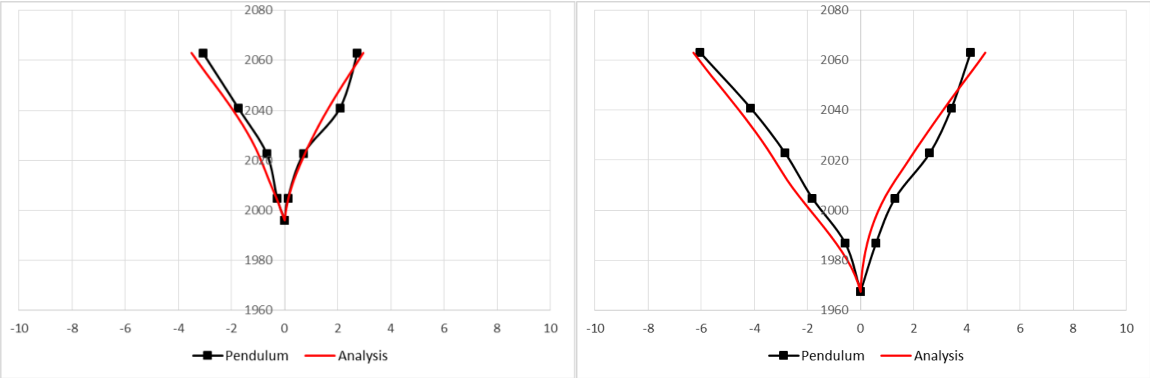

Figure 7. Relative displacement comparison: block 8 (left), block 12 (right)

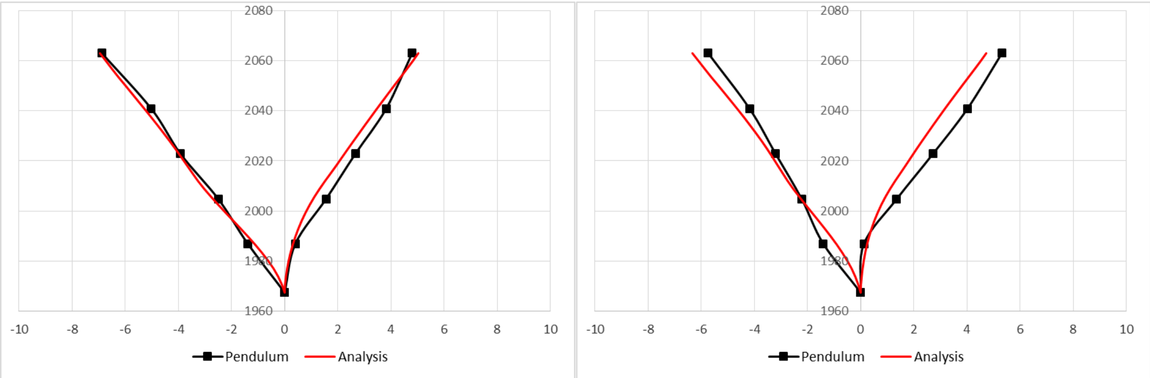

Figure 8. Relative displacement comparison: block 15 (left), block 18 (right)

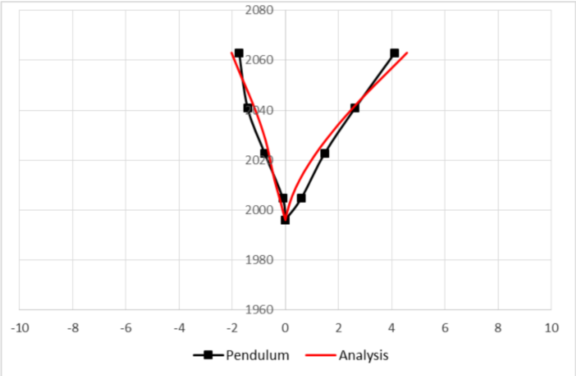

Figure 9. Relative displacement comparison: block 22

5. CONCLUSIONS

In this paper, thermal and mechanical calibration of ZayandehRud double curvature arch dam were performed. Thermal properties were calibrated using real data obtained from Thermometers and mechanical properties were calibrated using pendulum data. In thermal calibration of the dam, conduction, convection and radiation were included in system analysis.

As can be seen from the results, calibrating a complex system of arch dam-foundation-reservoir is a sensitive procedure. A simplified method of considering ambient temperature is applying nodal values as essential boundary condition to surface nodes, which often yields erroneous responses. This procedure omits the effects of convective terms and is employed in numerous studies. In this study, air temperature is not applied as a boundary condition but as an input to convective condition in surface of the dam, which help yield more realistic responses. The responses obtained in this study well conform to real data, obtained from dam body, which prove the acceptability of calibrated values.

6. REFERENCES

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