PREMIUM ADVANTAGE OF A CALIBRATED FINITE ELEMENT MODEL FOR A DAM UNDER OPERATION

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ABSTRACT

Concrete arch dams transfer most of the applied loads to the abutments due to special geometry. On the other hand, the geomechanical parameters of rock mass in the operation period will differ significantly with respect to the ones in dam design process.Knowing the characteristics of rock mass is necessary as long as evaluating the stability of dam body or even every study in which dam body is an essential element during the operating period is targeted. Performing in situ tests during operation is notoriously difficult and extremely expensive. One solution is defining rock mass geomechanical parameters based on the results of instruments. Calibrated instruments could be considered as a reference for acquiring required parameters for finite element model. In this regard a series of sensitivity analyses should be carried out in order to obtain an FEM model in which a rather well compatibility in comparison with instruments could be achieved.Dez concrete arch dam with a height of more than 200m located in south west of Iran was constructed in 1962. It has been under operation up to now. It is a vitally important structure and has a significant role in the economy of Khuzestan province. The dam possesses an innovative design so that a reinforced saddle dubbed pulvino is located all over the abutments. In order to calibrate the FEM model, a thorough model was constructed. In the model pulvino as well as contraction joints are included.In this paper the process of calibrating the Dez FEM model with the results of instruments will be presented. Dam behavior was compared with pendulum results for one year and a good compatibility was achieved.

Keywords *: Dez Dam, Finite Elements Method, Model calibration, Dam Instrumentation*

1. INTRODUCTION

Dez dam is a 203 meter high double-arch concrete dam built in southwestern Iran in Khuzestan province between Dezful and Andimeshk. The final construction plans were finalized in 1957 and the construction was between 1959 and 1963. Dez River originates from Zagros Mountains into Khuzestan plain. Before entering the Khuzestan plain, the Dez River passes through a narrow gorge, mainly made of Bakhtiary conglomerate formation. Bakhtiary formation is a uniform horizontal mainly not jointed formation with high modulus of elasticity. Figure 1 depicts a bird'seye view of the dam and gorge.

Figure 1 : Dez dam bird's eye view

The geotechnical studies of the dam site started in 1957 and most of the results appear in papers by Talobre et al [2] and Dodds [3]. The detail results are not available for many cases. Mehinrad et al. reinterpreted the original results using modern rock mechanics concepts [4].

The geotechnical data provided by the designers cannot be used to actually compare the numerical results with instrumentation readings. The main reasons are: (1) The initial geotechnical details are mainly prepared for design purposes with due factors of safety and (2) the passage of time, dam hydrostatic loading and consolidation grouting greatly affect the mechanical properties of both the foundation and dam body.

On the other hand, attaining a numerical model, which can predict the results of instrumentation greatly helps analyze and interpret sudden events such as floods and earthquakes and estimate the actual state of the structure.

In order to obtain such a model, the thermal and mechanical properties of the dam-foundation-reservoir system can be determined based on the instrument (mainly pendulum) reading and find properties which yield the best match between the numerical model and instrument reading.

In this paper, it is attempted to obtain a set of thermal and mechanical parameters for the Dez Dam using pendulum readings up until spring 2018 for a 5 year period. After that, the results of the calibrated model is compared with pendulum readings for the past year, which includes a major flood during winter and spring of 2019.

2. MODELLING

2-1 Finite elements model

A finite elements model is created using ANSYS with 20 node quadratic solid elements. The model is depicted in figure below.

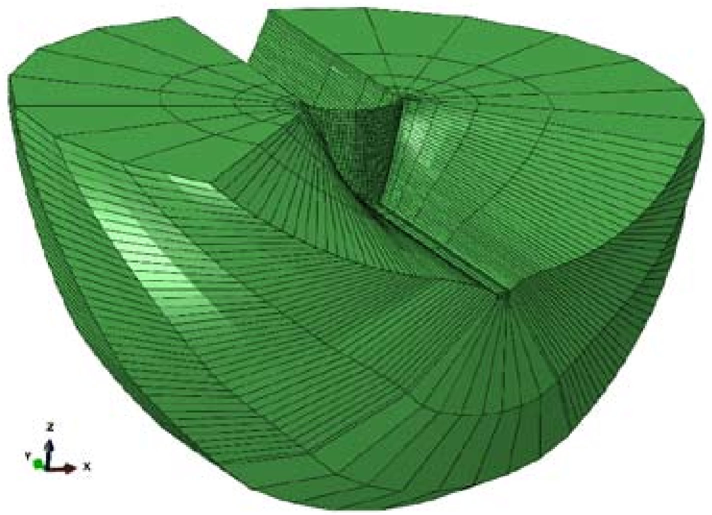

Figure 2 : Dam and foundation FEM model

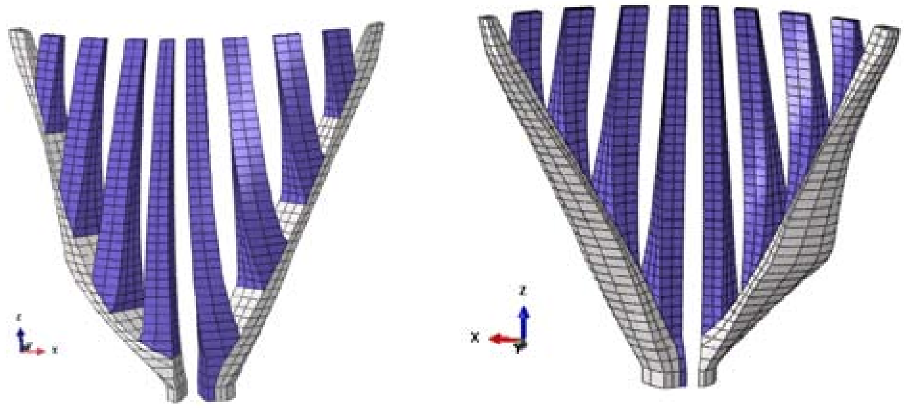

Figure 3 : Pulvino, with dam blocks

2-2. Dead Load

The dead load is applied on the model during 13 steps. One step for the plug and 3 steps at each of the 4 levels, as depicted in figure below. At each step, the weight of the current blocks is applied and higher level concrete is assumed to have no stiffness. The foundation is also considered to have to mass.

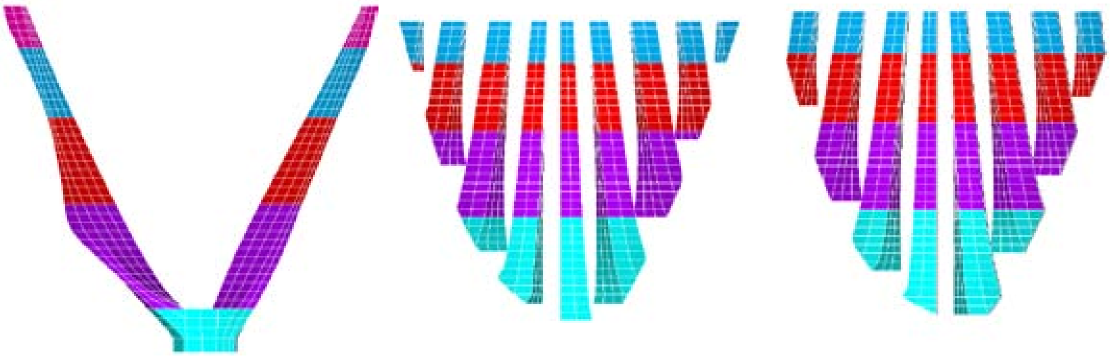

Figure 4 : Pulvino blocks (left), Even Blocks (middle), Odd blocks (right)

2.3 Hydrostatic Load

The hydrostatic load is applied on the upstream of the dam. The load at each day is the exact water level logged at that specific day. The water levels for the past six years are depicted in figure below:

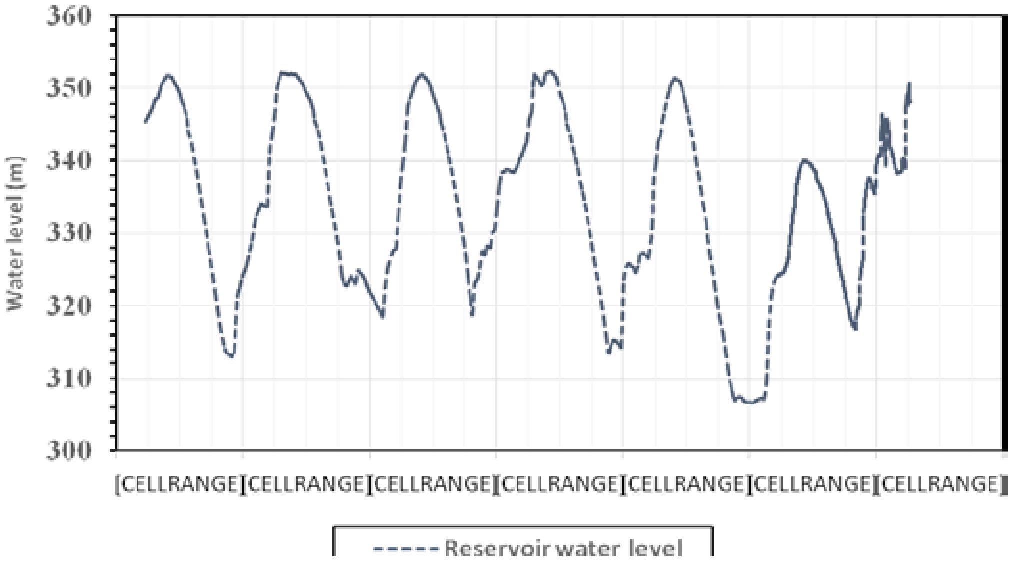

Figure 5 : Reservoir water levels during past 6 years

2.4 Thermal Transient Analysis

In order to find the temperature distribution of the dam body, the thermometer readings are used. The temperatures are assumed to vary sinusoidal on the upstream and downstream faces.

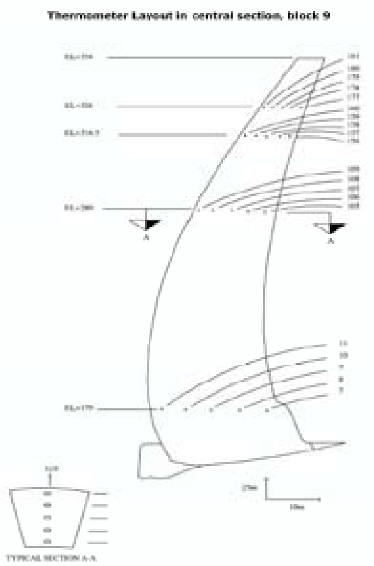

Figure 6 : Location of dam body thermometers

$$T^{US,DS} = M + A\cos[\omega(t + t_0)] \qquad \text{(Equation 1)}$$

The values for M, A and t_0 are described in tables below:

Table 1 : Upstream temperature parameters

Elevation (Z)	Amplitude (A)	Average (M)	Phase (t_0)
354	9.00	28.68	218
328	6.89	21.69	197
316.5	5.70	21.65	182
285	4.09	19.75	160
163	1.00	14.20	128
155	1.00	21.44	128

Table 2 : Downstreamtemperature parameters

Elevation (Z)	Amplitude (A)	Average (M)	Phase (t_0)
163 and above	9.00	28.68	218
155	1.00	28.68	218

The parameters are constant in a specific elevation and are interpolated linearly between two levels.

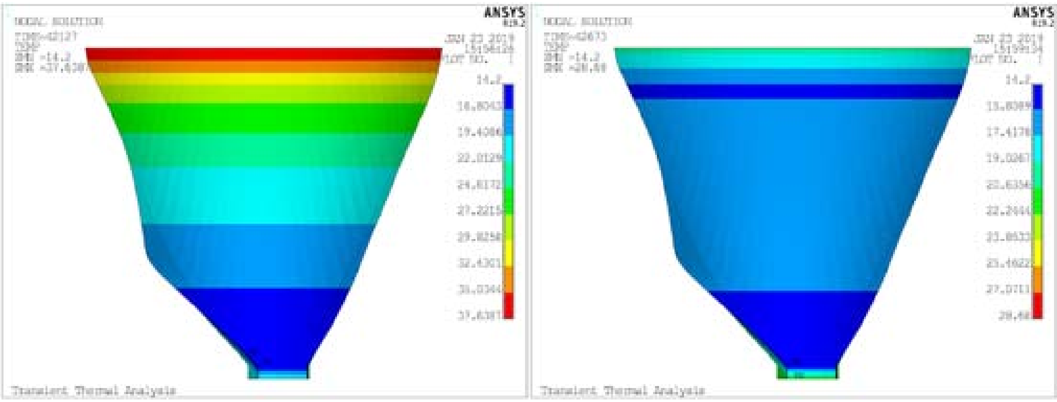

Figure 7 : Temperature distribution on the upstream – (left: Feb 24, 2018, right: Aug 24, 2017)

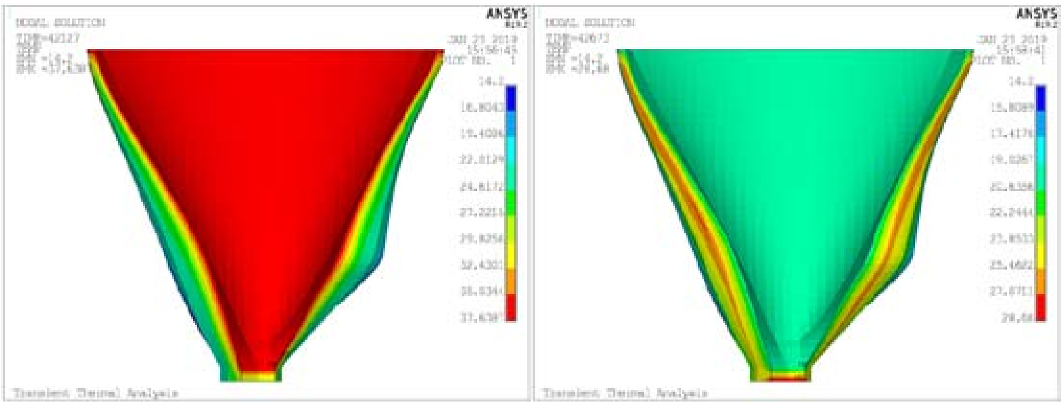

Figure 8 : Temperature distribution on the downstream – (left: Feb 24, 2018, right: Aug 24, 2017)

Next, a transient temperature analysis is performed since 1967, with a 5-day interval with the following parameters:

Table 3 : Transient temperature analysis parameters

Parameter	Value
Mass density(ρ)	2400.0 [kg/m^3]
Specific heat capacity (C)	0.9 [kJ/kg°C]
Thermal Conductivity (K)	240 [kJ/m day °]
Diffusivity (α)	0.111[m^2/day]

The temperatures inside dam body is depicted here for two different days:

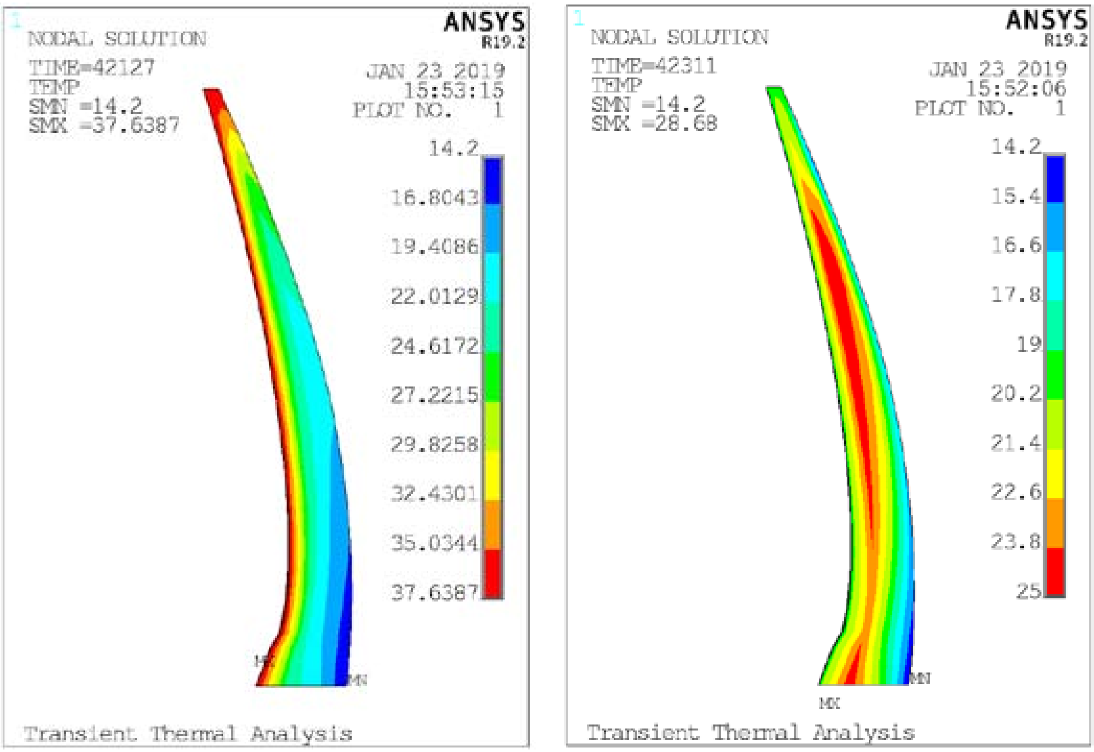

Figure 9 : Transient computed temperature distribution in the main block – (left: Feb 24, 2018, right: Aug 24, 2017)

Next, the results of inner dam body temperatures from the transient analysis is compared with those of inside body thermometers:

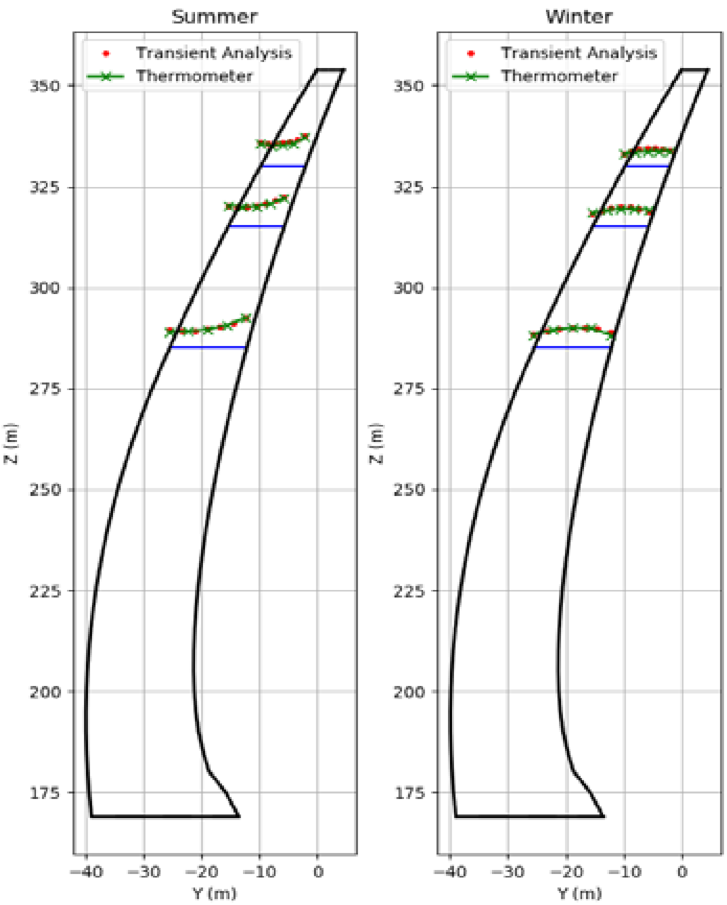

Figure 7 : Temperature distribution compared with thermometers in 2018

As can be seen in figure above, the computed temperatures are very close.

2.5 Static analysis and calibration parameters

2.5.1 *Loads*

In order to find the parameters that best match the instruments' results, a series of static analyses is performed for a period of five-year with a 5-day step. At each step, the water level pertaining to that specific day, along with the temperature obtained from transient temperature analysis for that date. The dead load is not involved in measuring the displacement since the instrumentation is installed after the dead load is applies. The silt load is also applied on the US face.

2.5.2 *Calibration Parameters*

The following parameters are chosen as variables to be determined: (1) Expansion coefficient (2) dam body modulus of elasticity (3) Pulvino modulus of elasticity (4) Near foundation modulus of elasticity (Foundation within 25 meters of the dam body which is subject to consolidation grouting) (5) Far foundation modulus of elasticity.

2.5.3 *Calibration criteria*

The following criteria is used as indicators of "similarity" between simulation results and pendulum readings. The first factor focuses on the displacements versus time and tries to describe how far the pendulum results are from the simulation results in terms of change in time. The second parameter tries to describe how the hysteresis results of the simulation and pendulum resemble each other.

$$E_1^i = \sum_t \left(d_p^i - d_m^i\right)^2 \quad \text{(Equation 2)}$$

$$E_1 = \frac{\sum_i E_1^i}{4} \quad \text{(Equation 3)}$$

The first parameter, E_1, is described above, as the mean deviation in time-series chart of pendulum and simulation. It is the square root of sums of squares of difference between the two charts.

$$E_2 = \left|\frac{p_1 - m_1}{p_1}\right| + \left|\frac{p_2 - m_2}{p_2}\right| \quad \text{(Equation 4)}$$

The second criteria, E_2, describes the difference between the percentage error of quadratic trend line's first and second coefficients of displacement-water level hysteresis chart. The hysteresis trend line equation for pendulum and numerical model will then be described by the following equations:

$$d_p = p_2 * w^2 + p_1 * w + p_0 \quad \text{(Equation 5)}$$

$$d_m = m_2 * w^2 + m_1 * w + m_0 \quad \text{(Equation 6)}$$

2.5.4 *Calibration problem definition*

The calibration problem can now be defined. The goal is to find the best value for the calibration parameters described above to minimize both E_1 and E_2 .In order to do this task, a series of 86 cases with various values for each parameter are defined and simulated. The cases with lower E_1 give a ballpark for the calibration parameters. In the next step, the range of parameters is refined and another 16 simulation tries to find the minimum value for E_2. These values give the final calibration parameters.

3. RESULTS AND DISCUSSION

3.1 Calibration step 1

In the first step, 86 different cases are made different values for each parameter

Table 4 : Range of each calibration parameter

$4*10^{-6}$ to $12*12^{-6}$	Thermal expansion coefficient
7GPa to 12GPa	Near and Far Foundation Coefficient
20GPa to 35GPa	Body Concrete modulus
5GPa higher than body modulus	Pulvino modulus

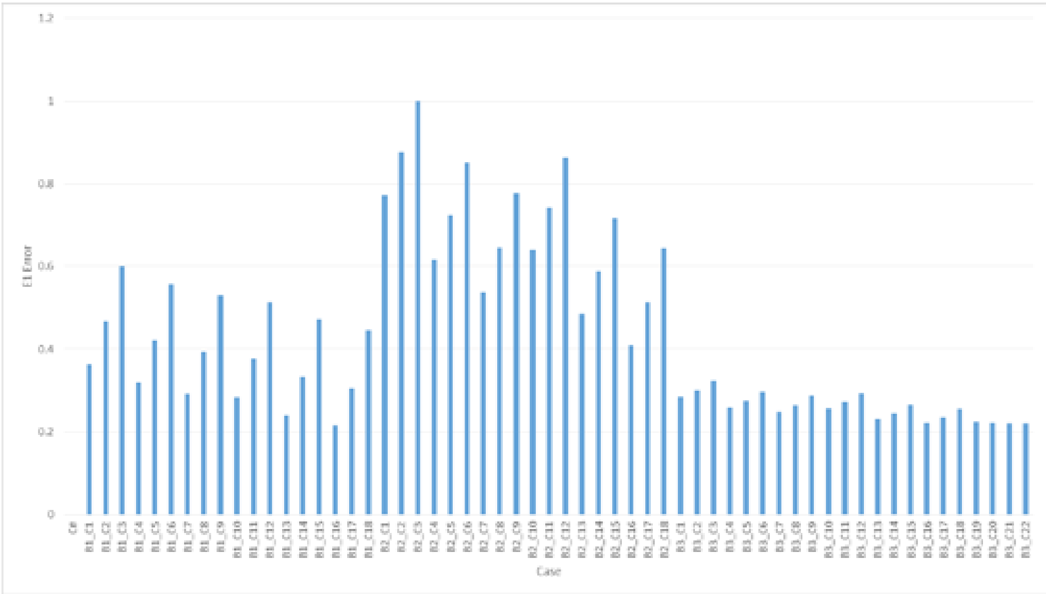

Figure 8 : E_1 Error for each case

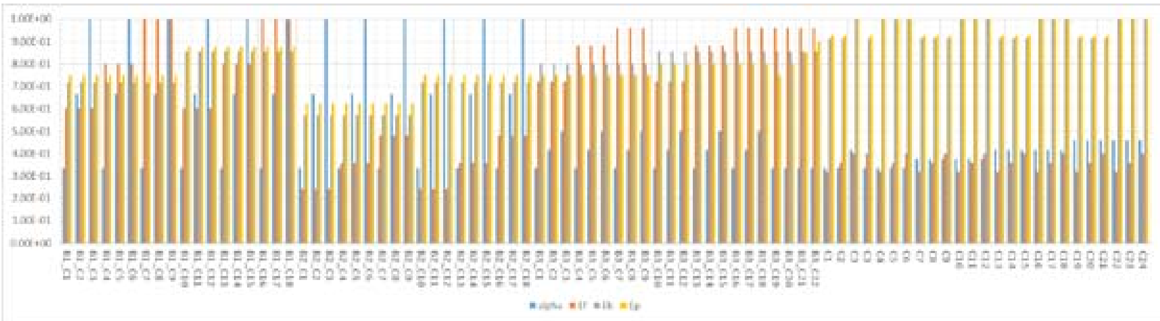

Figure 9 : Relative value of each parameter with respect to its maximum for each case

The following points are inferred from the first step of optimization:

1. A value of 5e-6 is suitable for the thermal expansion coefficient
2. Foundation modulus must be higher than 10MPa to get acceptable results
3. Body modulus is acceptable in the range of 28 to 35 GPa

3.2 Calibration step 2

In this step, the expansion coefficient is fixed, the pulvino modulus is assumed to be 2GPa higher than body modulus (because it is reinforced). The near foundation (within 25 meters of dam body) is assumed to have 50 percent higher modulus of elasticity with respect to far foundation, because of consolidation grouting. Because of the geological formation of the foundation, the rest of the foundation is assumed to have uniform modulus. At this stage, 16 different cases are simulated and the value E_2 is computed for each case.

The hysteresis quadratic trend line and the error are present in the following charts:

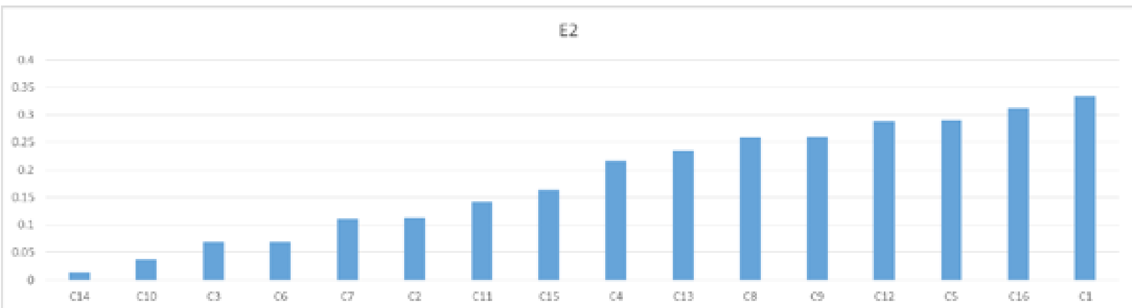

Figure 10 : E_2 Error

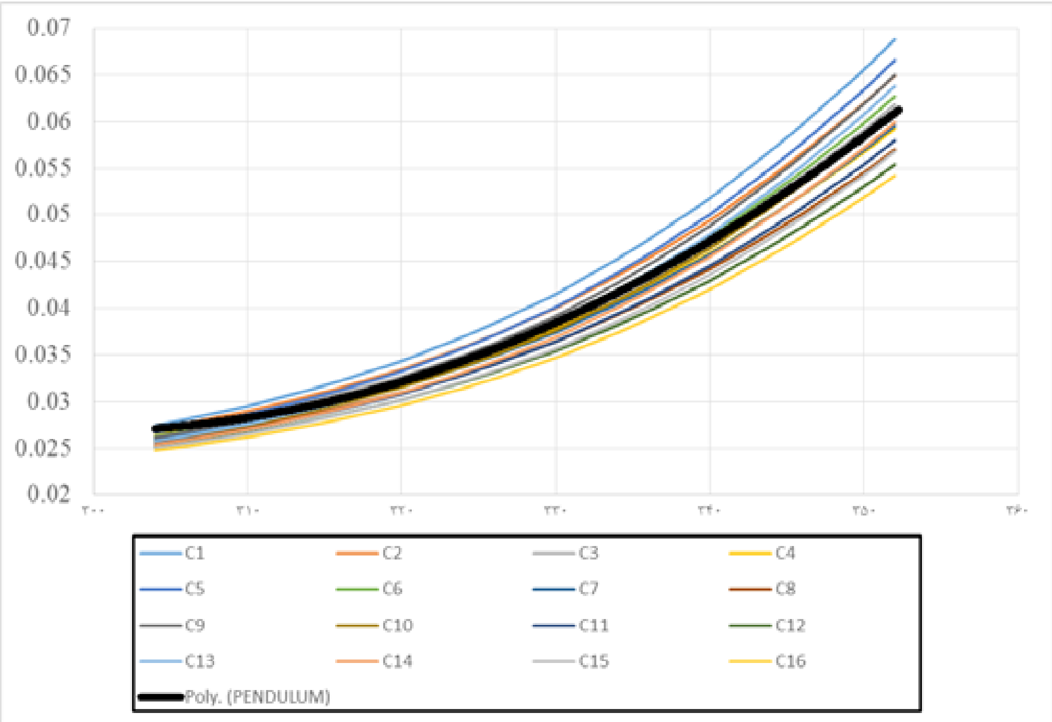

Figure 11 : Trend lines for each case

The winning case entails dam body f'c equal to 28GPa, which is verified by Mahab Ghodss's 1988 dam safety report [5].

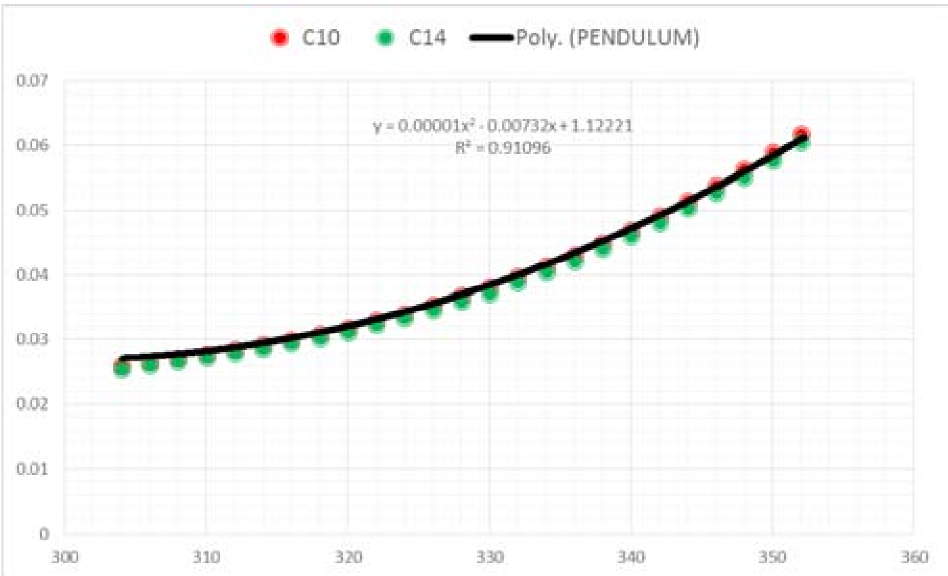

Figure 12 : The average hysteresis plot for two cases with least E2 error, compared with pendulum results.

The winning case, C14, has a very good correlation with pendulum results in terms of hysteresis chart, as shown in Figure 12. The following properties are therefore reached at the end of the calibration process for Dez dam:

Table 5 : Final calibrated parameters

Parameter	Value
Closing Temperature	25◦C
Thermal expcoeff.	5.00E-06
Body Elastic Modulus	28 GPa
Pulvino Elastic Modulus	30 GPa
Foundation modulus - Grouted	16 GPa
Foundation modulus – Not Grouted	24 GPa

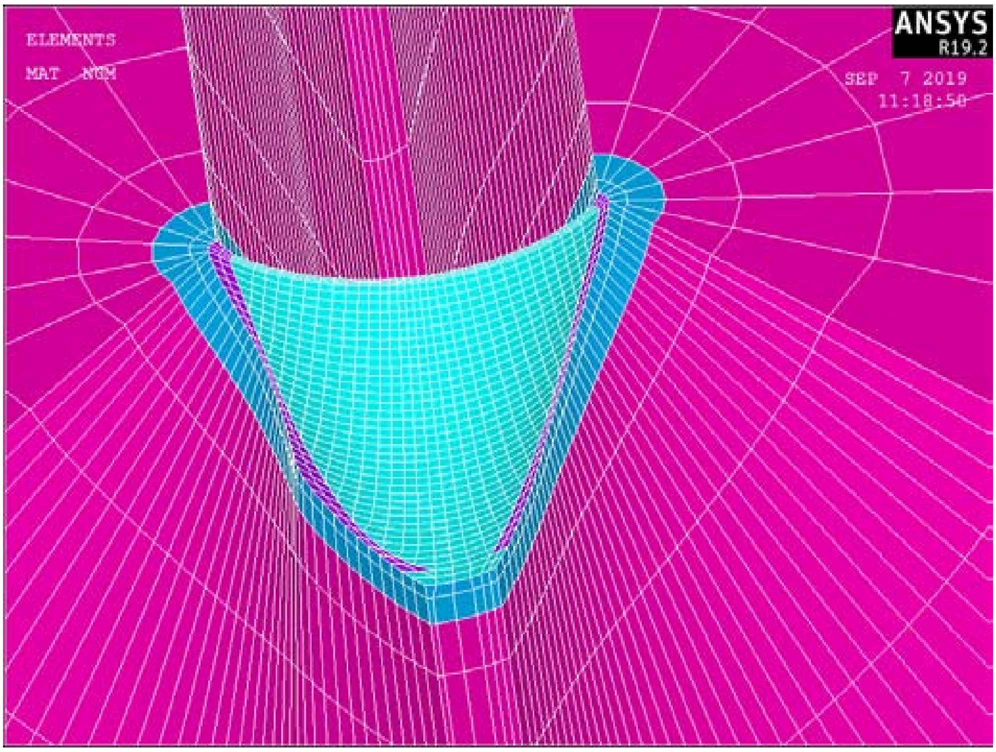

Figure 13 : Materials used in the model – Light blue: dam body, purple: pulvino, dark blue: grouted foundation, pink: foundation

3.3 Verification

The calibration process is carried out in a time period from March 2012 to March 2018. Then with the new parameters, the FEM analysis continued until March 2019 and the pendulum results are compared with FEM results.

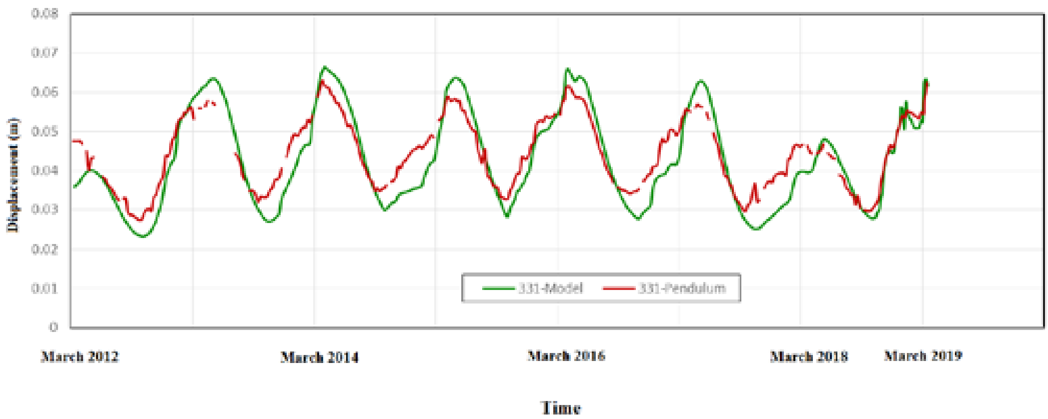

Figure 14 : Displacement comparison at elevation 331

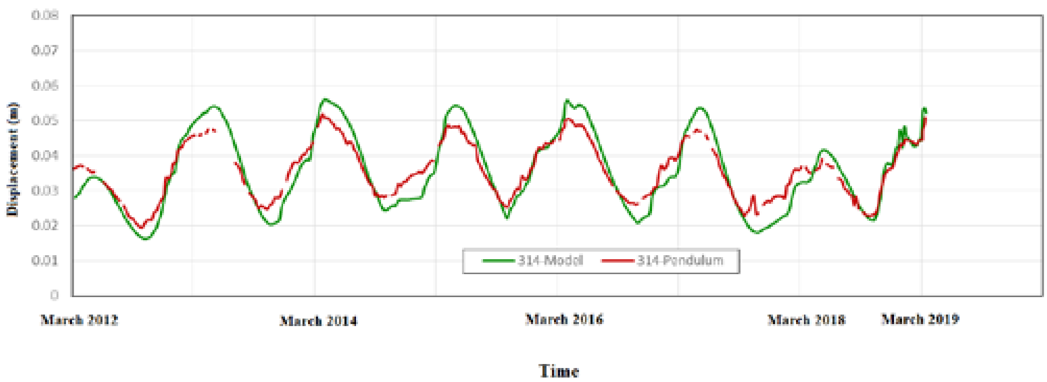

Figure 15 : Displacement comparison at elevation 314

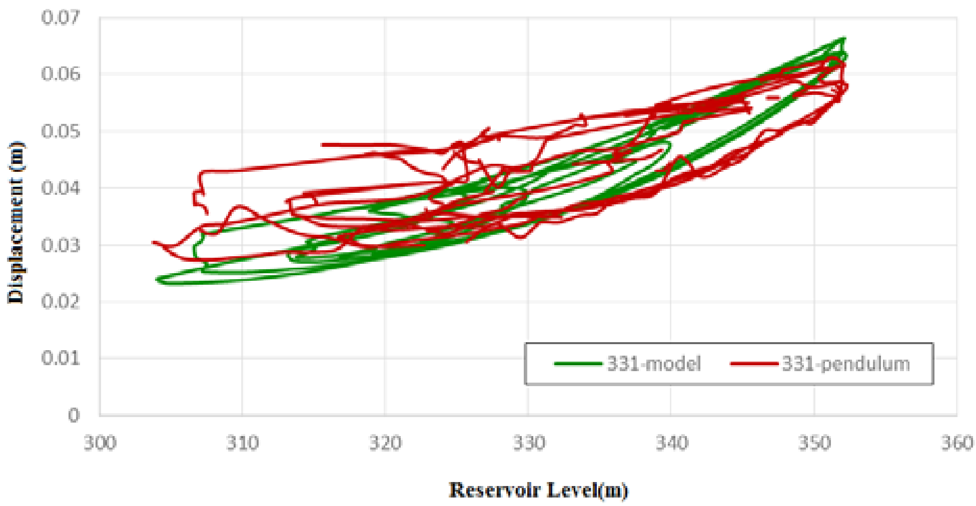

Figure 16 : Hysteresis displacement comparison at elevation 331

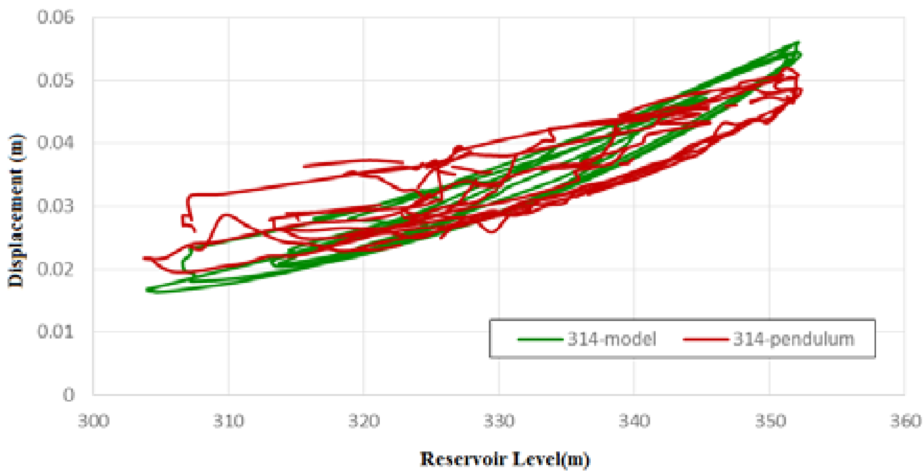

Figure 17 : Hysteresis displacement comparison at elevation 314

Figure 14 and Figure 15 show good results for year 2019. In Figure 16 and Figure 17, the overall hysteresis charts for FEM model and pendulum are compared for two levels are the results are close.

4. CONCLUSION

In this paper, the main mechanical parameters of Dez dam and its foundation were optimized to match pendulum displacements. This process was carried out during two stages and two different error measures were recruited during March 2019 to March 2018.

Next, using the winning combination of mechanical properties, the FEM results were computed until March 2019. The results for the control year, as well as previous years, closely matched.

One of the shortcomings of the current process is lack of accurate thermal data and accurate foundation details. The model used is very simple and parameters are assumed uniformly. Also, Dez dam has few instruments and only on central block, which makes the calibration process inaccurate.

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