Behaviour prediction of a concrete arch dam

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ABSTRACT: The paper presents a 3D numerical model that was conceived to predict the behaviour of a double curvature concrete arch dam. The model had the objective of reproducing the effective response of the dam to the hydrostatic load and to temperature loads. The calibration was performed on the base of monitoring data. The calibrated model was finally used to predict the short-term and long-term behaviour of the dam. This calculation exercise was proposed in the frame of the 16th International Benchmark Workshop on Numerical Analysis of Dams.

1 INTRODUCTION

The Theme A of the 16th International Benchmark Workshop on Numerical Analysis of Dams concerns the preparation of a behaviour model for a concrete arch dam. With the help of such models, engineers can evaluate the dam's performance, estimate the response of the dam for its actual loading conditions and define warning levels. The calibration and the prediction provided in the paper concerns the measurements of the pendulums and the crack opening.

A constitutive approach, preparing a 3D numerical model for reproducing the dam behaviour, is adopted at first. Also, the results that were obtained fitting the available monitoring data following a data-based approach are presented and commented in the light of comparison with the results that were obtained following the constitutive approach.

The dam is owned by Electricité de France (EDF) and it is located in the south of France at an altitude of approximately 2000 m asl. The name of the dam was kept undisclosed. The height of the dam is 45 m, the crest and base thickness is 2 m and 6 m, respectively. The crest has a radius of 110 m and a length of 166 m.

The dam is equipped with a comprehensive monitoring system, including pendulums, crack opening, displacement sensors, piezometers and seepage measurements. Monitoring data have regularly been acquired since the first impoundment. The monitoring data made available by the formulators are shown in Appendix, referring to the period from 1995 to 2017. The monitoring data to be predicted with the model refer to the period 2000-2012. As highlighted in the provided documents, all altitudes refer to a common value which is an arbitrary value, and not the sea level. It should be noted that when water level is lower than 196 m asl, there is only water in a lake located upstream and below the heel of the dam.

The air temperature is not measured at the location of the dam, and, as far as the authors know, the dam is not equipped with thermometers. Two time series of daily air temperature were available: T_a, which is a time series of measurements located in the area of the dam, carried out according to the standard of WMO (World Meteorological Organisation) and located 50 km from the dam, however at a different altitude; T_b, which is calculated by interpolation from several air temperature measuring stations, taking into account the altitude of the dam and is calculated on a mesh of 1 square kilometre. Some comment on this information and how these temperatures are used to compute thermal loads for the dam are given in Section 3.2.1.

The dam is equipped with several pendulums, as illustrated in Figure 1. Only the measurements of pendulums on the Central Block (labelled CB2 and CB3) were made available by the formulators. CB2 is the radial displacement between the altitudes 236 m (just under the crest of the dam) and 196 m asl (toe of the dam). CB3 is the radial displacement in the foundation between the altitudes 195 m asl and 161 m asl.

A crack opening displacement sensor is located at the rock-concrete interface of the Central Block (CB). The sensor measures the opening between C4 (in the foundation) and C5 (in the concrete, at the toe of the dam). The location of the crack opening sensor and of the piezometers is illustrated in Figure 1.

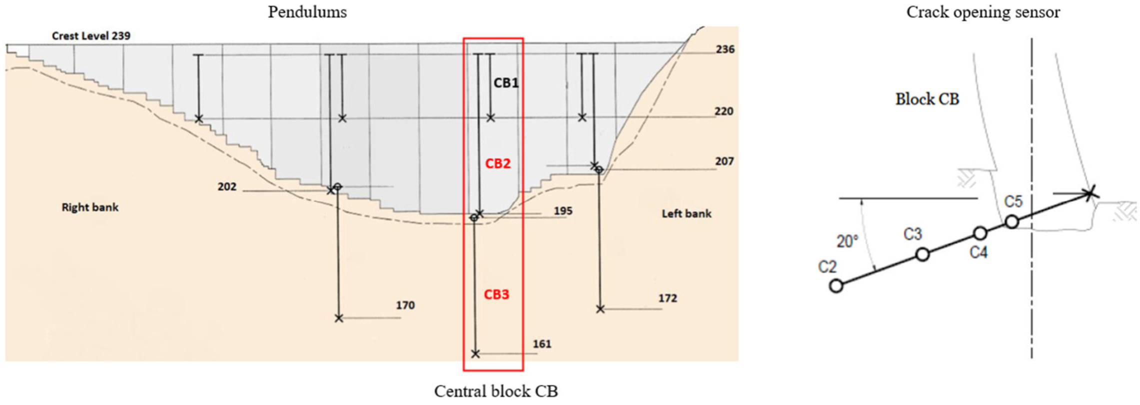

Figure 1. Monitoring equipment – pendulums and crack opening displacement sensor.

2 DATA TREATMENT AND COMMENTS

In Figure 2 pendulum and crack opening measurements are plotted as a function of the water level. It can be seen how the displacements vary over large ranges for each given water level, especially for the pendulum measurement CB2 and the crack opening. This must be related to the effect of the temperature on the displacements, which apparently has a strong influence on the dam response. A crack opening of about 4mm is measured for the highest water levels.

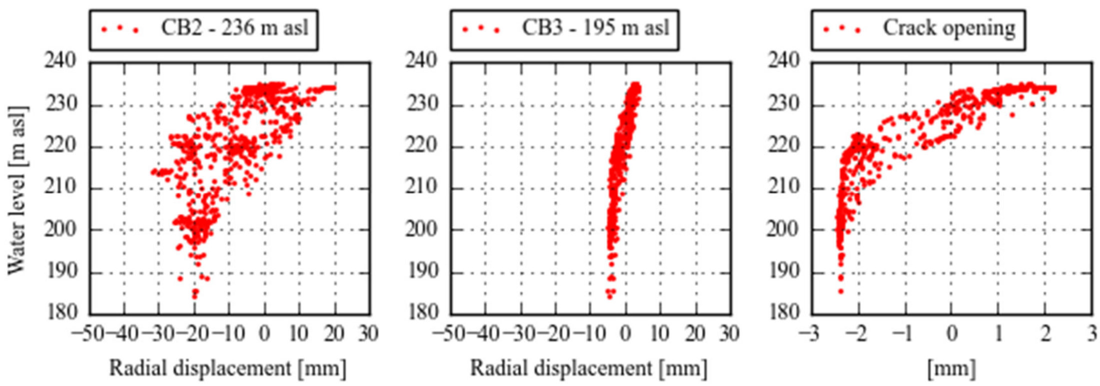

Figure 2. Pendulum and crack opening measurements as a function of the water level.

3 THE NUMERICAL MODEL

3.1 *The geometry*

The numerical model that was prepared is based on a three-dimensional explicit finite difference scheme. Material behaviour is simulated according to an elastic constitutive stress/strain law in response to the applied forces or boundary restraints. The software FLAC3D (Itasca Consulting Group, Inc., 2016) was employed for the simulations.

The geometry provided by the formulators has been processed to build a mesh that was suitable for the finite-difference model (FDM) that was prepared, as shown in Figure 3. The only significant difference with the mesh that was provided is that the dam is described as made of concrete blocks rather than a monolithic structure. This was done to properly simulate the dam construction considering the blocks as independent and not interacting between each other, thus fully neglecting the arch effect in this phase.

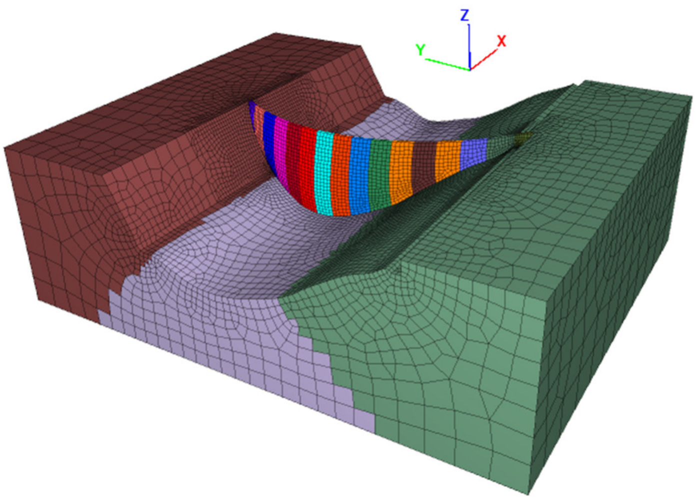

Figure 3. 3D view of the numerical FD model. Dam geometry described as made of concrete blocks. The rock foundation is described by three zones (left/right banks, valley floor) characterized by different mechanical properties (see Section 4.2).

No information was given on the construction phasing of the dam. The authors believed that given the age of the dam and the material of construction (traditional concrete), simulating the dam construction assuming independent blocks leads to a stress state close to the actual one. Having or not a realistic stress state at the end of construction does not impact in any way the elastic dam response to the loads. However, if one is interested in the stress state of the dam, to evaluate for example the possibility of onset of cracks, then having a consistent state of stress at the end of the construction phase is indispensable.

3.2 *Hydrostatic and thermal loads*

It was assumed that two effects have a dominant role on determining the behaviour of the dam: the effect of the hydrostatic load and the one of the thermal loads. Therefore, these two loadings only have been considered in the numerical model.

The hydrostatic load depends exclusively on the water level in the reservoir, and it was simulated by applying a mechanical normal stress to the dam upstream face. In this study the dam-foundation response is computed for five water levels in the reservoir, as represented in Figure 4, considering non-linear interfaces at the dam base and in correspondence of the vertical construction joints.

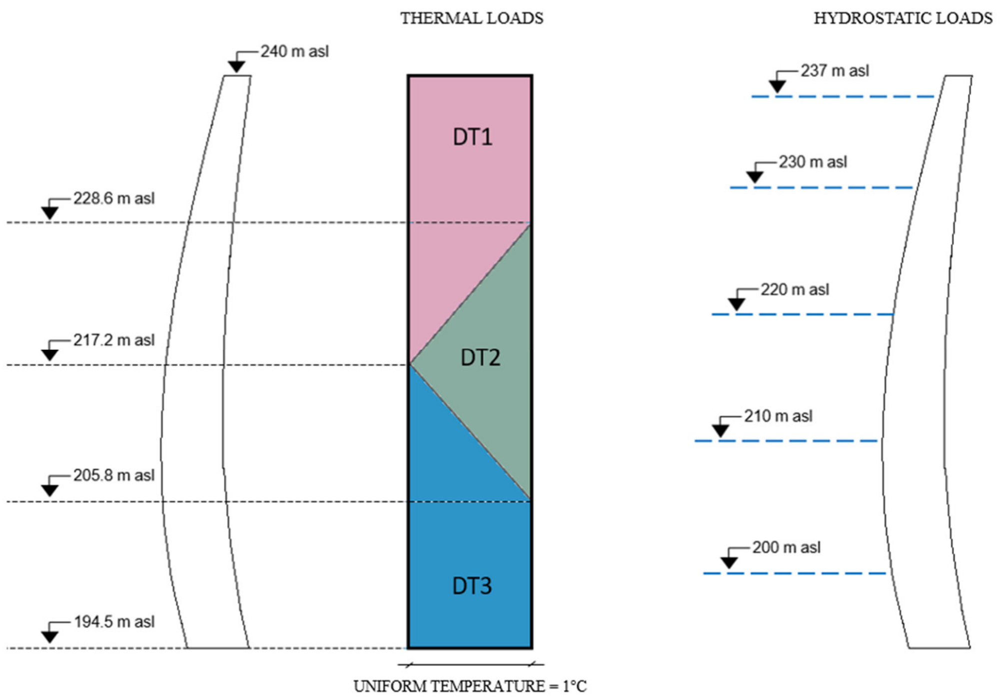

Figure 4. Thermal and hydrostatic loads.

Conversely, the dam response to the thermal loads is assumed to be elastic. The computation of thermal effects is therefore based on the superposition principle. The numerical model response to the thermal loads is computed for unit loads defined at various levels. Usually, the levels at which the unit loads are defined are related to the location of the dam thermometers. In the lack of such equipment, three different unit load patterns have been defined, as represented in Figure 4. Thermal loads are assumed to be constant towards the left/right abutments direction.

3.2.1 *Definition of thermal loads*

The thermal state within an arch dam is of primary importance for predicting its behaviour. In fact, the displacements of an arch dam are influenced also by the thermal elongation caused by temperature variations.

Although in most of the cases the temperature effects can be approximated by a seasonal effect which is repeated the same every year, in certain conditions (i.e., full and prolonged drawdown) the direct measurement of the concrete temperature by means of thermometers is necessary for correctly interpreting the dam behaviour. An extreme example is the case of the 250-300’000 m3 snow avalanche occurred in 1999 at the 67 m high Ferden arch dam (Switzerland), covering 35 m of the downstream face (Bianchi, 2000). In that case, the temperature measured by the thermometers installed in the dam body allowed to confirm the normal behaviour of the dam under such exceptional loading conditions, which had instead been questioned by the statistical interpretative model (Amberg, 2009).

Unfortunately, the examined dam is not equipped with thermometers in the dam body and the formulators provided only two time series of the air temperature (T_a, T_b). A comparison between the monthly averages of the two time series shows that T_a and T_b reproduce basically the same temperatures but with an offset of 8-9°C. Since T_b indicates temperatures which seems to be more compatible with the elevation of the dam (approximately 2000 m asl, according to the formulators), T_b is considered in the following for the definition of the thermal state.

The thermal state within the dam is evaluated by means of a transient thermal analysis. The thermal calculation is performed assuming 1D heat flow along the dam thickness. The thermal properties of the concrete are the following: conductivity: 2.0 W/mK, specific heat: 900 J/kgK, density: 2400 kg/m^3. Three calculation sections are considered at three different elevations: 205.8 m asl, 217.2 m asl, 228.6 m asl. Each section is characterised by a different concrete thickness: 5.2 m, 4.5m and 3.4 m, respectively.

The dam thickness is divided into 11 elements and the calculation procedure is based on a finite difference explicit method (see Amberg, 2003 for more details). Heat flow is assumed to occur by radiation and convection at the faces of the dam and by conduction within the dam.

The temperature boundary conditions at the upstream face depends on the upstream water level (see Figure 5): water temperature is considered in the case the water level is above the calculation section, air temperature is considered otherwise. In the first case a convective heat coefficient of 13 W/m^{2}K (concrete-air) is adopted, together with a surface emissivity equal to 0.7, while in the latter case a convective heat coefficient of 500 W/m^{2}K (concrete-water) is adopted, while the surface emissivity is assumed to be none.

The water temperature (T_w) is not directly measured, but it was derived from the air temperature by applying the following simplified approach suggested by the formulators:

$$T_w = \begin{cases} 0.7 \cdot T_b & if\ T_b > 0°C \\ 0 & otherwise \end{cases} \qquad (1)$$

For the downstream face, being always exposed to air, the air temperature is considered as a boundary condition. The thermal calculation starts in 1995 and ends in 2017.

The results of the thermal calculation are shown in Figure 6 in terms of average temperature along the dam thickness for the three considered elevations.

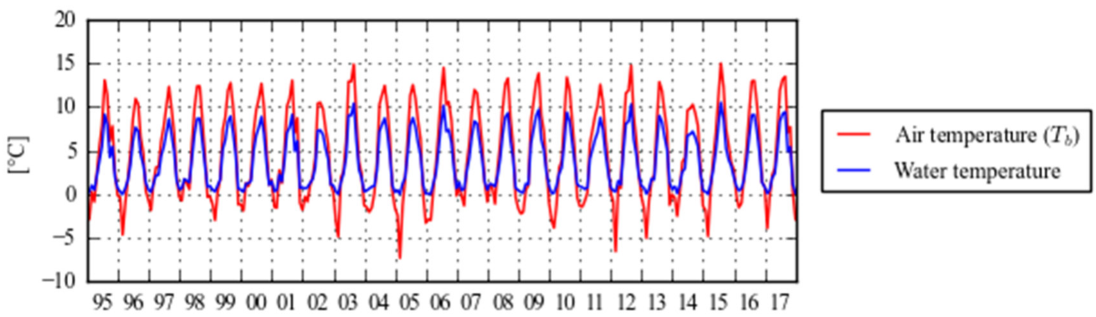

Figure 5. Air and water temperatures assumed in the thermal calculation (monthly averages).

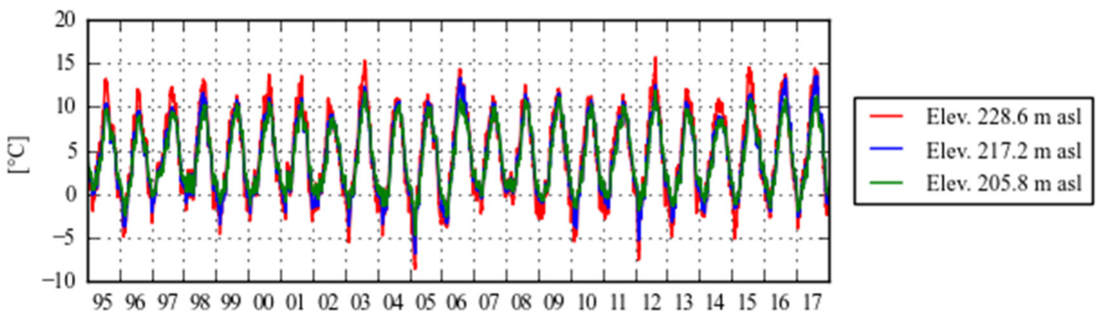

Figure 6. Concrete average temperature at the three elevations assumed in the thermal calculation.

4 MODEL CALIBRATION

4.1 *Procedure for model calibration*

A polynomial interpolation (4th degree) is performed on the displacements that are computed by the numerical model for each of the water levels that are represented in Figure 4. Computation of displacements for any water level is then possible.

The displacement $\delta_{W,i}$ induced by the hydrostatic load *Q*, at the measurement point *i* (i.e. measurement poinst of the pendulums), can be computed using the following expression:

$$\delta_{W,i} = a_i \cdot x + b_i \cdot x^2 + c_i \cdot x^3 + d_i \cdot x^4 \tag{2}$$

where:

- $x = \frac{Q-Q_{min}}{Q_{max}-Q_{min}}$ is the normalized level in the reservoir, with $Q_{min} = 160$ m asl and $Q_{max} = 237$ m asl.
- a_i, b_i, c_i, d_i are the coefficients of interpolation for the measurement point i (obtained from the results of the numerical model).

The displacement $\delta_{T,i}$ induced by thermal loads, at the measurement point *i* (i.e., measurement points of pendulums), can be computed using the following expression:

$$\delta_{T,i} = \sum m_{ij} \Delta T_j \tag{3}$$

Where:

- m_{ij} is the displacement at the measurement point i for a unit load at level j (result of the numerical model);
- ΔT_j is the average concrete temperature at level j.

The procedure for model calibration consists in testing several scenarios in terms of material properties of the simulated materials, to reproduce at the best possible the observed behaviour of the dam (monitoring data). The effectiveness of the calibration is evaluated on the base of the difference between measurements and model predictions, expressed by the following equation:

$$\delta_{C,i} = \delta_{M,i} - \delta_{W,i} - \delta_{T,i} \tag{4}$$

Where:

- $\delta_{C,i}$ is the difference between the measured displacement at the measurement point i and the model prediction for the measurement point i;
- $\delta_{M,i}$ is the measured displacement at the measurement point i.

Equation 4 is calculated for each date in which the measurement $\delta_{M,i}$, the water load Q and the average concrete temperatures ΔT_j are available.

The internal software P0863 developed by Lombardi is used as a tool for model calibration. The software helps the user in the definition of a new numerical scenario in terms of material properties (concrete and rock stiffness, thermal expansion coefficient) that could better reproduce the effective dam behaviour.

4.2 *Material properties*

In the benchmark formulation, the following information were made available:

- The dam is made of concrete with cement dosage at 300 kg/m3. The average value of compressive strength is 34 MPa (after 90 days) with values varying from 22 MPa to 45 MPa;
- The foundation consists of laminated metamorphic slate with a high compressive strength. However, the anisotropy of foundation confers a higher deformability to the left bank.

The mechanical properties that were recommended by the formulators for the concrete and the rock foundation are summarized, the initial estimate for the numerical analyses and the result of the calibration are summarized in Table 1.

Table 1. Mechanical parameters of the modelled materials proposed in benchmark formulation, initial estimate for the numerical analyses and result of the calibration.

	Young's Modulus [GPa]		
	Formulator proposal	**Initial estimate**	**Result of calibration**
Concrete of the dam	22	22	24
Foundation right bank	Parallel: 15 Perpendicular: 10	12.5	3.5
Foundation (approximately bottom of the valley)	Parallel: 5 Perpendicular: 1	3	0.5
Foundation left bank	Parallel: 10 Perpendicular: 1	5	1.4

Some preliminary comment can be formulated on the proposed material properties, in the light of the information that was available from monitoring data. In this study, pendulums information is quietly poor, since only one measurement of dam displacements and one measurement of foundation displacements are provided. This information is given for the central block of the dam (see Figure 1). No other information was given about foundation behaviour (e. g. from extensometers). In this context, the introduction of an anisotropic behaviour for the rock foundation has been considered too complex without having enough information to verify the effectiveness of the adopted material properties. For this reason, average isotropic moduli have been defined for the rock foundation. Different values for left and right banks, and for the foundation at the bottom of the valley, are maintained, even though information from other pendulums located towards the left and the right abutment would have helped the interpretation of dam-foundation response to the loads.

The calibration process leads to a slightly increase of the concrete modulus to 24 GPa and a general decrease of the modulus of the rockmass (0.5 GPa at the bottom of the valley, 3.5 GPa at the right bank and 1.4 GPa at the left bank). Regarding the coefficient of thermal expansion, the obtained value is 1.4e-5 $°C^{-1}$, which is increased with respect to the value proposed by the formulators (0.7e-5 $°C^{-1}$).

4.3 *Results of the numerical FDM model*

The results of the numerical FDM model are shown in Figure 7, by comparing the predicted and measured dam displacement due to the hydrostatic loads. The measured value is obtained by removing from the measurement the displacement due to the thermal loads.

Two observations can be made. First, the dispersion of the measurement, although reduced, remains quite high. This means that the thermal state within the dam is not reproduced with accuracy. The lack of concrete temperature measurements has a negative impact on the reliability of the simulation of thermal behaviour of the dam.

Second, the behaviour predicted by the model does not fully match with the actual one, especially for the pendulum CB2: the dam seems to be more rigid for higher water levels and less rigid for lower water levels, with respect to the numerical model.

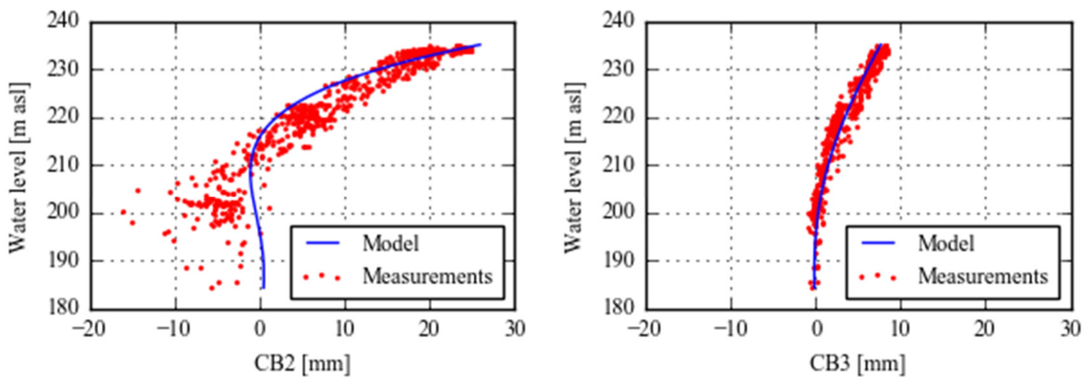

Figure 7. Pendulums – comparison of measurements and model results (note: the thermal effect is removed from the measurements).

Regarding the crack opening, Figure 8 shows a good agreement between the model and the measurements.

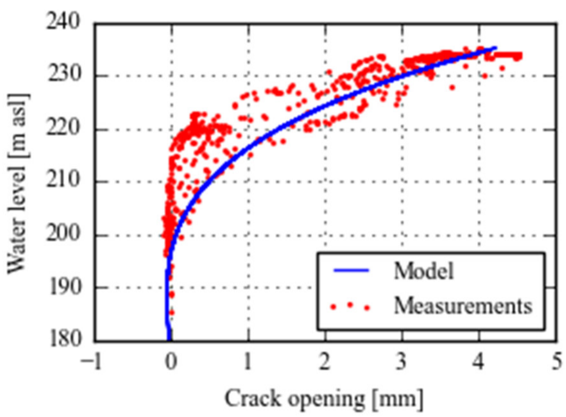

Figure 8. Crack opening – comparison of measurements and model results.

The behaviour of the pendulum CB2 could be explained with an opening of the vertical contraction joints in wintertime with a low reservoir level. Under these conditions the arch effect is reduced resulting in a more deformable structure than the monolithic one. With higher water levels, the joints are closing, restoring the full stiffness of the monolithic structure. This behaviour has been recognized in the past by the authors in other arch dams.

Because of the lack of information regarding the behaviour of the joints, hypothesis on the joint opening cannot be verified. Therefore, it was decided to reproduce the response of the dam to the hydrostatic loads by interpolating the measurements shown in Figure 7 with a polynomial function of 4th order.

In Figure 9 a comparison between the numerical model and the statistic interpolation is shown for the pendulums CB2 and CB3. It is evident that the polynomial interpolation better reproduce the actual behaviour of the dam.

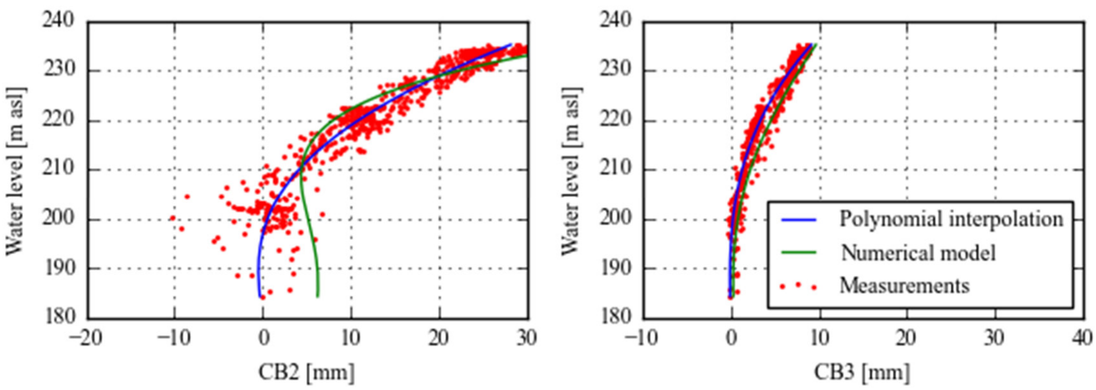

Figure 9. Pendulums CB2 and CB3 – comparison of measurements and the results of the polynomial interpolation and the numerical model (note: the thermal effect is removed from the measurements).

4.4 *Interpretative model*

Based on the considerations presented above, the final model used for the prediction presented in the following is based on a hybrid model composed by:

- A constitutive model, i.e., based on the numerical model, for the prediction of the dam response to thermal loads and for the prediction of the crack opening;
- A data-based model, i.e., based on the polynomial interpolation, for the prediction of the dam response to hydrostatic loads.

The equations of the model used for the prediction of the behavior of the dam are listed hereafter. The set of equations 5 represents the model for the pendulum CB2, while the set of equations 6 is for the pendulum CB3 and the set of equations 7 is for the crack opening. In the equations, $\delta_{CAL,i}$ is the predicted displacement of the pendulum i ($i = 2$ for CB2, $i = 3$ for CB3) and the predicted crack opening ($i = 4$). The constants that appear in the equations minimize the average difference between measured displacements and calculated ones.

$$\begin{gathered} \delta_{W,2} = 15.655 \cdot x - 98.312 \cdot x^2 + 158.751 \cdot x^3 - 45.256 \cdot x^4 \\ \delta_{T,2} = -1.413 \cdot \Delta T_{228} - 0.343 \cdot \Delta T_{217} + 0.284 \cdot \Delta T_{205} \\ \delta_{CAL,2} = \delta_{W,2} + \delta_{T,2} - 14.993 \end{gathered} \tag{5}$$

$$\begin{gathered} \delta_{W,3} = 3.028 \cdot x - 18.824 \cdot x^2 + 28.033 \cdot x^3 - 2.097 \cdot x^4 \\ \delta_{T,3} = 0.031 \cdot \Delta T_{228} - 0.039 \cdot \Delta T_{217} - 0.162 \cdot \Delta T_{205} \\ \delta_{CAL,3} = \delta_{W,3} + \delta_{T,3} - 4.428 \end{gathered} \tag{6}$$

$$\begin{gathered} \delta_{W,4} = 1.225 \cdot x - 7.088 \cdot x^2 + 8.097 \cdot x^3 + 3.421 \cdot x^4 \\ \delta_{CAL,4} = \delta_{W,4} - 3.172 \end{gathered} \tag{7}$$

The measured and calculated displacements are shown in Figure 10, while their difference between is shown in Figure 11.

The correspondence between the measured and calculated displacements is considered satisfactory, given the available information. The standard deviation of the difference between the measured and calculated displacement is 2.3 mm for the pendulum CB2, 0.6 mm for the pendulum CB3 and 0.6 mm for the crack opening.

4.5 *Warning levels, short-term and long-term predictions*

The warning levels should be defined to identify anomalies in the dam behaviour. Assuming that the dam behaviour is regular in the calibration period, an excessive deviation from the model prediction should be considered as an anomaly. In the definition of what one should consider "excessive" the precision of the model in the calibration period must be accounted.

Therefore, it is proposed to define the warning levels as the envelope of the maximum differences between the measurements and the model predictions in the calibration period (2000-2012):

- for the pendulum CB2: ±6 mm with respect to the model prediction;
- for the pendulum CB3: ±3 mm with respect to the model prediction;

for the crack opening: ±2 mm with respect to the model prediction.

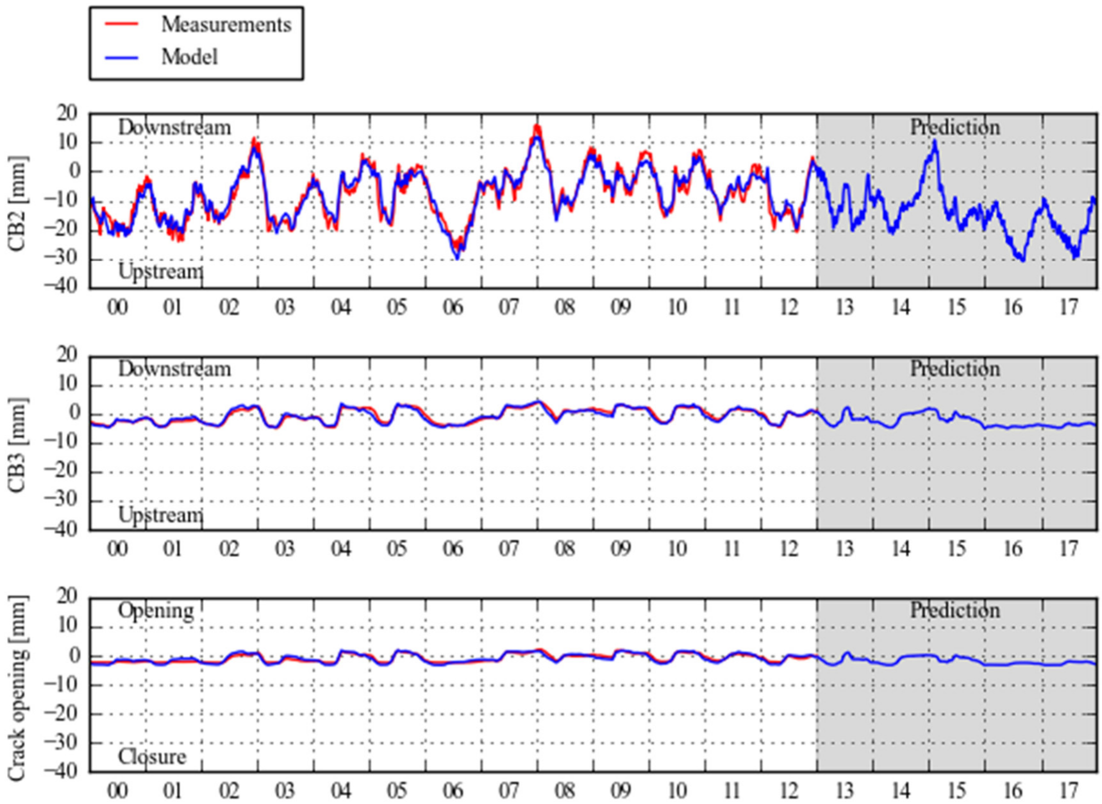

Figure 10. Pendulums and crack opening – comparison of measurements and model prediction.

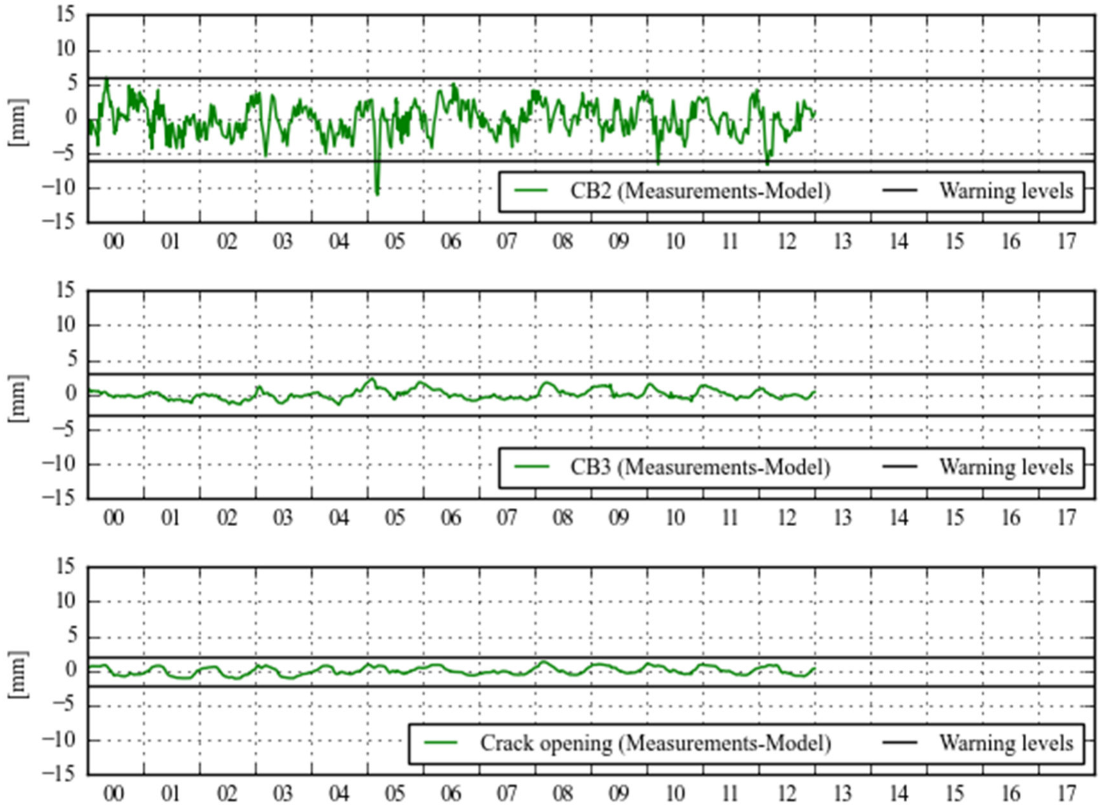

Figure 11. Pendulums and crack opening – difference between the measurements and the model.

An excessive deviation from the expected behaviour should not be necessarily interpreted as a safety concern for the dam. The warning levels, as defined above, has the scope to highlight as soon as possible any anomaly in the dam behaviour or in the measurement instrumentation, in order to promptly analyse it and, if necessary, implement the appropriate corrective measures.

The figures above also show the predictions of the model for the period 2013-2017, which is one of the tasks of the Benchmark. It worth mention that the period 2016-2017 is characterised by a low water level and the displacements of the pendulum CB3 are quite completely caused by the thermal loads.

5 INTERPRETATION

The information gained from the monitoring measures, together with the results of the numerical model allow to point out some important aspects regarding the behaviour of the analysed dam.

The rock modulus obtained from the calibration process are quite low, in the order of 0.5-3.5 GPa, and significantly lower than those proposed by the formulators (1-15 GPa). Although the obtained moduli allow to reproduce the displacements measured by the pendulum with a good agreement, drawing some conclusions regarding the actual stiffness of the rock mass is questionable. The reliability of the estimate is higher for the modulus of the central part of the valley (0.5 GPa), due to the presence of the pendulum CB3 which measure the response of the rock to the forces transmitted by the dam. However, the lack of information regarding the rock mass deformations in the left and right banks, makes the estimate less reliable.

The measurements of the pendulum CB2 has a high dispersion when plotted as a function of the water level (Figure 2). In fact, the range of variation of the displacement for a certain water level is of the same order of magnitude as the variation of the displacement due to the full reservoir. In this context, the lack of direct information regarding the thermal state within the dam (e.g., thermometers), leads to a reduced precision of the prediction of the model. The thermal analysis conducted to overcome this issue leads to a reduction of the measurement dispersion (**Figure 7**), which however remain quite high affecting the precision of the model.

The comparison between the measurements and the model shows that the dam behaviour is basically reversible, without any drift or irreversible displacements. Only a very modest delay between the measurements and the model is visible for the pendulum CB3, possibly indicating that the rock mass behaviour is affected by some viscous effect. Regarding the pendulum CB2, the numerical model results highlighted that the actual behaviour of the dam could be influenced by an opening of the vertical contraction joints in wintertime with a low reservoir level, leading to a progressive activation of the arch effect as a function of the water level.

The numerical model is used also for estimating the maximum compressive stress in the arch for the load combination of maximum water level in summertime. It is remarked that the summertime condition is simulated in a simplified way by considering a temperature increase of 10°C for the whole dam. This value derives from assuming a reference temperature of 5°C and considering the maximum temperatures shown in Figure 6. The horizontal stresses in the direction of the arches are shown in Figure 12, while the vertical stresses are shown in Figure 13. The maximum compressive stresses are horizontal and located at the upstream face in the middle of the dam and reach 4 MPa, which is far below the compressive strength of the concrete (34 MPa as provided by the formulators).

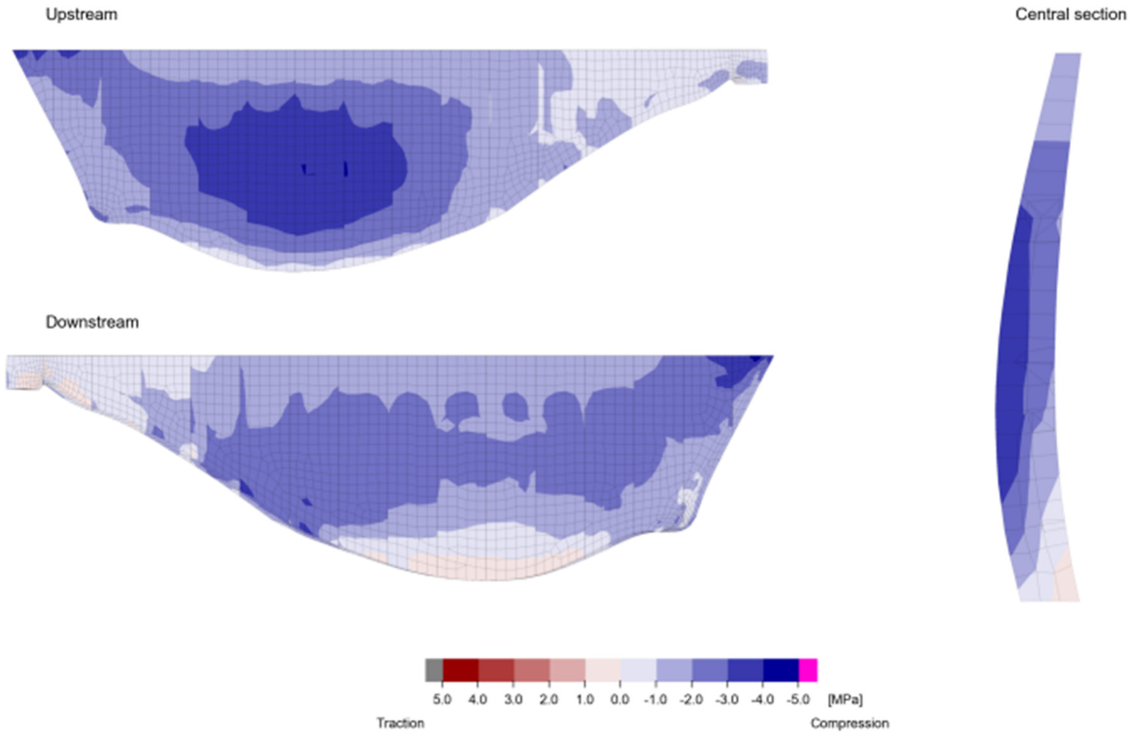

Figure 12. Horizontal stress in the direction of the arch for the condition of full water level and summer temperatures.

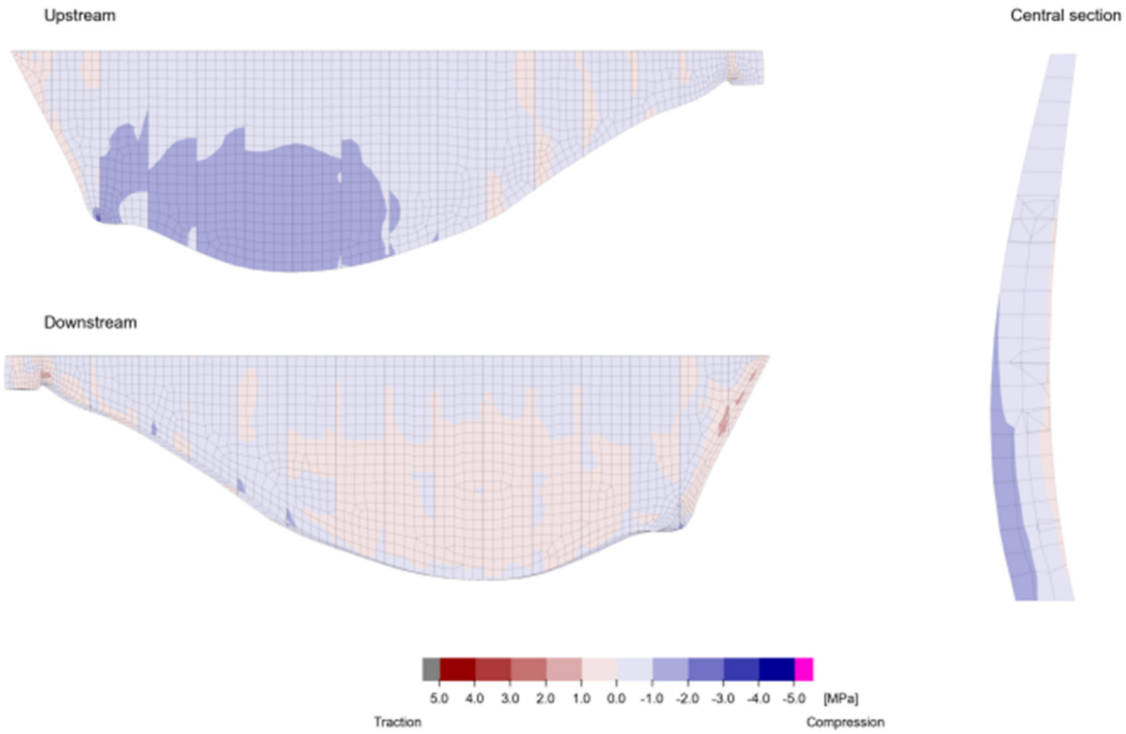

Figure 13. Vertical stress for the condition of full water level and summer temperatures.

6 CONCLUSIONS

The Theme A of the 16th International Benchmark Workshop on Numerical Analysis of Dams concerned the preparation of a behaviour model for a concrete arch dam.

The numerical model that was prepared is based on a three-dimensional explicit finite difference scheme. Material behaviour is simulated according to an elastic constitutive stress/strain law in response to the applied forces or boundary restraints.

The model had been calibrated to fit as best possible the measurements coming from monitoring equipment. However, some problems were encountered.

On one hand, the model was not able to capture properly the dam response to thermal loads. The reason for that could probably be related the poor available information on the thermal state of the dam over the calibration period.

On the other hand, measurements of dam displacements for low water levels indicate a deformability of the structure that the model was not able to capture. Dam response to the highest water levels is better reproduced by the model. Crack opening measurement from sensors near the base of the dam were also well reproduced. Some hypotheses have been formulated on this deviation between the measurements and the model results, such as the opening of vertical contraction joints in wintertime with low reservoir level. No information on joint opening was available, so this hypothesis could not be verified.

Finally, a data-based approach has been followed to interpolate the dam response to the hydrostatic load. The deterministic (constitutive numerical) approach was maintained in making predictions on thermal behaviour and crack opening. The result of the model can be considered satisfactory.

As engineers often involved in similar situations, we had a new opportunity to observe that following a constitutive approach when preparing dam behaviour models allows going in a deeper detail while interpretating dam's response. Calibrating a constitutive numerical model often brings to a better knowledge of dam's behaviour and of the characteristics of the materials. The data-based statistical approach is inherently valid as long as the *usual* conditions that characterize dam life are met again in the future (which is highly probable, though!). In case of *unusual* conditions, for which the information given by a model regarding dam safety are most valuable, the reliability of a statistical model could be lower.

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APPENDIX – AVAILABLE MONITORING DATA