A coupled statistical and numerical approach for the arch dam monitoring

Chady El Moataz Billah, Nicolas Ulrich and Frédéric Andrian.
Artelia, Grenoble, France

ABSTRACT: Monitoring is a major part of dam safety and surveillance provisions. Monitoring is a decision-making tool which allows a relatively detailed understanding of the behavior of the dam at a weekly timescale or even more frequently when required. In France, it is usual practice to calibrate the numerical model used for the stability analysis of arch dams by means of data from the monitoring system and use the mentioned numerical model for prediction of behavior and safety assessment. The aim of this paper is to present the results of different methods and assumptions used to process dam monitoring data for explaining the current behavior of an arch dam and predicting its future behavior. Two different methods are used: statistical analysis and numerical modelling. The monitoring data are used to set up HST (Hydrostatic, Season, and Time) and Thermal HST (HSTT) statistical models. Then a numerical thermo-hydro-mechanical model is performed to predict the arch dam's future behavior after being calibrated by means of the monitoring data. Then, a preliminary safety analysis of the dam with the numerical model is carried out by determining a few strength parameters allowing the dam to fulfill the current French Guidelines on stability analysis of arch dams.

1 INTRODUCTION

The aim of this paper is mainly to detail the used methods for filling up the excel files for reporting the results. The used assumptions are described, and some interpretations of the different analyses is made.

Two approaches are carried out: statistical methods and numerical models. Concerning statistical models, the three cases (calibration, short and long term predictions, and interpretation) have been carried out for all devices except for leakage device.

Warning levels are defined for each device based on usual practice.

Three different approaches are used in the current case study. The participants are requested to rank the ability of each of them in terms of best guess of the future behavior of the dam. In the point of view of the authors, the statistical models seem to be more accurate in predicting the future behavior of the current arch dam. Firstly, they are useful tools that allow complex phenomena involved in the raw data to be explained with a rather good confidence. Secondly, as long as the expected loadings (in a separate way) have already been submitted to the dam, statistical approaches are believed to be also of good accuracy to predict the future behavior under a specific load combination. On the other hand, numerical models must consider all the involved physical phenomena and related parameters in order to accurately simulate the behaviour of the real structure. In the current case, several assumptions are made for the missing data. Consequently, as only a few relevant data for the numerical analysis are available, the results are ranked at the third place. Regarding the statistical models, the HSTT method is judged better in this specific case. As the HSTT method has one more parameter to explain raw data and as the case study is a relatively thin arch, HSTT model is judged more accurate in this case where the concrete temperature can rapidly vary across the thickness of the dam. And finally, the data covers several years of dam operation, enhancing the ability of the statistical model to explain and predict the behavior. Therefore, HSTT models is ranked at the first place.

A reminder of the excel files content is given below

Table 1: Reminder of analysed data

Method	Device	Case A	Case B	Case C
HST models	CB2	Yes	Yes	Yes
	CB3	Yes	Yes	Yes
	C4_C5	Yes	Yes	Yes
	PZCB2	Yes	Yes	Yes
	PZCB3	Yes	Yes	Yes
	Leakage	No	No	No
HSTT models	CB2	Yes	Yes	Yes
	CB3	Yes	Yes	Yes
	C4_C5	Yes	Yes	Yes
	PZCB2	Yes	Yes	Yes
	PZCB3	Yes	Yes	Yes
	Leakage	No	No	No
Numerical models	CB2	No	Yes	Yes
	CB3	No	Yes	Yes
	C4_C5	No	No	No
	PZCB2	No	No	No
	PZCB3	No	No	No
	Leakage	No	No	No

2 DATA BASED MODELS

2.1 *HST method*

2.1.1 *Description*

HST Method is statistical model developed by EDF (Willm et al., 1967). The aim of this method is to explain dam monitoring data with three independent and additive effects. The first effect is the hydrostatic effect induced by the hydrostatic pressure of the water level in the reservoir. The second is the seasonal effect, it reflects such as a periodic behaviour of the dam regarding the period of the year. The last one is the time effect, which model the ageing behaviour of the dam or of a monitoring device over time. The hydrostatic and seasonal effect are supposed to be reversible whereas the time effect is considered as irreversible. These three effects are defined as follows:

$$f_{hydrostatic}(Z) = a_1 Z + a_2 Z^2 + a_3 Z^3 + a_4 Z^4 \tag{1}$$

$$f_{season}(S) = a_5(1 - \cos(S)) + a_6 \sin(S) + a_7 \sin^2(S) + a_8 \sin(S)\cos(S) \tag{2}$$

$$f_{aging}(\tau) = a_9 \tau + a_{10} \tau^2 + a_{11} e^{-\tau} \tag{3}$$

Z is the dimensionless water level in the reservoir defined by $Z = (Z\_PHE - h)/H\_br$. In this equation Z_{PHE} is the maximum water height in the reservoir (corresponding to the design flood), h is the current water level, and H_{br} is the dam's height above its foundation.

S is a radiant angle between 0 rad on the 1st January and 2π on the 31st December, S=$2\pi(d/365.25 - \lfloor d/365.25 \rfloor)$ with d the date of the day.

$\tau = t/T\_bt$ where t is the time of measurement expressed in years from a reference date, T_{bt} a constant expressed in years.

Coefficients $(a_i)_{i \in [\![0;11]\!]}$ are computed by least-square minimisation. Let Y be series of raw data and Ŷ be modelled data. The HST method models raw measurements and modelled data with

$$Y = a_0 + f_{hydrostatic}(Z) + f_{season}(S) + f_{aging}(\tau) + \varepsilon \tag{4}$$

$$\hat{Y} = Y - \varepsilon = a_0 + f_{hydrostatic}(Z) + f_{season}(S) + f_{aging}(\tau) \tag{5}$$

a_0 and ε are the constant and the residual error due to the linear regression.

An HST model is evaluated with the correlation coefficient $R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \in [0;1]$ and with the adjusted coefficient correlation $(R_a)^2 = 1 - \left(\frac{n-1}{n-p}\right)(1 - R^2)$. $\bar{y}$ is the mean of the sample Y, n is number of data and p the number explanatory variables. The clothier to 1 R_a^2 is, the better statistical model is adjusted.

2.1.2 *Application to the case study*

The same calibration period is used for pendulums CB2 and CB3 and crack opening C4_C5. They are calibrated between 19/01/2000 and 31/12/2012. Regarding piezometers, calibration periods are not identical. For both piezometers, the calibration considers the cleaning of the drainage system in February 2008. Consequently, the piezometer PZCB2 is calibrated between 20/09/2008 and 31/12/2012. Piezometer PZCB3 is calibrated between 01/01/2000 and 31/12/2012, but a drop in data is assumed to model the cleaning of the drainage system and to take into account the lack of data in early 2008. This drop is modelled on 10/09/2008.

Regarding the case C (long term predictions), a long period where the water level was below the lowest level experienced during the calibration period is noticed. In order not to misevaluate the hydrostatic function of HST method, the raw data are modified so as not to include any water level below that minimum value experienced during the calibration period, i.e., El. 185. When the water level values are lower than this elevation, this value is used as a replacement.

Finally, there isn't any successfully calibrated model for leakage. The best correlation coefficient reached about $R^2=0,5$. This range of value is not high enough to result in an accurate HST model and to perform realistic monitoring analysis. Actually, leakage behavior is difficult to model with basic HST model. Indeed, leakage is subjected to strong non-linearities which is basically described by the law of Poiseuille, some threshold and/or cross-effects between thermal, mechanical and hydraulic effects (de Bigaut de Granrut, 2019).

The correlation factors of statistic models are given below.

Table 2: HST models correlation coefficients

	R^2	R_a^2
Pendulum CB2	0.9135	0.9130
Pendulum CB3	0.9646	0.9642
Crack opening C4_C5	0.9749	0.9747
Piezometer PZCB2	0.9925	0.9921
Piezometer PZCB3	0.9331	0.9326

2.2 *Thermal HST method (HSTT)*

2.2.1 *Description*

Thermal HSTmethod (HSTT) is an improvement of the classical HST method described in §2.1.1. It was developed by EDF after a heatwave in 2003 (Penot et al., 2009). HSTT considers one supplementary explanatory variable: air temperature. This new variable aims to explain raw data in which a high-frequency change in temperature occurs. Actually, the seasonal effect of the HST method explains only the low-frequency temperature changes, i.e., annual temperature changes. HSTT method allows the daily temperature changes to be considered.

This new variable called E_R and is added to the seasonal effect. The other effects of the HST method stay identical (eq. (1) and (3)). Thus, the seasonal effect from HSTT method is defined as follows:

$$f_{season}(S) = a_5(1-\cos(S)) + a_6\sin(S) + a_7\sin^2(S) + a_8\sin(S)\cos(S) + b_1 E_R \qquad (6)$$

Coefficients $(a_i)_{i\in[\![0;11]\!]}$ and b_1 are computed by least-square minimisation.

Theoretically E_R is the impulse response to the unidirectional conduction equation

$$\frac{\partial\theta}{\partial t} = \frac{\lambda\rho}{c}\frac{\partial^2\theta}{\partial x^2}$$

where the arch dam is assumed to be a finite medium of width L and only submitted to a temperature E at its extremities. (Penot et al., 2009)

In the modelling E_R is computed by

$$E_R(t+dt) = E(t+dt)\left(1-\exp\left(-\frac{dt}{T_0}\right)\right) + \exp\left(-\frac{dt}{T_0}\right)E_R(t) \qquad (7)$$

T_0 is the thermal response time of the dam and E represents deviations from the average temperature. It only represents deviations from the average temperature as the behaviour of the dam against the average temperature is modelled by the HST seasonal effect.

The average temperature is calculated from temperature data with linear regression. Let be θ_a the average temperature, modelled by

$$\theta_a = c_1 \cos(S) + c_2 \sin(S) + c_3 \cos(2S) + c_4 \sin(2S) \tag{8}$$

and thus, E is defined by $E = \theta - \theta_a$, θ is air temperature.

For each device, the thermal response time is calibrated with statistical optimisation but the value of T_0 is checked to ensure the physical consistency of this parameter which is supposed to represent the response time of the instrument to a thermal variation.

2.2.2 *Application to the case study*

The Hypotheses for HSTT method are the same as that of HST method. The same period of calibration between January 2000 and December 2012 is also used. PZCB2 is calibrated between 20/09/2008 and 31/12/2012 and PZCB3 is calibrated between 01/01/2012 and 31/12/2012 with a drop in the data on 10/09/2008. Regarding case C, the same hypothesis regarding minimum water level is made in order not to misevaluate hydrostatic effect.

The correlation factors of statistic models are given below which highlight the better correlation compared to the HST model.

Table 3: HSTT models correlation coefficients

	R^2	R_a^2	T_0 [days]
Pendulum CB2	0.9681	0.9677	5
Pendulum CB3	0.9690	0.9687	14
Crack opening C4_C5	0.9752	0.9749	10
Piezometer PZCB2	0.9936	0.9932	9
Piezometer PZCB3	0.9340	0.9334	9

2.3 *Warning levels*

Warning levels are defined on the corrected data from the calibration period. Corrected data are computed by subtracting reversible effects to the raw data.

$$Y_{corrected} = Y_{raw} - f_{hydrostatic}(Z) - f_{seasonnal}(S; E_r) \tag{9}$$

Corrected data allows the dispersion of the data to be reduced and the analysis of the dam behaviour or monitoring devices to be facilitated. Warning levels are set to be equal to $\pm 2.5 \cdot \sigma_C$ in addition to the irreversible data modelled by HST/HSTT models. σ_C is the standard deviation of the corrected data during the calibration period and irreversible data are defined by

$$Y_{irreversible} = Y_{modelled} - f_{hydrostatic}(Z) - f_{seasonnal}(S; E_r) = a_0 + f_{aging}(\tau) \tag{10}$$

Thus, warning levels are defined by

$$Upper\ Warning\ level\ = 2.5 \cdot \sigma_C + Y_{irreversible} = 2.5 \cdot \sigma_C + a_0 + f_{aging}(\tau) \tag{11}$$

$$Lower\ Warning\ level\ = -2.5 \cdot \sigma_C + Y_{irreversible} = -2.5 \cdot \sigma_C + a_0 + f_{aging}(\tau) \tag{12}$$

The value of 2.5$\cdot$ σ_C is based on ARTELIA’s feedback in dam monitoring engineering. Based on experience, this value allows to not have too wide margins and not to have to narrow margins and to have significant alerts. Still, this is a preliminary initial value that may required to be gradually adjusted based on the corrected data after several years of monitoring analysis.

Figure 1: examples of corrected data and warning levels

Warning levels help in distinguishing erroneous measurements from a rather unusual dam behaviour. Typically, in case of erroneous measurements, one device is usually out of its warning levels whereas in case of unusual dam behaviour, several devices usually exceed the thresholds. Still, the dam operator shall ensure that the only device with a peculiar measurement does not relate a local unusual behavior of the dam. Sometimes, when a device is regularly out of warning levels, this may require the warning levels to be adjusted.

In the case of the current case study, for examples between February and March 2005 three devices were out their warning levels (Figure 1). This may be explained the 2004/2005 winter which was colder than the mean winter, -15.5°C at 26/01/2005, combined with a high water level in the reservoir, at El. 230 m at the end of 2004.

3 NUMERICAL MODEL

For this benchmark workshop, the used numerical model is calibrated from statistical models and not directly from raw data.

3.1 *Geometry and meshing*

The numerical model is carried out with FLAC3D, an explicit finite difference calculation code. The used model involves a new meshing layout after slight changes in the provided geometry.

The mentioned changes include the consideration of the vertical joints between the cantilevers as based on ARTELIA's experience, such approach results in a more realistic modelling for arch dams (Mouy et al., 2019). The width and the position of the cantilevers are assessed from the few sketches from the formulation document but also from the original geometry files.

Moreover, the keying of the dam toe is deleted for geometrical convenience. On the other side, the dam / foundation interface is provided with numerical Shear keys so as to simulate the effect of the aforementioned keying.

The numerical model is made of 56000 linear elements distributed as follows:

- 16000 elements in the dam, mainly hexahedral. There are 6 elements across the thickness of the arch in order to accurately simulate bending and achieve a satisfactory resolution of analysis at the dam / foundation interface;
- 40000 elements in the foundation, mainly tetrahedral.

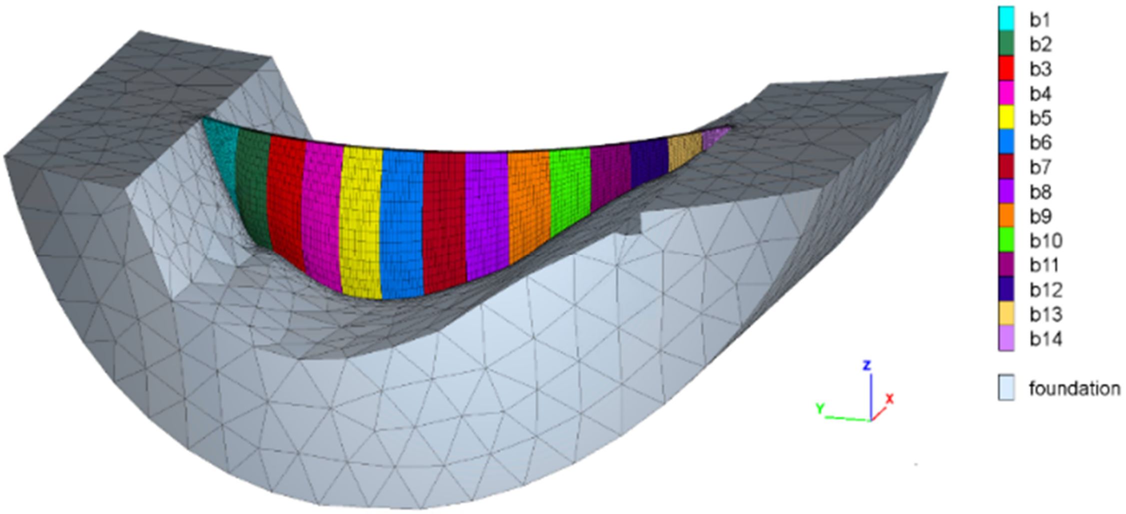

Figure 2: Case study dam's block modelling

3.2 *Mechanical properties*

3.2.1 *Foundation*

As suggested in the formulation document, the foundation is divided into 3 different parts: left bank, right bank and bottom of valley. The Young's modulus of the bottom valley is calibrated using the pendulum CB3's HSTT model. The Young's modulus is determined from the simulation of hydrostatic effect and the thermal expansion coefficient from the simulation of seasonal effect.

The final model parameters are the results of many attempts of model calibration conducted considering both isotropic and anisotropic bedrock foundation. The best fitting is reached with the anisotropic plane presented in Figure 3.

The normal vector to the anisotropic plane is $\vec{n} = (1.25,1,0)$. The calibration is made by varying the reservoir level between 221.5 m and 237 m. The synthesis of calibration is given in the following table and shows a model base which is still slightly stiff with regards to hydrostatic effect:

Table 4: Young modulus of foundation Calibration

	Numerical anisotropic model		HSTT model	
Radial displacement pendulum CB3 [mm]	Computed hydrostatic effect [mm]	Computed seasonal effect [mm]	Target hydrostatic effect [mm]	Target seasonal effect [mm]
	4.34	2.52	5.88	2.52

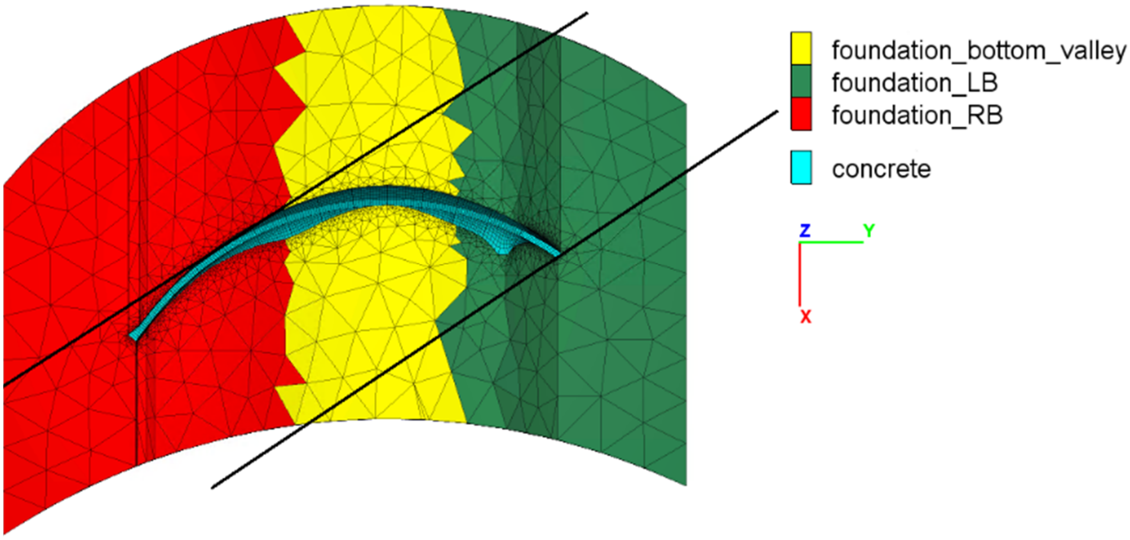

Figure 3: The best fitting anisotropic plane for the foundation

The following table shows the selected material parameters in which the thermal conductivity and the specific heat capacity are usual values which are not assessed from the calibration process. One may notice the rather low Young's modulus normal to the anisotropic planes

Table 5: Foundation mechanical properties

	Left bank	Bottom of valley	Right bank
Young modulus in anisotropic plane $E_{\parallel}$ [GPa]	10.00	5.00	15.0
Young modulus normal to anisotropic plane $E_{\perp}$ [GPa]	0.300	0.300	3.00
Poisson ration	0.30	0.30	0.30
Density [kg/m3]	2700	2700	2700
Thermal conductivity [W/(m.K)]	3.00	3.00	3.00
Specific heat capacity [J/(kg.K)]	850	850	850
Coefficient of thermal expansion [K^{-1}]	$3.00 \cdot 10^{-6}$	$3.00 \cdot 10^{-6}$	$3.00 \cdot 10^{-6}$

3.2.2 *Concrete*

To calibrate concrete's Young's modulus, the same approach as the foundation's calibration is carried out. Hydrostatic effect from pendulum CB2's HSTT model is used to calibrate concrete Young's modulus. Seasonal effect from this HSTT model is also used to calibrate the coefficient of thermal expansion of the concrete.

The synthesis of calibration is given below:

Table 6: Young modulus and thermal coefficient of concrete Calibration

	Numerical anisotropic model		HSTT model	
Radial displacement pendulum CB2 [mm]	Computed hydrostatic effect [mm]	Computed seasonal effect [mm]	Target hydrostatic effect [mm]	Target seasonal effect [mm]
	22.89	23.50	22.34	20.97

The following table shows the selected material parameters in which the thermal conductivity and the specific heat capacity are again usual values which are not assessed from the calibration process:

Table 7: Concrete's mechanical properties

Young modulus [GPa]	35
Poisson ration	0.2
Density [kg/m^3]	2400
Thermal conductivity [W/(m.K)]	2
Specific heat capacity [J/(kg.K)]	900
Coefficient of thermal expansion [K^{-1}]	$8.5 \cdot 10^{-6}$

3.3 *Interfaces and joints*

The vertical joints of the dam are modelled and provided with numerical shear keys allowing the opening but not the sliding even under opened state.

To model the keying at the dam toe, the same numerical feature is also used. Note that because of this shear key and because of the elastic constitutive law, time effects cannot be considered in the prediction model.

3.4 *Loads*

Thermo-mechanical simulations have been carried out for prediction periods, thermal and mechanical loadings were updated for each days of predictions. The calculations involve the use of a thermo-hydro-mechanical simulation for which the features are described in the following. The calculation timestep (update in thermal and in mechanical loadings) is 1 day. As the calibration is performed in a separate way, this stage consists only in predicting the future behavior.

3.4.1 *Pore pressure, uplift and hydrostatic loading*

The simulations are carried out in effective stress state: pore pressure acts as calculation variables in the same way as geotechnical analyses and influences total and effective mechanical stresses (without any backward coupling) with a Biot's coefficient which equals 1. Several pore pressure distributions are computed with flow calculation (Darcy's approach) for several water levels in reservoir. The foundation is assumed to be isotropic in terms of flow and neither the drainage system nor the grout curtain is considered. The calculated pore pressure contour matches with good accuracy to PZCB3, but not so much with PZCB2.

During the prediction calculations, the pore pressure distribution chosen for each day corresponds to the one that has the closest water level among the previously calculated distributions.

The full uplift propagates as external force in any opened region of the dam / foundation interface with an opening higher to 0.2mm as long as the region is in contact with the reservoir.

If the water level in the reservoir is very low (i.e., under dam's toe elevation), the pore pressure is set at the lowest level computed: 193.5 m.

Table 8: Hydraulic properties

	Permeability m/s
Concrete	$1 \cdot 10^{-8}$
Foundation	$1 \cdot 10^{-7}$

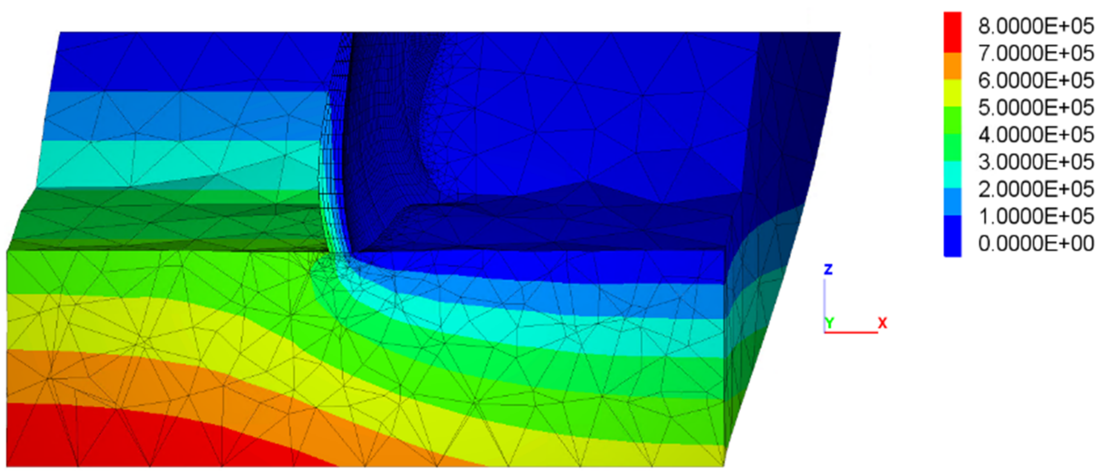

Figure 4: Pore pressure distribution (Pa) corresponding to water level at El. 237 m

3.4.2 *Thermal loadings*

The temperature distribution in the dam and in the bedrock is determined from a transient thermal-only simulation with a timestep of 1 day and applied as thermal loading to the mechanical model. The thermal loadings are calculated from air and water temperature data with a few more assumptions based on ARTELIA's experience.

20 m under water surface, water temperature is assumed to be constant and equal to 4°C. Furthermore, across the 20 first meters under water surface, the temperature is assumed to vary linearly between 4°C and the air temperature.

The temperature of transverse joint grouting is considered to be the annual mean temperature between 2000 and 2012 and leads to 5°C. This uniform temperature distribution corresponds to zero thermal stress in the dam. The transient thermal analysis considers the variations of the water level in the reservoir.

The following table gives the thermal parameters related to heat exchange with air and water.:

Table 9: thermal properties related to heat exchange with air and water

Convective heat coefficient air-concrete [W/(m²K)]	13
Convective heat coefficient air-rock [W/(m²K)]	13
Convective heat coefficient water-concrete [W/(m²K)]	500
Convective heat coefficient water-rock [W/(m²K)]	500

3.5 *Short and long term predictions*

The prediction simulations lead to the results presented in Figure 5 where also superimpose the HST and HSTT prediction curves. The numerical predictions for CB2 are in good agreement with that of HST and HSTT approaches except when the reservoir water level is below the modelled dam's toe. This denotes some poroelastic behavior of the bedrock justifying the use of the pore pressure as state variable but here not very accurate due to the lack of calibration data. The numerical predictions for CB3 are of lesser accuracy due to the stiffer model base compared to reality with regards to hydrostatic effects. Based on the authors experience in arch dam modelling, this case study is one of the very unusual cases where the model base is stiffer than reality. It is suspected that the orthotropy plane is somewhat different that the one modelled. Otherwise, the Young's modulus of the bedrock which would be able to simulate the real behavior of the dam would be too low to denote a bedrock suitable for constructing an arch dam. Moreover, the model is not able to consider the time effect which is rather low e in this case (0.03mm/year) and can then be neglected.

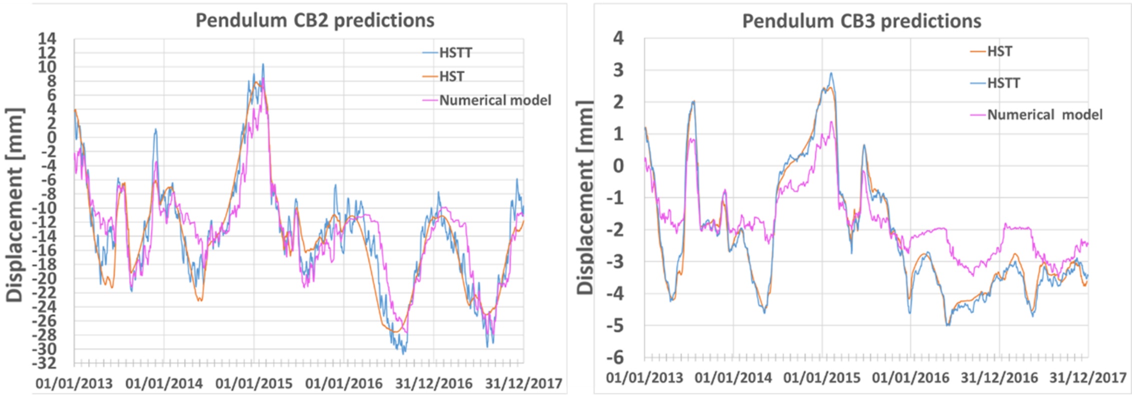

Figure 5: Pendulum predictions results – numerical, HST and HSTT approaches

4 SAFETY ANALYSES

The main advantage of numerical simulation compared to statistical approach is its ability to assess in a quantitative way the safety of the dam with regards to existing national or international guidelines. Consequently, it is considered less valuable to define warning levels based on the numerical simulation predictions. On the other hand, one can assess the safety margin of the dam for a defined load case with regards to a specific failure mode. The one analysed here as an example is the sliding along the dam / foundation interface.

With a maximum base width of 6 m and a maximum height above the bedrock of about 45 m, the case study is thin arch dam. With a straight distance between the abutment of about 158 m, the dam is built on a wide valley (relative to its height). This type of dam usually exhibits extended crack opening (or foundation extension) at their upstream toe when being impounded with full uplift/pore pressure propagating toward the downstream part. Such behavior is exacerbated by winter thermal loading with the shear strength being strongly mobilized at the dam / foundation interface.

The monitoring data confirm this crack opening and the uplift/pore pressure propagation toward downstream. In the numerical model, this opening is localized at the dam / foundation interface with a maximum magnitude of about 3 mm at NWL without thermal loadings. This opening may actually be distributed over several discontinuities within the bedrock.

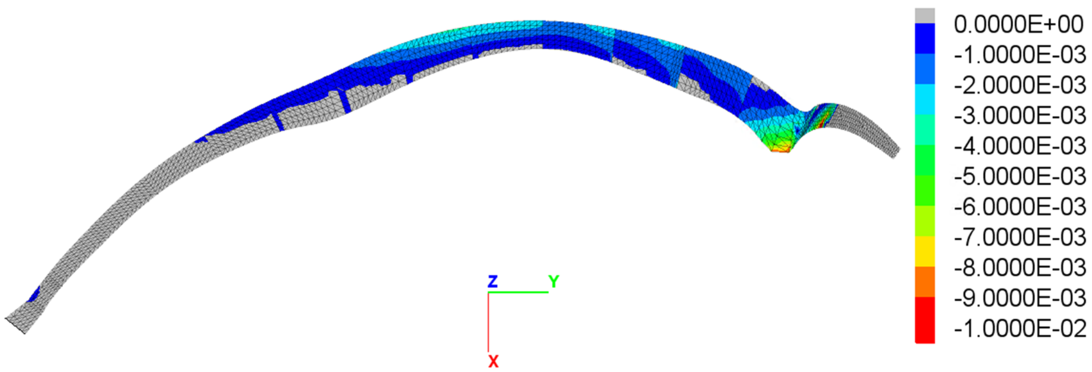

Figure 6: Cracks opening (m) at NWL

A first analysis consists in assessing the mobilized cohesion at the dam / foundation interface when considering a friction angle of 45°. Such cohesion denotes the contact roughness: the cohesion is mobilized even when the dam / foundation interface is in an open state. The maximum mobilized cohesion at the scale of one cantilever is about 800 kPa at NWL under winter thermal loading (Figure 7). This is in the higher range of encountered values for several arch dams studied so far (Robbe et al. 2022).

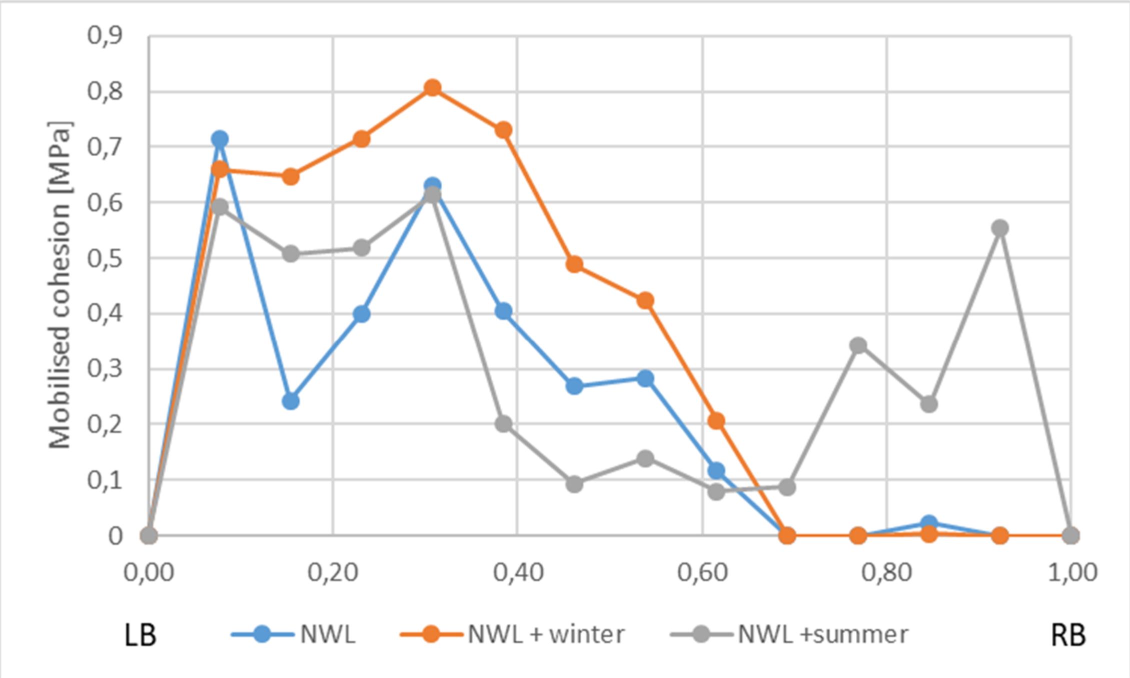

Figure 7: Necessary cohesion to avoid the sliding of each block

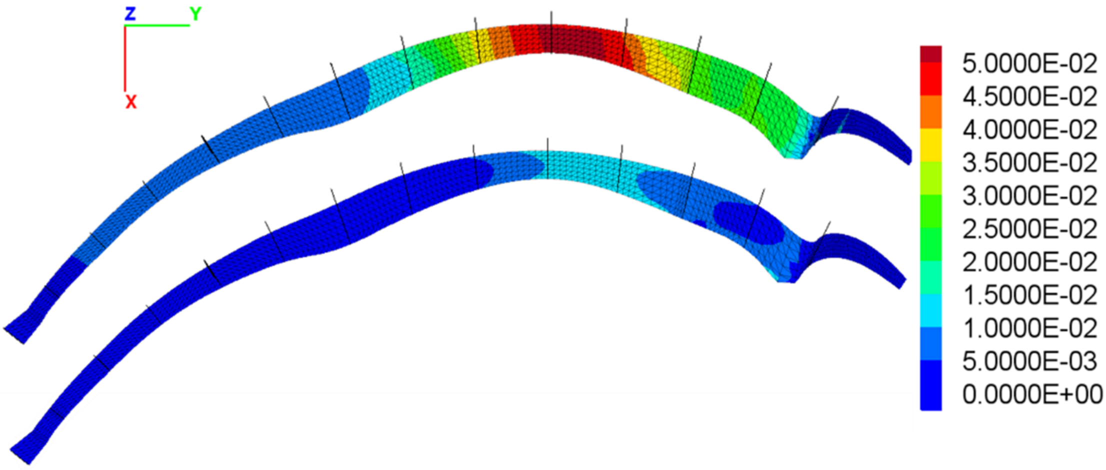

Figure 8: Irreversible shear displacement (m) at rock concrete interface under normal conditions winter Upper interface's properties are c=0 kPa $\varphi = 45°$, *Lower interface's properties are c=600 kPa and* $\varphi = 45°$

Then a sensitivity analysis is carried out regarding the dam / foundation shear strength parameters. A first deterministic approach considers a friction angle of 45° without any cohesion (CFBR 2018, FERC 2018). With these assumptions generally used at design stage, a sliding up to 5 cm is calculated, without any failure mechanism being triggered (Figure 8). Such behaviour is not in line with the current French guidelines, though not specifically edited for newly designed dams. A second calculation considering 600kPa cohesion leads to about 1 cm sliding, at the limit of allowable value as per the current French guidelines. One may envisage that such cohesion can actually be mobilized at the dam / foundation interface through roughness or also deeper in the rock mass if there is not any unique localized crack. Moreover, the keying of the dam in the bedrock is also another reassuring aspect for this case study. But finally, it is also deemed possible that the calculated sliding displacements have gradually developed during several seasonal and drawdown cycles of the dam without jeopardizing its safety (Andrian et al. 2018).

5 CONCLUSIONS

The statistical HST and HSTT models are very often used in French arch dam engineering because they are simple, efficient and robust approaches based on the real behaviour of the dam. They can provide with rational explanation to raw and intricate data. They can be directly handed over to the dam operators in order to perform a regular check on the periodic behaviour of the dam based on the continuously collected data. On the other hand, the accuracy and the ability of the model to learn from the behaviour of the dam and to be able to explain or predict gradually increase with new data. However, based on the authors experience who are currently in charge of the monitoring analysis of more than 30 large dams, statistical approach is seldom used for predictions. Actually, they are not able to extrapolate data when the loadings are out of the range already experienced by the dam and hence unable to assess the safety of the dam in a clearly quantitative way.

On the other hand, numerical modelling is a rather complex tool which cannot be easily handed over to dam operators. In the authors experience, such tool is usually applied in a deterministic way at design stage with regards to the material parameters which are not directly related to safety. At the beginning, the strength parameters can be determined through tests but also by means of empirical approaches. Then the numerical model can be gradually calibrated by means of the regularly collected monitoring data. In the case of numerical models, the more physical phenomena are known and well modelled, the closer is the numerical model behaviour from the real behaviour of the dam. Through years, the gradual adjustments of such numerical model can turn the model into an actual digital twin of the dam which can more and more confidently be used predict the dam behaviour and to assess with a higher accuracy its safety.

The combination of statistical approaches on one hand and the gradually learning numerical model on the other hand is believed to become a higher range monitoring decision-making tool to be used by both the operator and the engineer in a tight collaboration.

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