Data-Driven & Model-Based Structural Behaviour Prediction of a Concrete Arch Dam

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ABSTRACT

This paper focuses on the benchmark problem Theme A ‘‘Behaviour prediction of a concrete arch dam’’ of the 16th International Benchmark Workshop on Numerical Analysis of Dams, Organized by ICOLD Committee on Computational Aspects of Analysis and Design of Dams. The calibration of the statistical regression HST model and the Finite Element model are presented, both capable to predict the behavior of the dam under examination in terms of radial displacements with respect to measurements of both pendulums. A training period of 13 years has been considered for the calibration, whereby temperature and water level data have been used as regressors. Two prediction periods have been considered for the prediction, namely short-term and long-term. On the one hand, a good agreement has been demonstrated between time series of measured and statistically estimated displacements, with very high determination coefficients. In particular, in the long-term period, the statistical model has been capable of estimating displacements which are compatible with the recent scenario of an exceptional drastic decrease of the measured water level. On the other hand, thermo-mechanical analyses have been carried out with FEM, whereby a staggered approach is adopted. In particular, the main steps include transient heat-flow analysis to define the dam-foundation system temperature states, and nonlinear structural analysis to determine displacements, strains, stresses, crack pattern, initiation and propagation. FEM has shown stress distribution and direction and zones subjected to cracks. These zones are mainly concentrated along the foundation of the dam, perpendicular to the rock surface. The observed crack pattern is rather typical and does not compromise the stability of the dam. While the statistical model demonstrates a higher accuracy for the predictions of radial displacements, the FE simulated opening of the joints in the upstream face of the dam potentially provides the reason of the exceptional lowering of the reservoir water level in the last two years of the monitoring period.

1 INTRODUCTION

The current analyses are performed following the requirements and using the data provided within the benchmark problem of Theme A ‘‘*Behaviour prediction of a concrete arch dam*’’ of the 16th International Benchmark Workshop on Numerical Analysis of Dams, Organized by ICOLD Committee on Computational Aspects of Analysis and Design of Dams.

The investigation aims to calibrate and predict the behavior of the dam based on the provided measurements. Namely, the radial displacements measured by dam pendulums are used as the parameter that describes the behavior of the dam and reservoir water level and ambient temperature (daily and seasonal variations) are the parameters governing dam behavior.

In order to achieve the objective, two approaches have been adopted:

- Statistical prediction, later called data-driven prediction;
- Finite element model, later mentioned as model-based prediction.

The 1st approach is a quick strategy to analyze the response of a dam, i.e. the so-called dependent variable that can be of static (displacement, tilting, crack opening/closing, settlement, etc) and dynamic (natural frequencies, mode shapes) nature. Based on the independent variables (or predictors or regressors), such as temperature, reservoir water level, ground water level, etc, a statistical model is calibrated over a sufficient first period of time (training period), to be finally used for predicting further developments of the response of the dam.

Among several predictive statistical models, whose scope is essentially to statistically reconstruct such measured data, the hydrostatic-seasonal-time (HST) model has been implemented in the present case. The HST model is the most used data-driven model for dams [4] and is particularly advantageous because it allows the decomposition of response time series in separate components (irreversible effects, hydrostatic and thermal variations).

The 2nd approach relies on finite element modeling for the prediction, which can be time-consuming and less straightforward method. It involves the assumptions regarding material properties, modeling of the weak zones, etc., that could be crucial in decision making. Moreover, this method, while carefully implemented, provides more details and insights to the behavior of the entire dam and particular elements. This method uses the time history of the measurements to define the current state of the dam and is able to predict further evolution, based on the applied load and material properties.

The obtained results have demonstrated that both models are capable to reproduce the provided measurements in the training period, and to predict in the prediction period. The HST statistical model has reached a smaller deviation from the measurements, while the numerical model requires more sophisticated adjustments in order to reach the same level of accuracy. Nevertheless, the results from the FEM have been exploited to further understand the behavior of the dam and suggest possible reasons for the observed operational sequences.

The paper is organized as follows. Section 2 illustrates the proposed statistical model and its validation. Section 3 presents the model-based approach. Sections 4 and 5 describe the calibration of the FEM model and the first results. Section 6 reports the result prediction from both data-driven and model-based approaches. Finally, Section 7 summarizes the main conclusions of the work.

2 DATA-DRIVEN STATISTICAL PREDICTION OF THE STATIC RESPONSE

2.1 Methodology

The dam response is driven predominantly by hydrostatic load (i.e. water level) and temperature (daily and seasonal variations). Several predictive statistical models (based on the monitoring data measured over a certain sufficiently time span) have been presented in the literature to statistically reconstruct such measured data. Among the relevant and recent ones, the most used data-driven model for dams is the *hydrostatic-seasonal-time* (HST) model. The HST model is particularly useful because it allows the statistical reconstruction/estimation of response time series and their decomposition in separate components, such as irreversible effects $f_1(t)$, hydrostatic $f_2(w)$ and thermal $f_3(s)$ variations. The adopted component's equations can be reported as follows:

$$f_1(t) = a_1 + a_2 \cdot t + a_3 \cdot t^2$$

$$f_2(w) = a_4 \cdot w \; + \; a_5 \cdot (2 \cdot w^2 - 1) \; + \; a_6 \cdot (4 \cdot w^3 - 3 \cdot w) \; + \; a_7 \cdot (8 \cdot w^4 - 8 \cdot w^2 + 1)$$

$$f_3(s) = a_8 \cdot \sin(s) \; + \; a_9 \cdot cos(s) \; + \; a_{10} \cdot sin(2s) \; + \; a_{11} \cdot cos(2s)$$

Where *t*, *w* and *s* represent the normalized variables, computed as follows:

$$w = \frac{2 \cdot WL - NWL - MWL}{NWL - MWL} \qquad -1 \leq w \leq 1$$

$$s = day\ of\ year \cdot \frac{2\pi}{365.25} \qquad 0 \leq s \leq 2\pi$$

$$t = \frac{(actual\ date - first\ date)}{365.25} \quad 0 \leq t \leq total\ numer\ of\ years\ since\ 1st\ measure$$

WL refers to actual water level, NWL refers to normal water level and MWL refers to minimum water level. In the present case: NWL=237 m. and MWL=174 m.

2.2 Validation of the statistical model

The statistical regression analysis has been carried out by the *DamReg* software [4]. A typical representation of the results is shown in Figure 2-1.

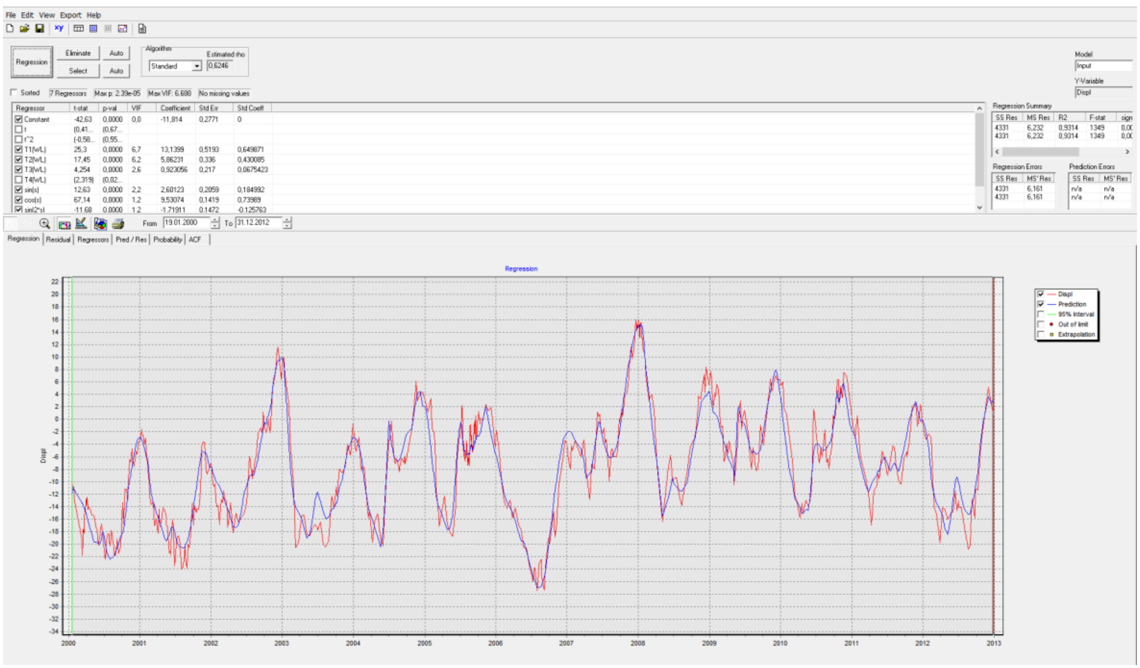


Figure 2-1. View of results from the DamReg software: time series of measured and statistically estimated displacements (CB2_236_196) in 13 years time window (10 regressors).

On the one hand, thirteen (13) years of water level and temperature time series have been exploited as input to the HST model defined within the software. On the other hand, data measured from both pendulums, CB2_236_196 and CB3_195_161, have been considered as the output variable. Ten (10) regressors have been defined according to the above equations (linear as well as polynomial powers, and sinusoidal/cosinusoidal). In particular, the 4th power of WL has been omitted because the regression coefficient is not significantly different from zero. Overall, the coefficient of determination resulted R^2=0.93. Figure 2-2 illustrates the time series of measured and statistically estimated displacements (CB2_236_196 pendulum) from January 1st 2000 to December 31st 2012.

Noteworthy to say, Figure 2-2 depicts an abnormal irreversible component (of the estimated displacements) both in trend and amplitude. In particular, it begins from zero, increases up to less than 2 mm, and returns to zero at the end of the period. On the basis of this consideration, the Authors conclude that introducing this component to the statistical model is irrelevant and not beneficial. Hence, for a more accurate prediction, it is omitted for the following validation.

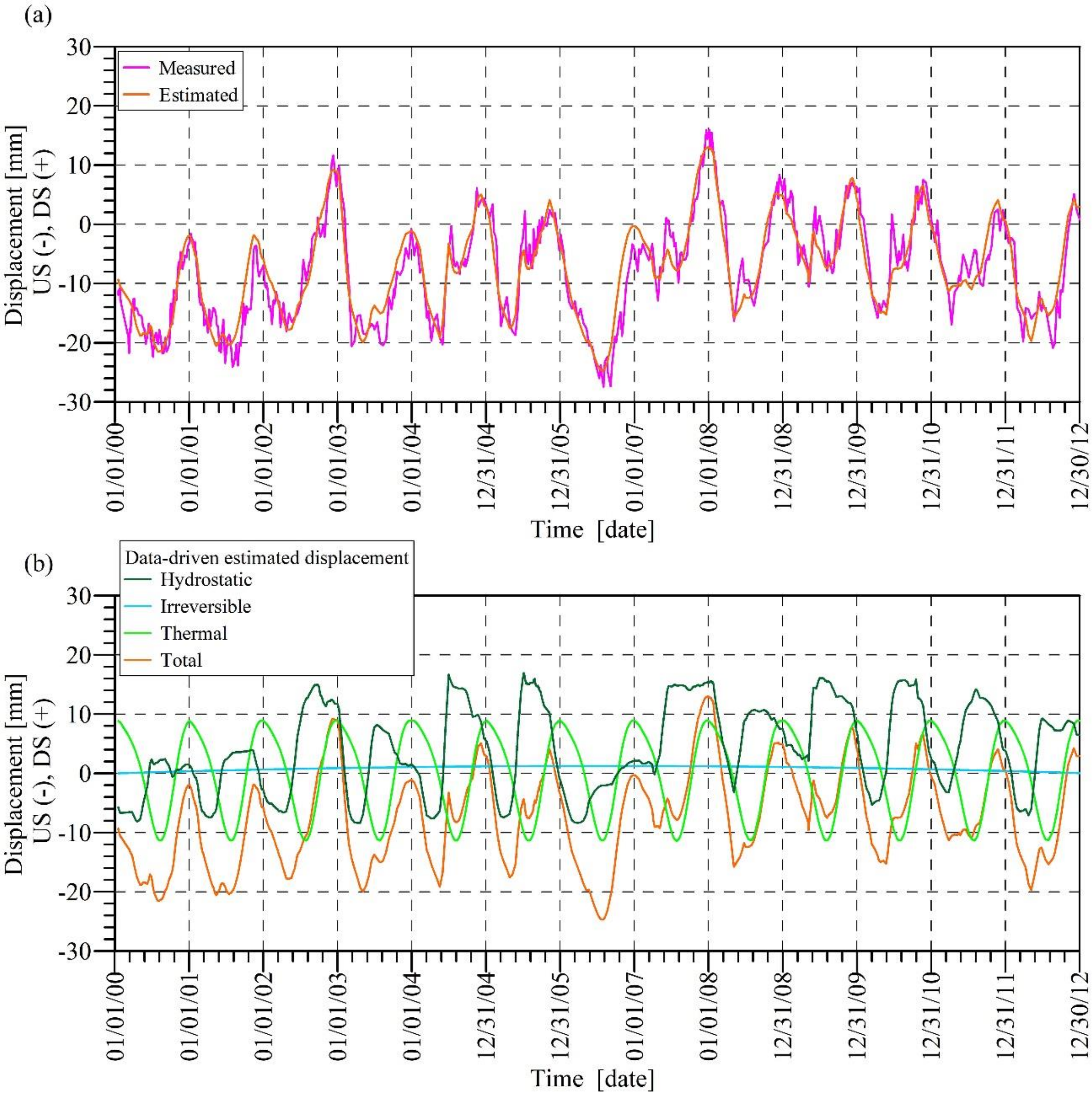


Figure 2-2. Time series of measured and statistically estimated displacements (CB2_236_196) in 13 years time window (10 regressors).

The statistical regression analysis has been carried out again by the software, this time by exploiting water level and temperature data only, for the same 13-year period. In this way, eight (8) regressors have been used ($a_2 \cdot t + a_3 \cdot t^2$ terms are not considered). In analogy to Figure 2-2, the time series of measured and statistically estimated displacements have been illustrated in Figure 2-3. The range spans from -30 mm to about 15 mm. Total values are presented in Figure 2-3, while time histories of each separate component (see HST model) of estimated displacements are presented in Figure 2-3b. From a visual investigation of the graph, it can be observed that the two separate components are out of phase between them, e.g. during summer the hydrostatic component has the most downstream displacements (15-20 mm), while the thermal component presents the less downstream displacements (highest values towards upstream, equal to -10 mm).

Overall, a good prediction can be visually observed in the case of the high pendulum CB2_236_196, whereas the coefficient of determination resulted R^2=0.932.

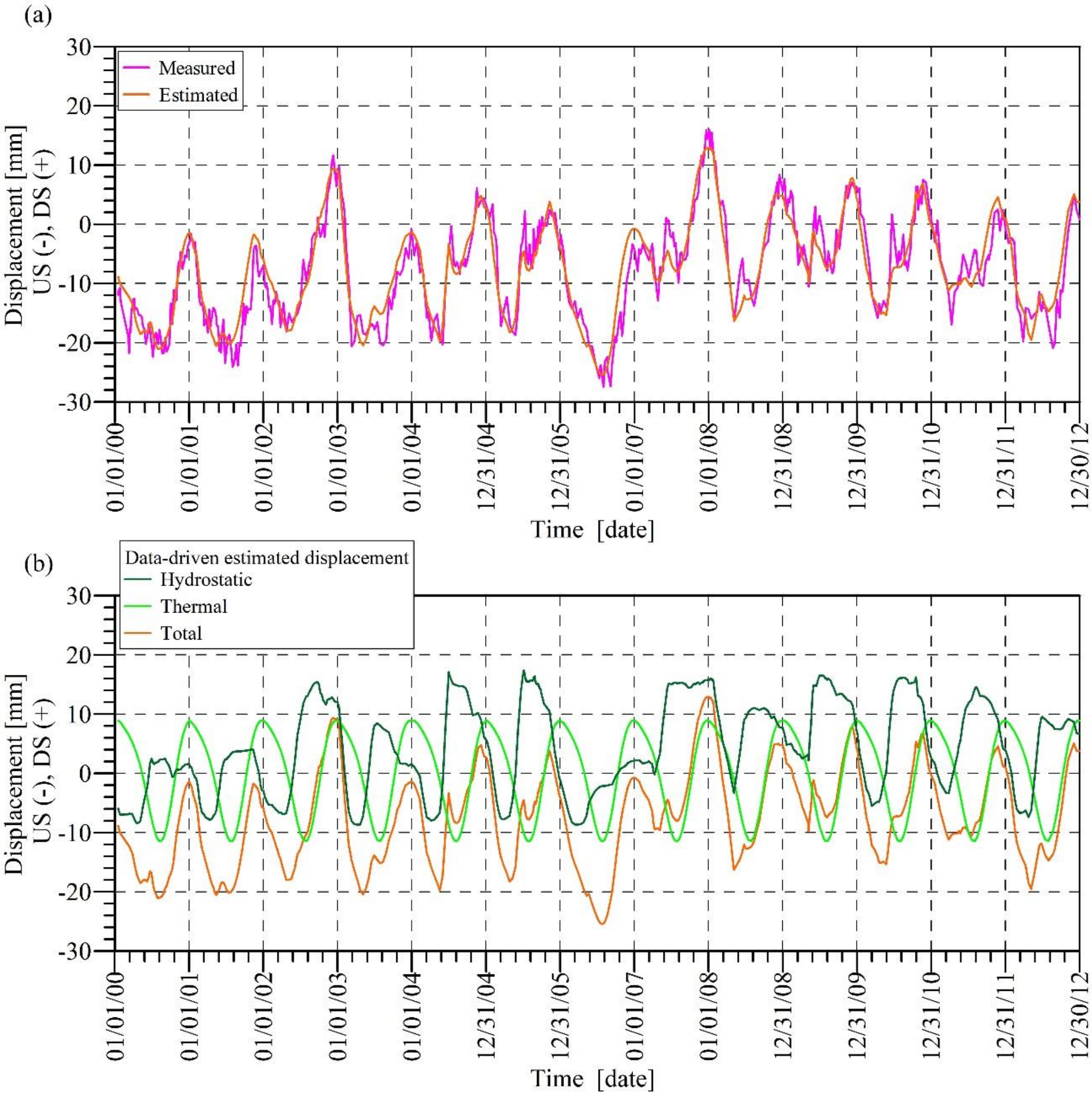


Figure 2-3. Time series of measured and statistically estimated displacements (CB2_236_196) in 13-years time window (8 regressors).

In analogy to the CB2_236_196, the statistical regression prediction has been carried out also in the case of the CB3_195_161 pendulum.

The same 13-year time series of measured water level and temperature data have been used as regressors (8) within the HST statistical model. Time series of measured and statistically estimated displacements have been comparatively illustrated in Figure 2-4 (January 1st 2000 to December 31st 2012). The range spans approximately from -6 mm to about 6 mm. The separate components (thermal and hydrostatic) of estimated displacements are presented in Figure 2-4 b. On the one hand, a limited thermal component is observed (between – 2 and +2 mm). On the other hand, the higher amplitudes of the hydrostatic component with respect to the thermal one can be directly observed, demonstrating its predominant role for the low pendulum. This is because the top head of the low pendulum is located at the base of the dam, thus considering a much higher water head, and a region less subjected to high temperature variations.

The out of phase nature of the two separate components is confirmed also for the low pendulum CB3_195_161: during summer maximum values of the hydrostatic component (5 mm) and minimum values of the thermal component (-2 mm)

Overall, a good prediction can be visually observed in the case of the low pendulum CB3_195_161, whereas the coefficient of determination resulted R^2=0.964.

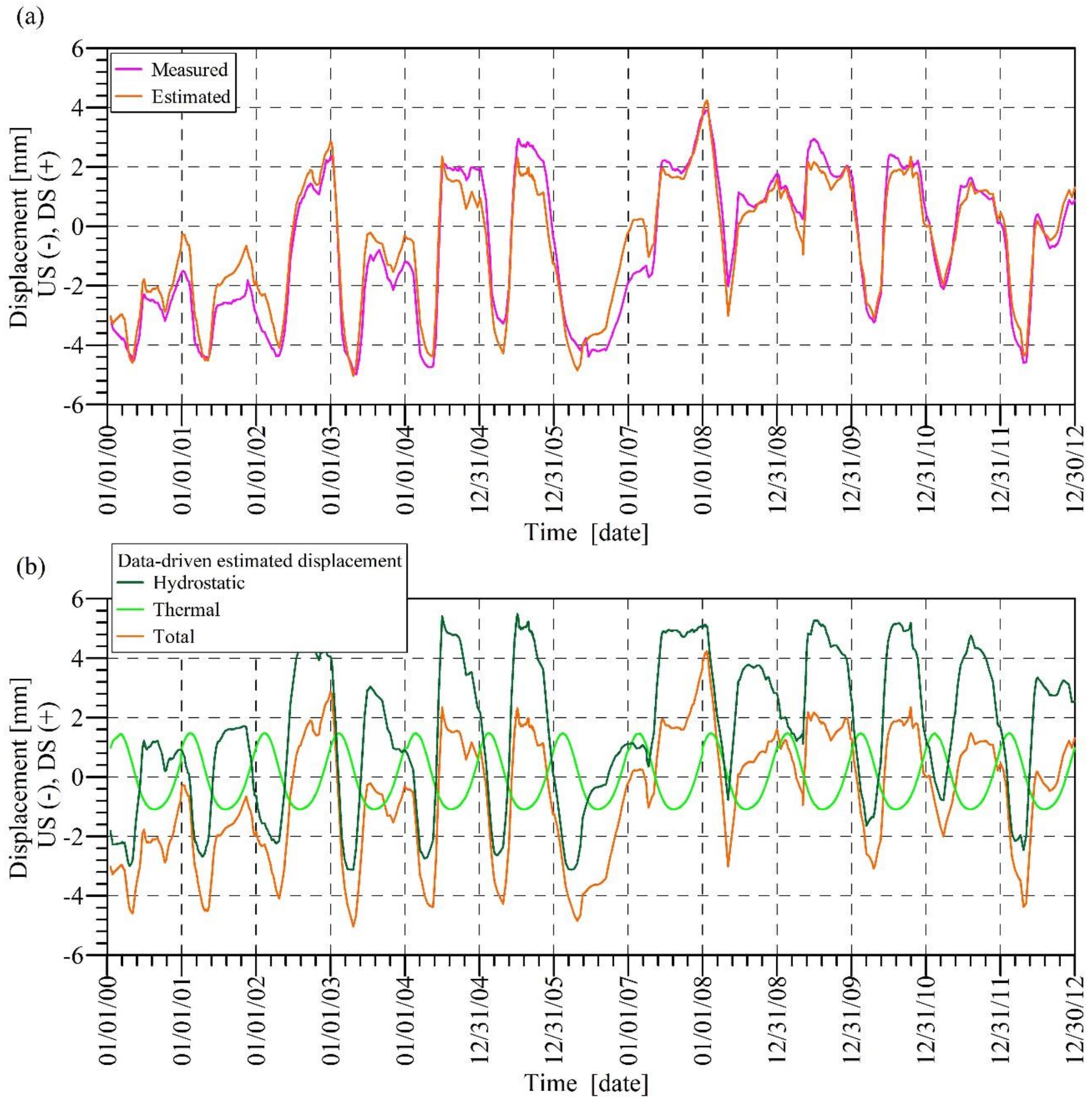


Figure 2-4. Time series of measured and statistically estimated displacements (CB3_195_161) in 13-years time window (8 regressors).

To better emphasize the accuracy of predictions for both pendulums, measured and statistically estimated displacements are plotted against each other as depicted in Figure 2-5, where the positioning along/around the diagonal is clearly visible.

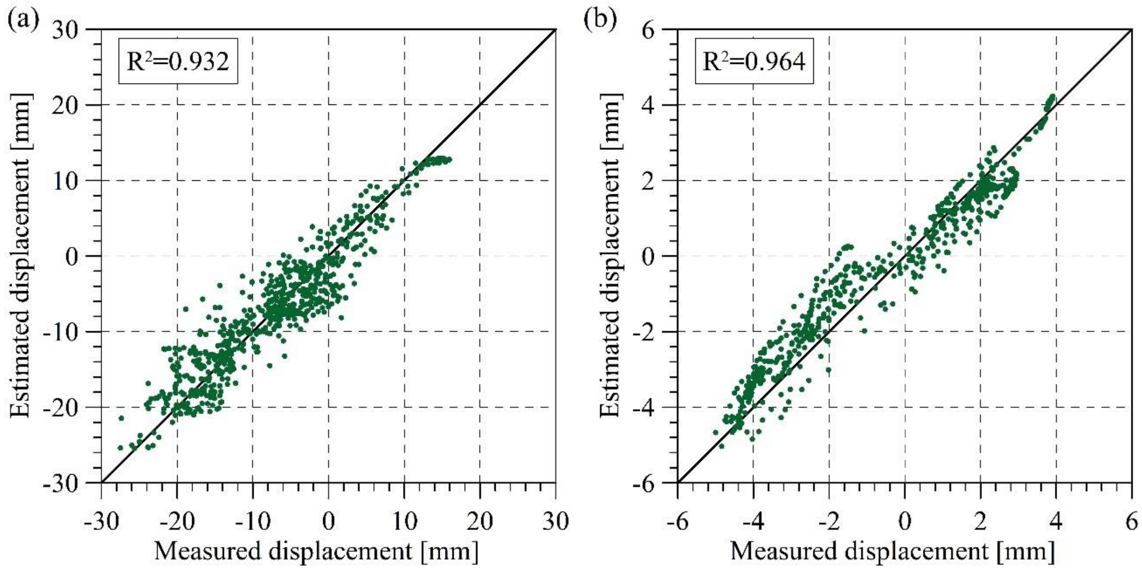


Figure 2-5. Measured versus statistically estimated displacements: (a) CB2_236_196, (b) CB3_195_161.

3 MODEL-BASED APPROACH

3.1 Methodology

In order to assess the current state of the dam and predict its further behavior thermo-mechanical analysis is adopted and includes self-weight, hydrostatic load due to reservoir water level and thermal load. The last two loads are time-dependent and based on the provided measurements.

For the thermo-mechanical analysis, a staggered approach is adopted. First, temperature distribution, based on the applied boundary conditions is calculated. Second, these temperature fields are applied as an external loading in the following structural analysis.

In particular, the staggered thermal-mechanical analysis performed consists of the following main steps:

1. Transient heat-flow analysis to define the dam-foundation system temperature states;
2. Nonlinear structural analysis to define the displacements, strains, stresses, crack initiation and propagation, crack pattern and crack width for a load combination involving the basic load cases (self-weight and hydrostatic pressure) and the temperature variations as defined in the previous analysis step.

3.2 Transient heat-flow analysis

The transient heat-flow analysis is performed by applying the entire sequence of the available temperature measurements starting from 1995. An initial condition of a uniform temperature distribution of 3°C is assumed for the dam-foundation system. However, considering that the period of interest starts 5 years later in 2000, the initial temperature assumption does not play a significant role.

Two analyses are performed with time-step equal to 2 days. Larger time step gives fair results for the temperature distribution, however, in order to improve the precision of the nonlinear structural analysis smaller time step is considered.

3.3 Nonlinear structural analysis

The main source of the nonlinearity is the nonlinear constitutive model associated with the concrete material.

The loading sequence on the dam-foundation system is numerically simulated in two main phases: self-weight; hydrostatic pressure; and temperature variations in time.

Self-weight of the dam is obtained by the staged construction. Afterwards, the time dependent load that includes the hydrostatic load and the thermal load defined by means of the transient heat-flow analysis are applied in time-steps of 2 days.

3.4 Material parameters

The following material parameters supplied by the formulators of Theme A are used:

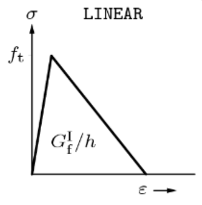
Table 1: Material parameters

Material parameters	Units	Concrete
Modulus of elasticity	GPa	15.4
Poisson’s ratio	-	0.2
Density	kg/m^3	2400
Thermal expansion	K^{-1}	10^{-5}
Thermal conductivity	W/(m*K)	2
Specific heat capacity	J/(kg*K)	900
Compressive strength	MPa	34
Tensile strength	MPa	2.0

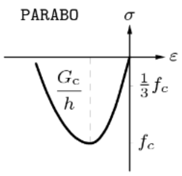
The additional material parameters that are adopted to describe the nonlinear behavior of the concrete and the arch dam–rock foundation interface are given in the following.

3.5 Concrete

The total strain rotating crack model with linear tension softening curve defined in DIANA [2] is used to investigate the nonlinear effects in concrete. This material model requires input for Mode I fracture energy G_f^I. It is emphasised that the value of fracture energy of mass concrete used in dams is significantly higher than that of structural concrete, since in the former the fracture takes place mostly due to failure of the aggregates [1]. In the same study, it is mentioned that the value of fracture energy is assumed equal to 280 N/m is considered reasonable. The compressive fracture energy is taken $G_c = 50\ 000$ N/m.



Linear tension softening, fracture energy based



Parabolic compressive behavior

Figure 3-1. Total stain crack model

As far as the stiffness of the concrete is concerned the "sustained" modulus approach is introduced [3]. It allows taking into account long-term behavior of the concrete such as creep, and slow thermal load application. Under these conditions, the reduction of the Young Modulus could reach 50%. In the current analysis, the reduction of 30% is implemented.

3.6 Dam – rock foundation and joints interfaces

A linear elastic interface is adopted in the dam-rock foundation connection. Based on the concrete and mass rock moduli of elasticity, interface linear stiffness moduli of $1.5E + 12$ N/m³ and $1.5E + 9$ N/m³ are specified for the normal and the tangential stiffness, respectively.
The joints between blocks are modeled by means of the linear elastic interfaces with the reduced stiffness in normal direction that equals to $1.35E + 9$ N/m³ and tangential stiffness remained equal to the stiffness of the concrete $1.54E + 9$ N/m³.

4 FEM MODEL AND BOUNDARY CONDITIONS

4.1 3D FEM model

The layout of the concrete arch dam and its abutments and foundation is shown in Figure 4-1.

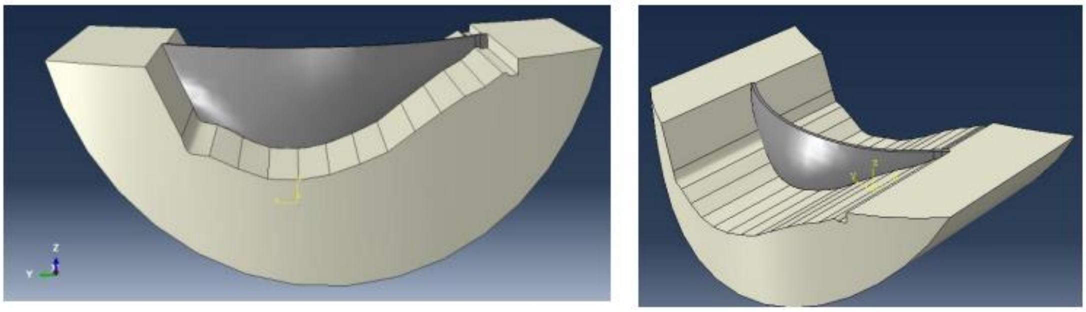


Figure 4-1: Illustration of the layout of the concrete arch dam and its abutments and foundation

Based on the provided geometry a FEM model of the dam-foundation system is constructed in DIANA FEA[2]. Solid element types with linear interpolation are used for mesh discretization. 2D boundary elements are used to apply heat flow boundary conditions with the external temperature.

The average element sizes of the dam and foundation are 3m and 40 m, respectively. The obtained model is presented in Figure 4-2.

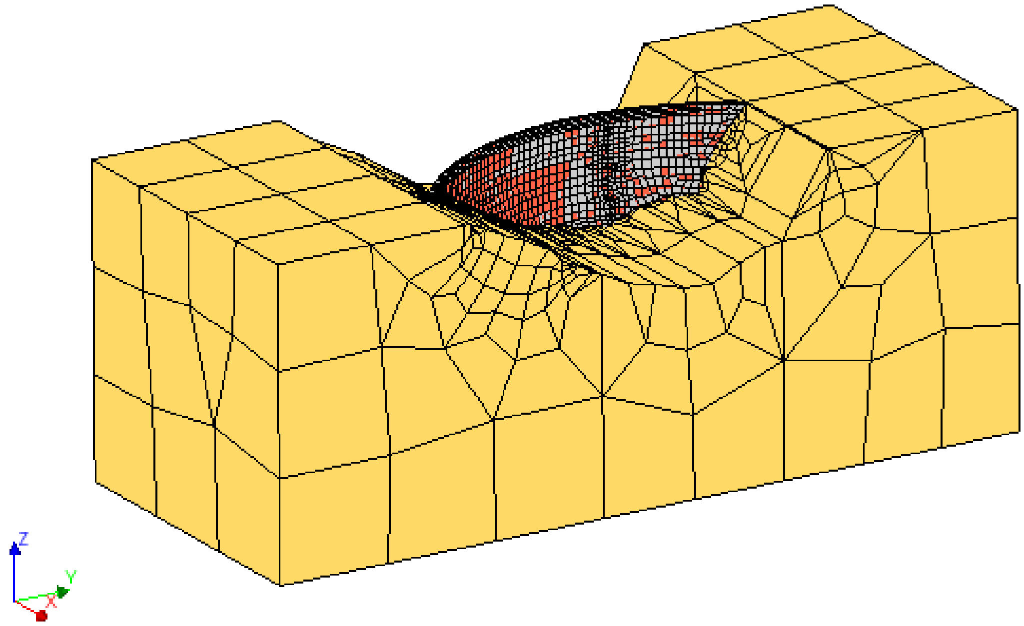


Figure 4-2 Finite element mesh of the dam with foundation

4.2 Transient heat transfer analysis

Time variable air temperature is applied as a boundary condition on the surface of the dam. It was considered that the time series Tb better approximates the ambient conditions.

The operational conditions do not allow to distinguish typical temperature zones of the US face: permanently underwater, transition (variable water level) and air temperature. Instead, the reservoir water level varies such that the entire height of the dam is exposed to the air temperature. Therefore, the following approach is adopted for better temperature approximation:

For the DS face, the air temperature is prescribed.

US face is divided by 2m height intervals. For each interval, the corresponding temperature is assigned depending on the reservoir water level varying in time. Namely, if the water level for a certain time is above the elevation of the interval, water temperature is assigned, otherwise, air temperature is prescribed. The proposed formulation of water temperature approximation is adopted in the analysis:

$$T_{water} = \begin{cases} 0.7T_{air} & if\ T_{air} > 0\ C \\ 0 & otherwise \end{cases}$$

Zero flow condition is assumed for foundation surfaces.

4.3 Nonlinear structural analysis

Translational supports in the respective normal direction are specified as structural boundary conditions on the bottom and on the side surfaces of the foundation model.

Variational Water level load is considered on the US face of the dam and part of the foundation subjected to the hydrostatic load. The provided time series is employed in the analysis.

5 CALIBRATION OF FEM AND RESULTS

The results of the calibration are given for August 2006 and January 2008 as it is demonstrated in Figure 5-1. The reason behind this choice is that according to the provided measurements at these periods peak displacements in US and DS directions were observed.

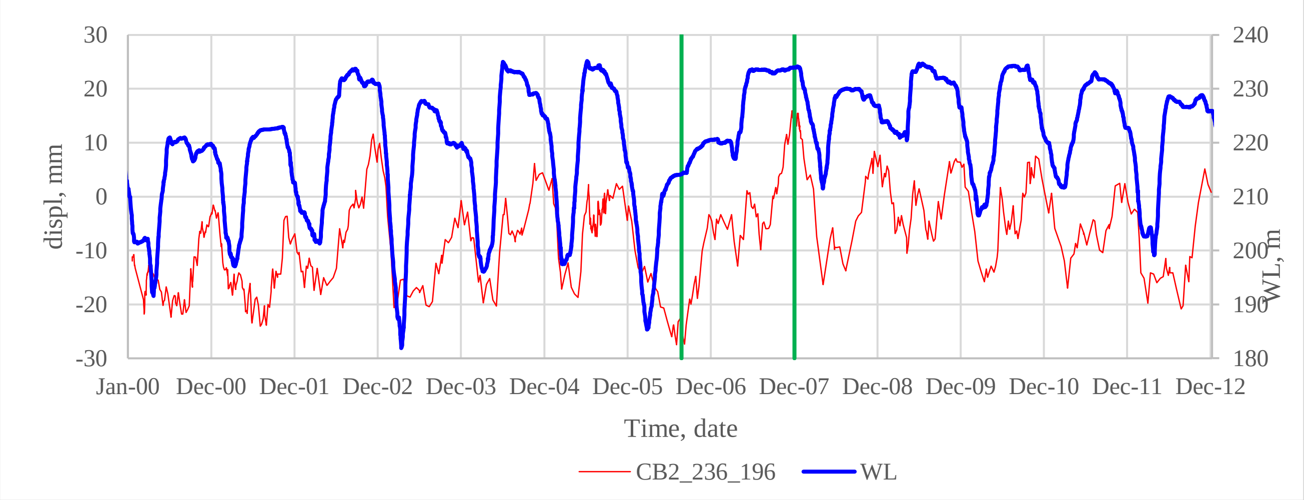


Figure 5-1 Radial displacements and reservoir Water Level measurements, the green line indicates time periods for data presentation

As far as the cross-section distributions are concerned it is given along the surface that corresponds to the position of the pendulums CB2, CB3.

The stress sign convention is such that a negative value means compression and positive one tension. For the displacements positive means movement in the downstream direction, negative towards upstream.

5.1 Transient heat transfer analysis

The calculated temperature distributions for the selected cross-section and time periods are shown inFigure 5-2. Additionally, temperature variation plot at the selected points of the dam body is given in Figure 5-3. These points are selected in the middle of the dam at different elevations, mainly to represent top, middle and bottom parts of the dam.

The plot shows that the biggest temperature amplitude is found in the top part of the dam and the lowest in the bottom, that corresponds to the expected behavior. Due to the fact, that the water in the reservoir isolates the dam from air temperature variations, in opposite, the top of the dam is not covered with the water and quickly reacts to the ambient changes. The average temperature amplitude inside the dam is found around 12 deg.

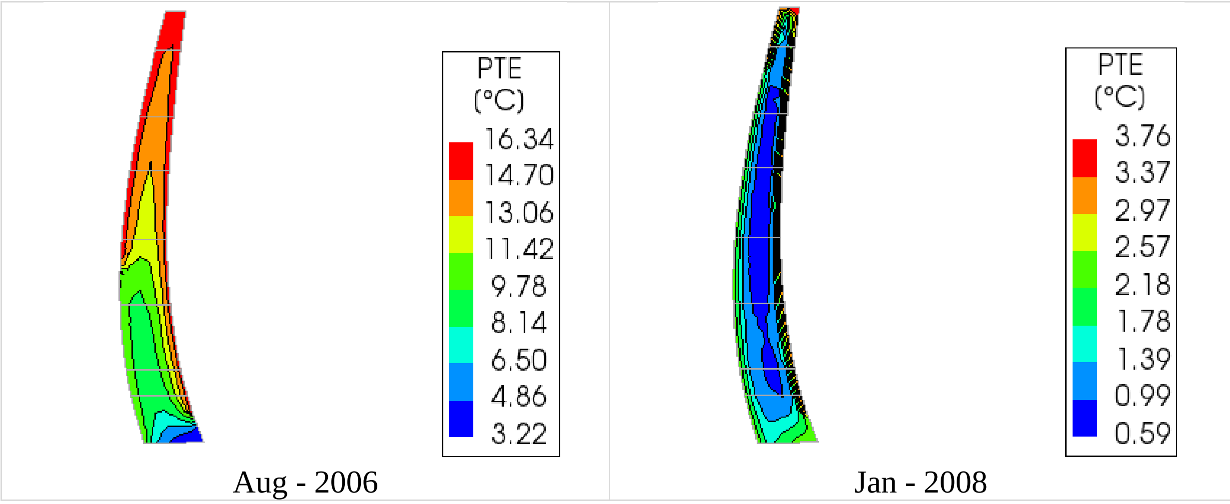


Figure 5-2 Temperature distributions for the considered periods of time

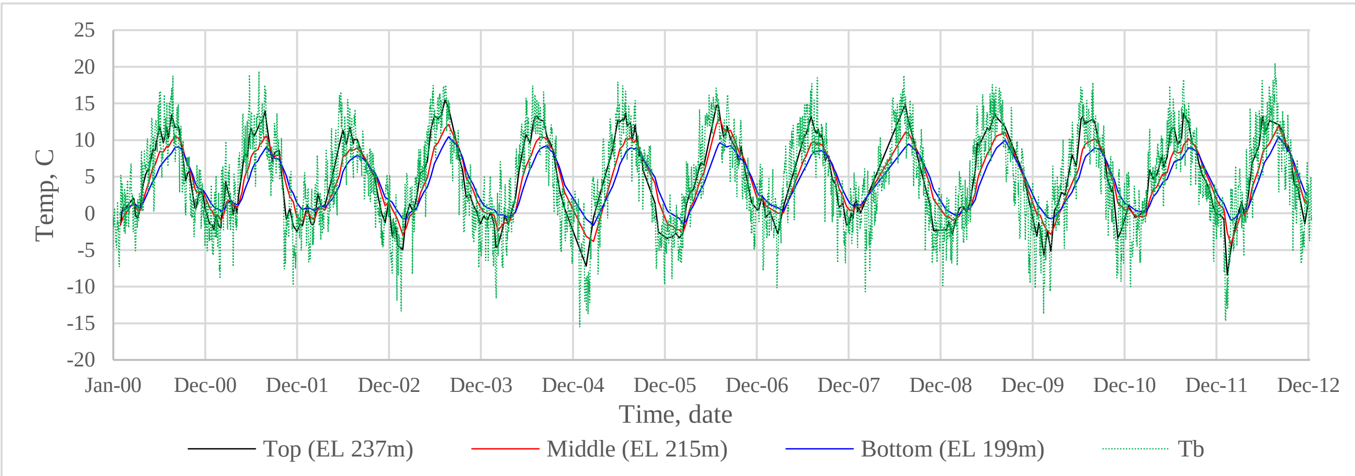


Figure 5-3 Temperature variation in the dam body at different elevations

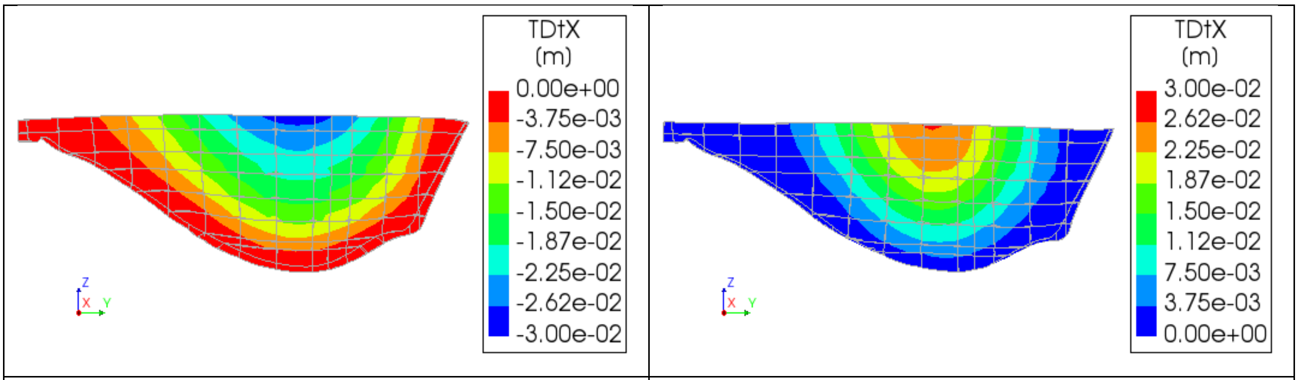
5.2 Nonlinear structural analysis

In this section, the results obtained from a non-linear structural analysis with non-linear material properties of concrete are presented. It should be noted that the foundation remains elastic.

Radial displacements distribution is given in Figure 5-4 showing:

- expansion during warm period, that causes the movement in the upstream direction;
- shrinkage during cold period, creating deformation in the downstream direction.

It is noted that the overall seasonal amplitude is higher in the upstream direction than in downstream direction. Insight of the radial displacements of the dam along the height is given in Figure 5-5, where initial case includes self-weight of the dam and seasonal variations consists of a temperature and hydrostatic loads of the dam. Water load was not included in the initial conditions since it is not permanent through the year and almost empty during cold season.



Aug - 2006	Jan - 2008

Figure 5-4 Radial displacements distribution during warm and cold periods

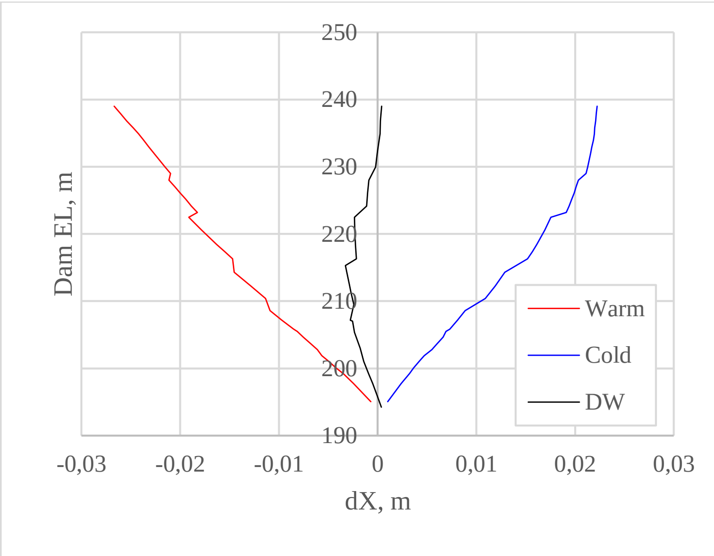
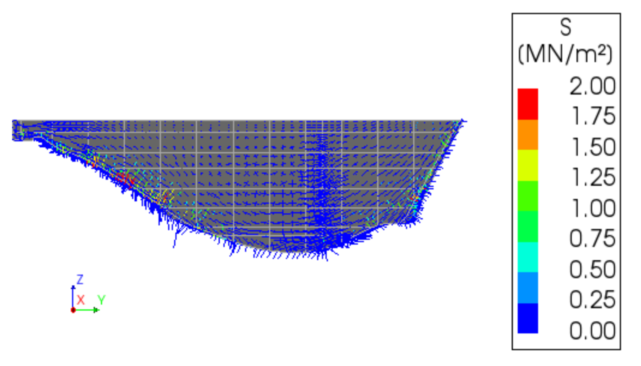


Figure 5-5 Radial displacements along the selected cross section

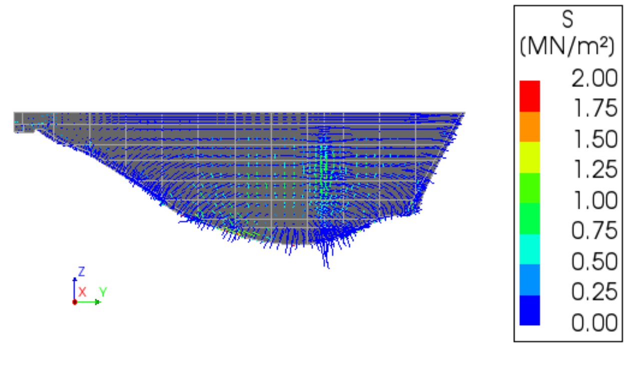
The obtained deformation pattern provokes certain stress distribution in the dam. Due to the low resistance to tension, the direction and intensity of maximum principal stress distribution is of interest while analyzing potential damages. Therefore, the stress distributions are given in Figure 5-6,Figure 5-7 followed by the observations:

- The tension zone in the foundation of the dam on the right bank is presented permanently. This artefact is explained by significant stiffness difference for the rock in the valley and right bank, that prevents continuous dam deformations.
- During warm period the tension zone is mainly concentrated in the dam foundation area due to the “pulling” effect of the expansion, eventually initiating the cracks perpendicular to foundation.
- Cold period produces tensile stress in vertical direction in the middle of the dam due to the bending in the downstream direction. Depending on the tensile strength of the concrete that is a potential zone of the horizontal cracks development. In the current analysis tensile stress equal to 2MPa is adopted and did not produce cracks in the downstream face.
- Cross section distributions show that the tensile stress remains rather superficial (around 0.5m) in downstream face of the dam.
- Upstream face of the dam remains under compression in vertical direction during

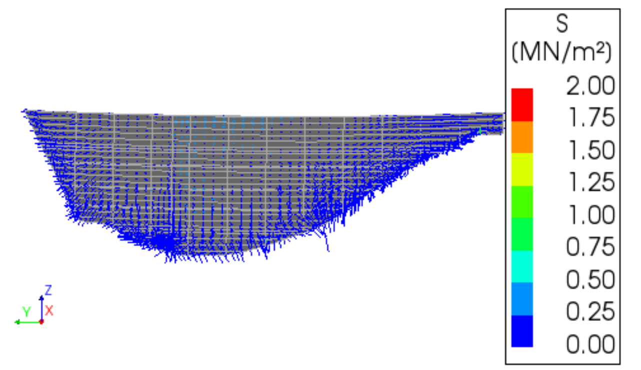
the provided time.



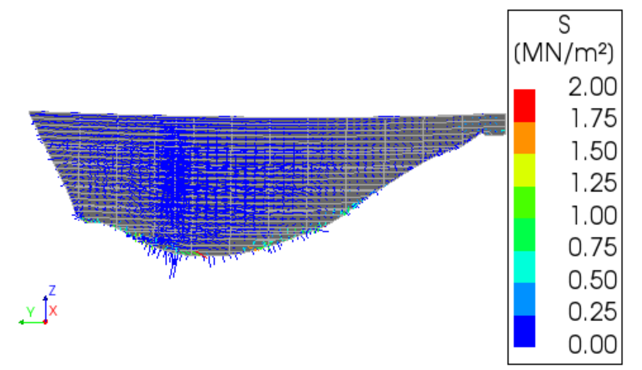
DS face Aug - 2006



DS face Jan - 2008

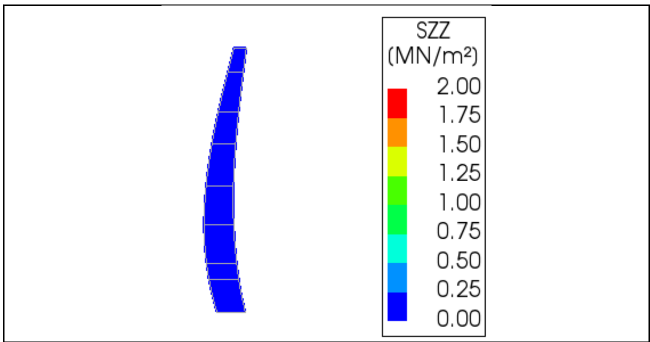


US face Aug - 2006

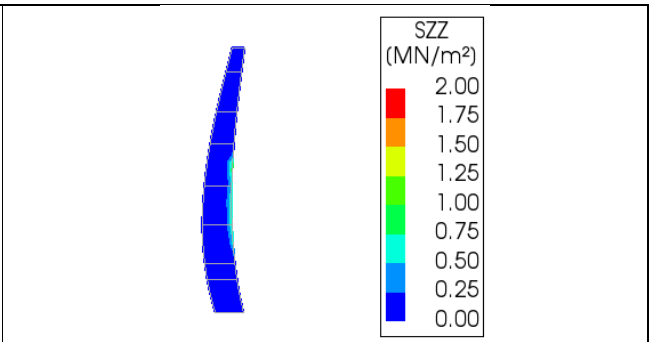


US face Jan - 2008

Figure 5-6 Stress directions during warm and cold periods



Vertical stress, Aug-2006

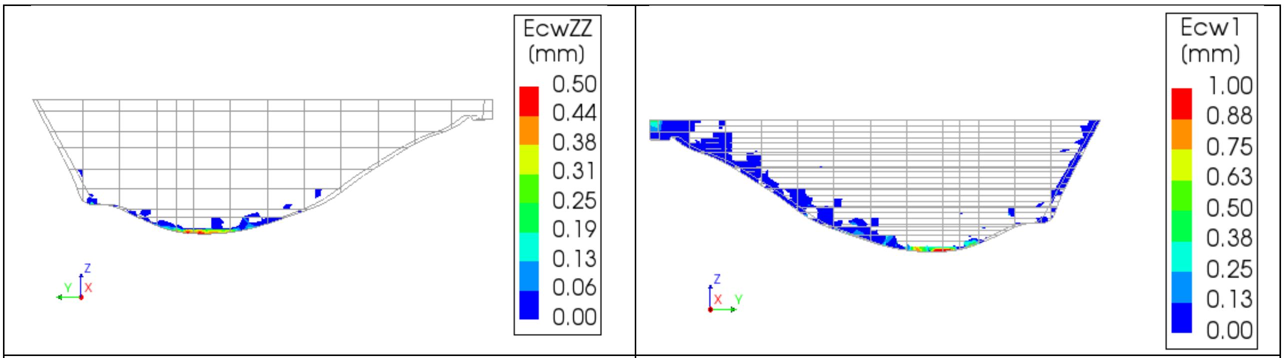


Vertical stress, Jan-2008

Figure 5-7 Vertical stress distributions for the warm and cold periods

Eventually, the cracks distribution is analyzed and given in Figure **5-8**. The initial localization of the cracks applying self-weight and hydrostatic water pressure corresponding to WL 237 m is found in the connection of the dam with foundation.

Crack distributions at the end of the calibration period (end of 2012) shows the development of the damage in the dam blocks next to the right abutment and along the dam foundation is observed with time. First one is explained by the shape of the dam, these blocks have thinner height, therefore behave in a more rigid way, that eventually, could cause damages. The second one is a rather typical observation in the dam behaviour which is a result of the hydrostatic and temperature loads.



Initial state	End of 2012

Figure 5-8 Cracks distribution

5.3 Calibration from FEM

FEM model results have been used to compare with the provided displacement measurements from two pendulums: bam body (CB_236_196) and dam foundation (CB_195_161) pendulums. The results for FEM are provided in Figure 5-9 and Figure 5-10 for the period of 13 years from 2000 to 2013.

FEM model is able to reproduce the displacement variations following the temperature and water level fluctuations. Similar to the provided measurements the dam tends to move in the upstream direction during warm season due to an expansion process. On the other side, the peak displacements towards downstream occur before the cold season when the reservoir water level reaches its maximum.

As far as the crest radial displacements are concerned fair correspondence between the measurements and calculated data is found. On the other hand, the model underestimates the displacement of the dam foundation in upstream direction. Furthermore, the crack opening measurements (C4_C5) brings the evidence for the movement of the dam. Therefore, it is suggested that the tensile stresses obtained in dam foundation is in reality partially compensated by the opening of the crack.

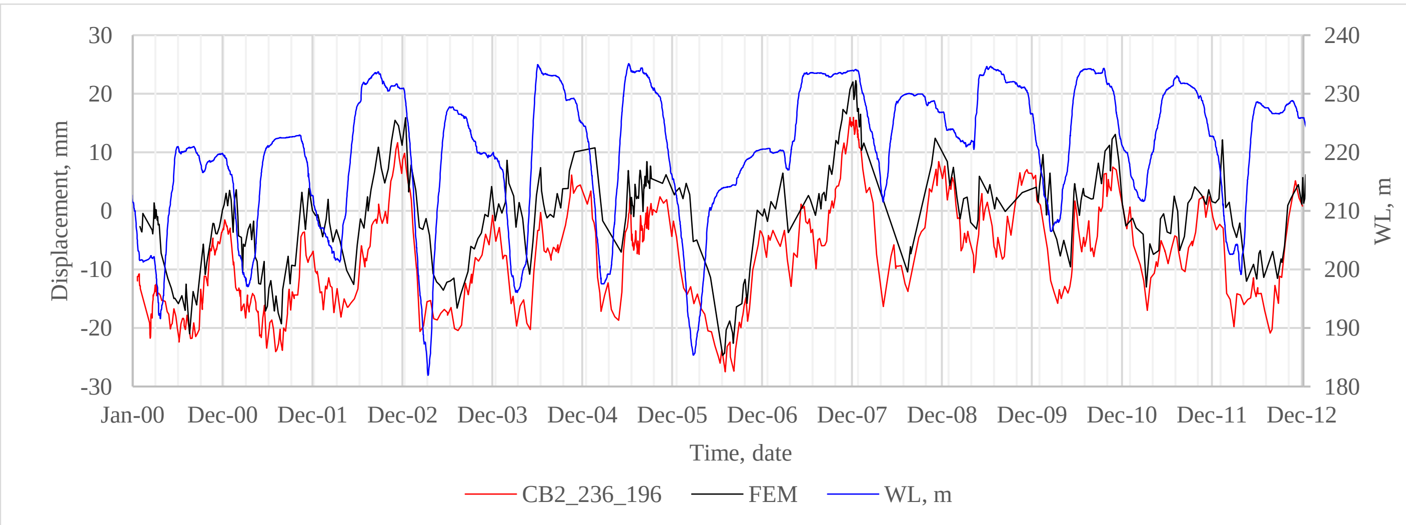


Figure 5-9 Calibration of the dam body pendulum CB_236_196

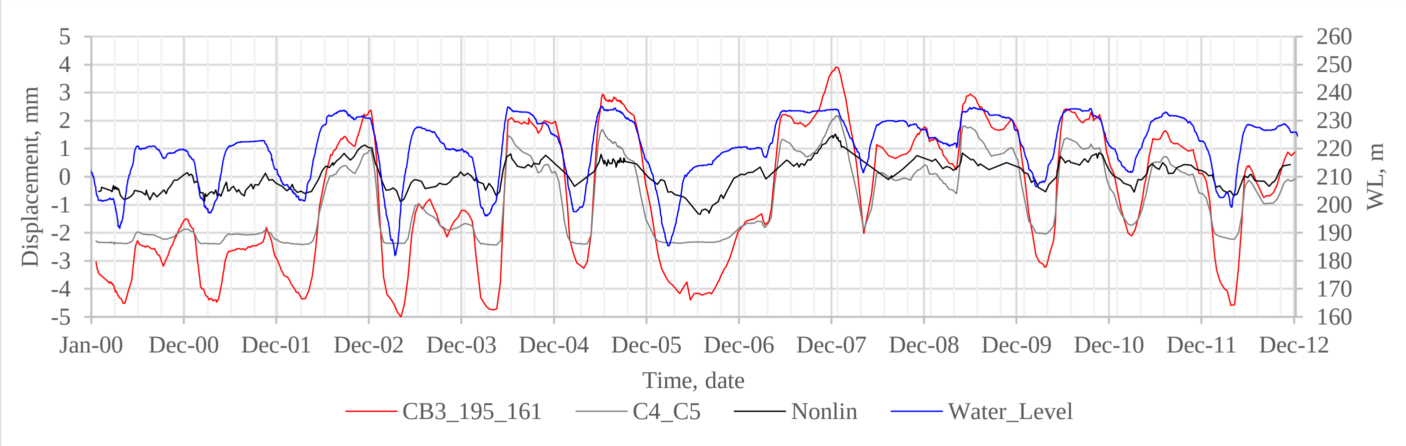


Figure 5-10 Calibration of the low pendulum CB_195_161

6 PREDICTION FROM DATA-DRIVEN AND MODEL-BASED APPROACHES

6.1 Data-driven prediction

The 13-year time window has been used as a validation period of the statistical models, as described in the previous Section. In other words, it refers as *training period*, e.g. a sufficiently long period to model the variations of response displacements as driven from predictors or regressors (water level and temperature, in the present case). Therefore, these data have been used as regressors in the prediction period (from January 1st 2013 onwards) to statistically reconstruct displacements.

By a deep visual investigation of Figure 6-1 (CB2_236_196), observations can be derived about the two components of estimated displacements (due to water level and driven by temperature) during the training period (01/01/2000-31/12/2012) and the prediction period (01/01/2013-31/12/2017). Constant reference is dedicated to the measured water level.

During the training period:

- The temperature component of estimated displacements presents a regular trend, with oscillation in the range of approximately [-10, 10] mm. It decreases from winter towards summer, meaning that movements of the dam towards upstream are induced. Indeed, upstream displacements are maximum in summer due to material expansion (during spring a major sun exposure also), resulting in a closure of cracks in concrete and an overall increase of the stiffness.
- The water level component of estimated displacements has less regular trend if compared to the thermal one. The highest downstream displacements are observed in summer. Indeed, an increase of the water level (typically observed from spring to summer) produces movements of the dam towards downstream. In particular, during winter, a low water level (e.g. 31/12/2005) induces less downstream displacements (- 4 mm); a high water level (e.g. 31/12/2007) induces higher downstream displacements (13 mm).

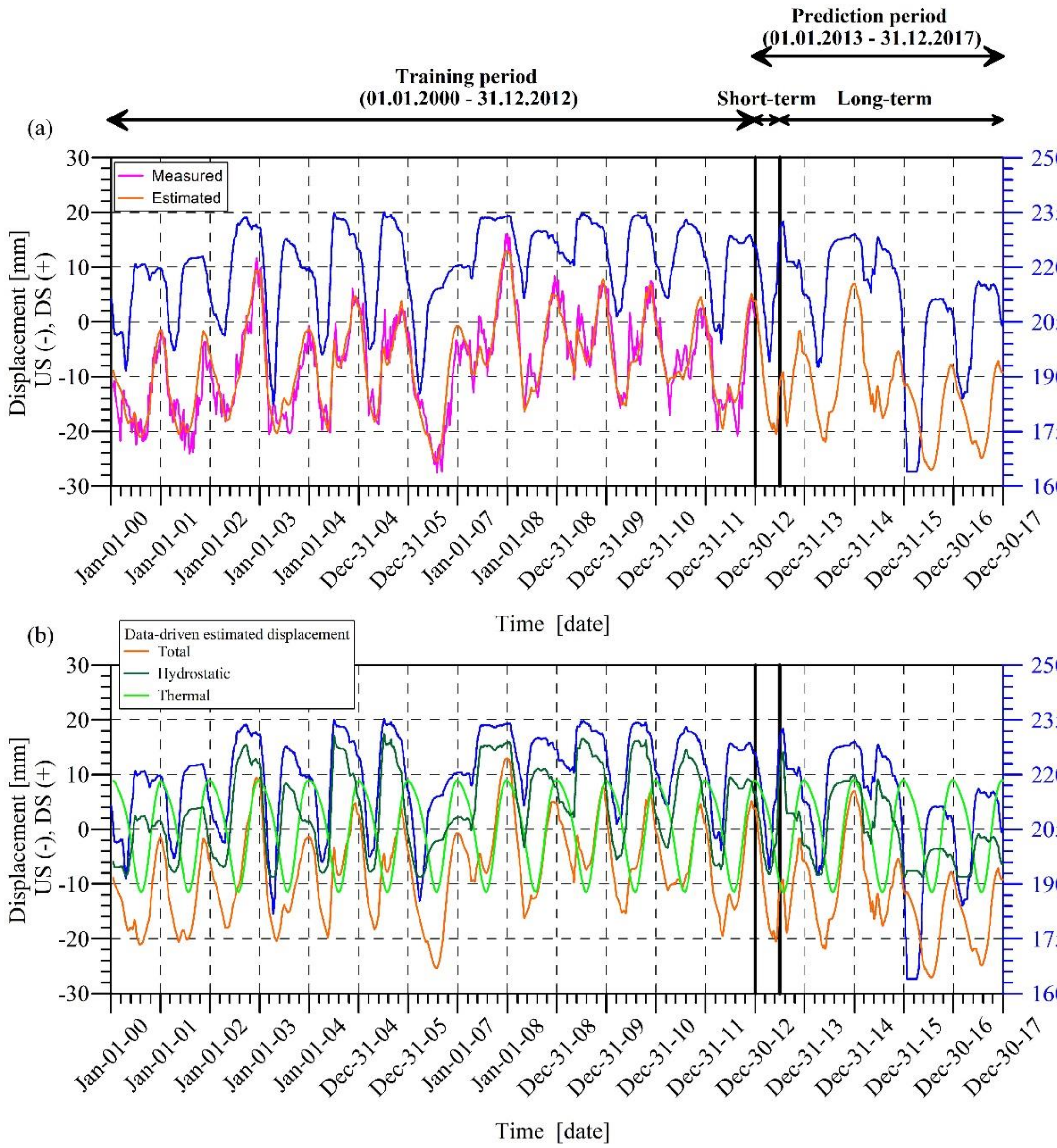


Figure 6-1. Statistical prediction of displacements (CB2_236_196) in the prediction period.

During the short-term prediction period (01/01/2013-30/06/2013):

- The same trend in terms of displacements during the training period can be essentially observed in the short-term prediction period. It has been noticed that measured maximum water level during summer in 2012 was lower (227 m) than during previous years (235 m), producing smaller amount of displacements towards downstream. Therefore, further reduction of the reservoir water level and changing to the warm season of 2013 mainly produce upstream movement and reaches its peak (-20mm) for the end of the short-term prediction period.

During the long-term prediction period (01/07/2013-31/12/2017):

- The regular trend of the temperature component is continuously confirmed.
- The minimum water level measured in spring-summer transition of 2015 is equal

to 213.11 m (02/05/2015), lower with respect to previous similar periods.

- Following, an exceptional drastic decrease of the measured minimum water level is observed from autumn 2015 until 26/01/2016, reaching value of 164 m, which is lower than the minimum operating level (174 m). This abnormal decrease can be directly observed through the statistically estimated displacements due to water level that are very low. The estimated total values of upstream displacements are the lowest values of all estimations, reaching approximately -27 mm and -25 mm (summers 2016 and 2017, respectively).
- On the other hand, after the drastic decrease abovementioned, the measured maximum water levels never went back to typical values about 230-235 m. Indeed, a decrease is observed in the summers of 2016 and 2017 (less than 215 m, if compared with typical levels of the training period, about 235), leading to less downstream estimated total displacements.
- It can be stated that the temperature-driven component of estimated displacements is predominant with respect to the water level component.
- Overall, in the long-term period, the statistical model has been capable to estimate displacements which are compatible with the abovementioned scenario, reaching very low values of -27 and – 25 mm, much smaller if compared to previous statistically estimated displacements.

For the sake of accuracy, the following Table summarizes three examples of measured as well as estimated displacements in correspondence to instants with similar water levels (during the long-term prediction period with reference to the training period).

Table 2: Comparatively investigation of measured and estimated displacements (CB2_236_196).

Water level	Measured	Estimated	Estimated
	Training period		Long-term prediction period
212.5 m	-6.9 mm (02/01/02)	-5.9 mm (02/01/02)	-6.0 mm (05/01/14)
197.4 m	-17.25 mm (17/04/03)	-17.97 mm (17/04/03)	-18.52 mm (20/04/13)
185.5 m	-15.84 mm (28/03/06)	-16.51 mm (28/03/06)	-16.05 mm (21/03/17)

Statistically estimated displacements (total and separate components) during the training and prediction periods have been illustrated in Figure 6-2 for the low pendulum (CB3_195_161). Based in these results, similar observations can be stated for predictions of displacements.

During the training period:

- The temperature component of estimated displacements presents a regular trend, with oscillation in the range of approximately [-2, +2] mm. It decreases from winter towards summer, meaning that movements of the dam towards upstream are induced.
- The water level component of estimated displacements has less regular trend if compared to the thermal one. The highest downstream displacements are observed in summer (5 mm), induced by an increase of the measured water level.
- The water level component is predominant if compared to the thermal one.

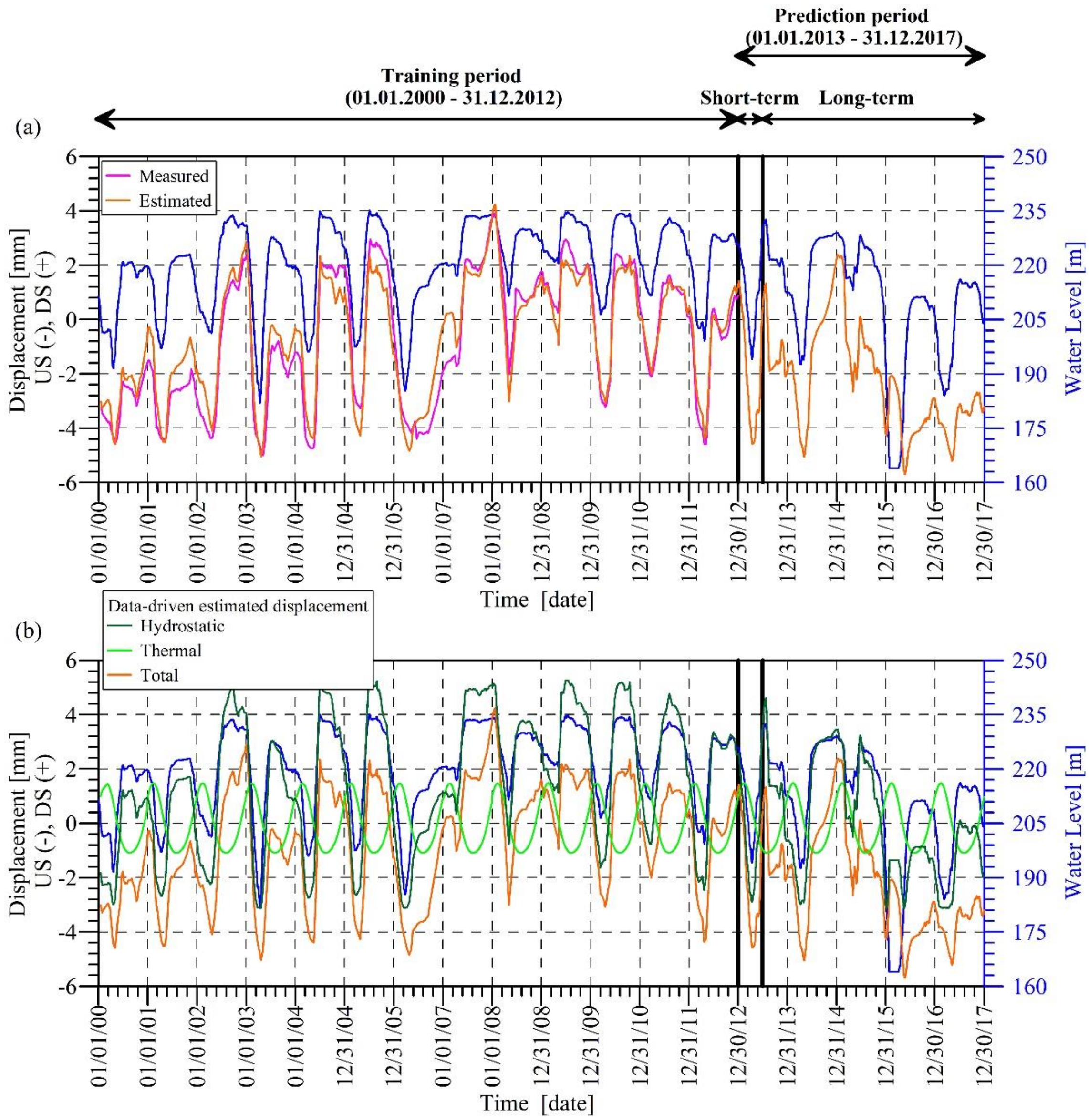


Figure 6-2. Statistical prediction of displacements (CB3_195_161) in the prediction period.

During the short-term prediction period (01/01/2013-30/06/2013):

- The same trend in terms of displacements during the training period can be essentially observed in the short-term prediction period.

During the long-term prediction period (01/07/2013-31/12/2017):

- The regular trend of the temperature component is continuously confirmed.
- The exceptional drastic decrease of the measured minimum water level (from autumn 2015 until 26/01/2016) is directly mirrored through the statistically estimated displacements. The estimated total values of upstream displacements are the lowest values of all estimations, reaching approximately -6 mm and -5.5 mm (summers 2016 and 2017, respectively).
- With minimum water levels in the summers of 2016 and 2017, the temperature-driven component of estimated displacements is predominant with respect to the water level component.

- Overall, in the long-term period, the statistical model has been capable to estimate displacements which are compatible with the abovementioned scenario.

6.2 Model-based prediction

The model-based estimated displacements of both pendulums (obtained from the FE model) are presented in the present Section.
Figure **6-3** and Figure **6-4** illustrate the displacements of the high and low pendulum, respectively. They are plotted comparatively with the statistically estimated displacements. Model-based predictions seem to be closer to statistical predictions in the 1st case, in trend and amplitude.

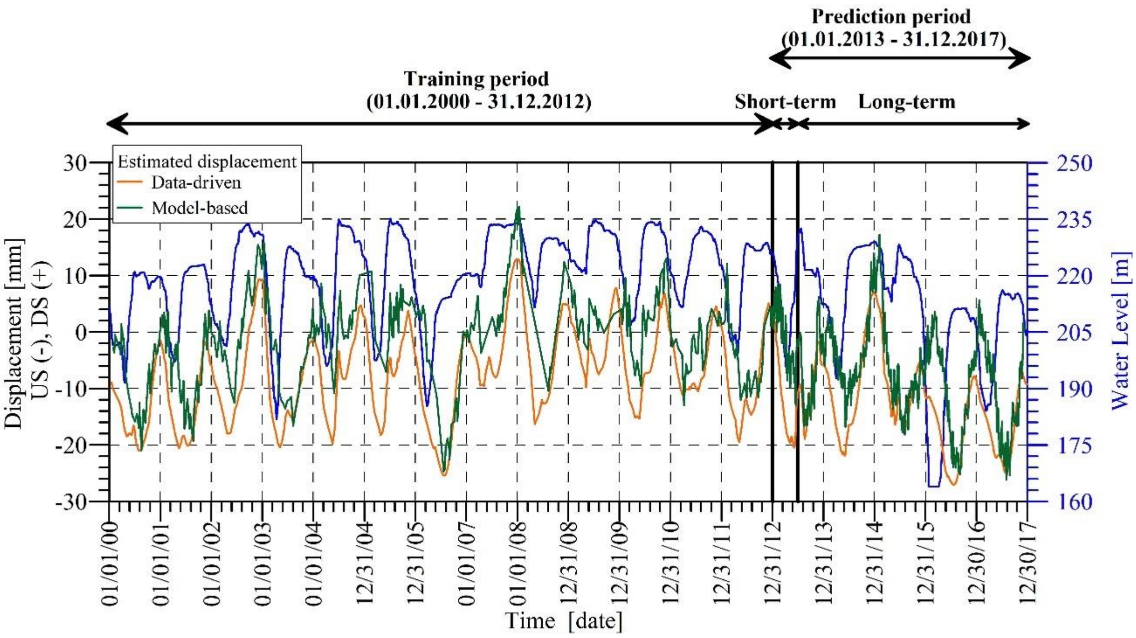


Figure 6-3 Data-driven and model-based predicted displacements (CB2_236_196).

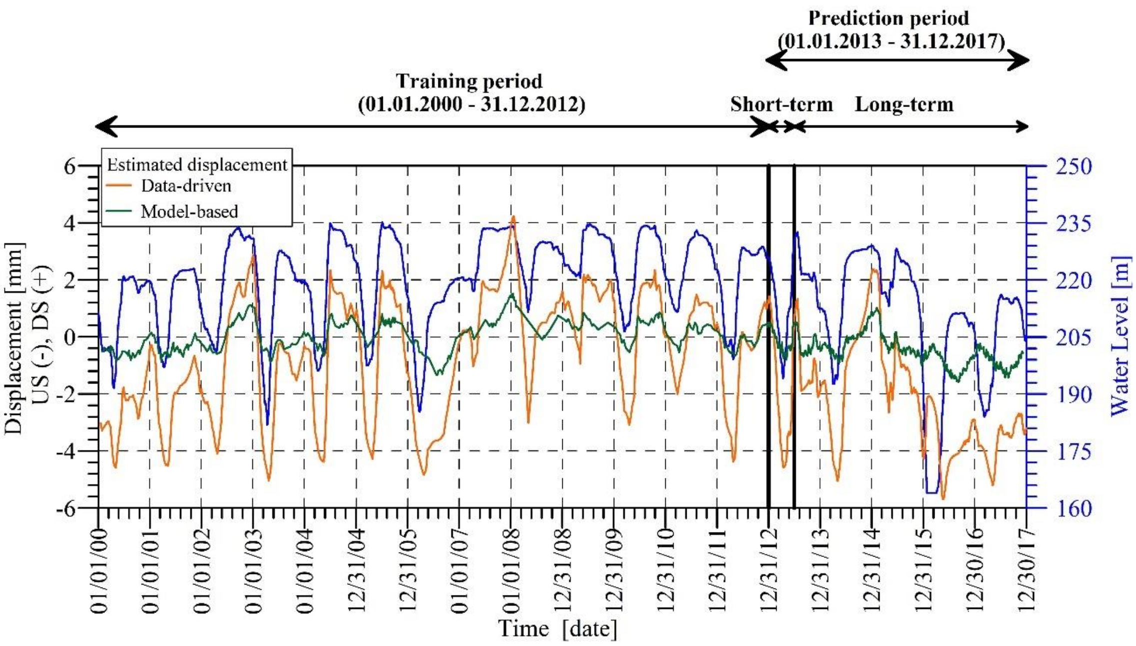


Figure 6-4 Data-driven and model-based predicted displacements (CB3_195_161).

6.3 Discussion

By analyzing the provided measurements data, possible explanation for the abnormal operation during the last two years of the prediction period (2016, 2017) has been suggested.

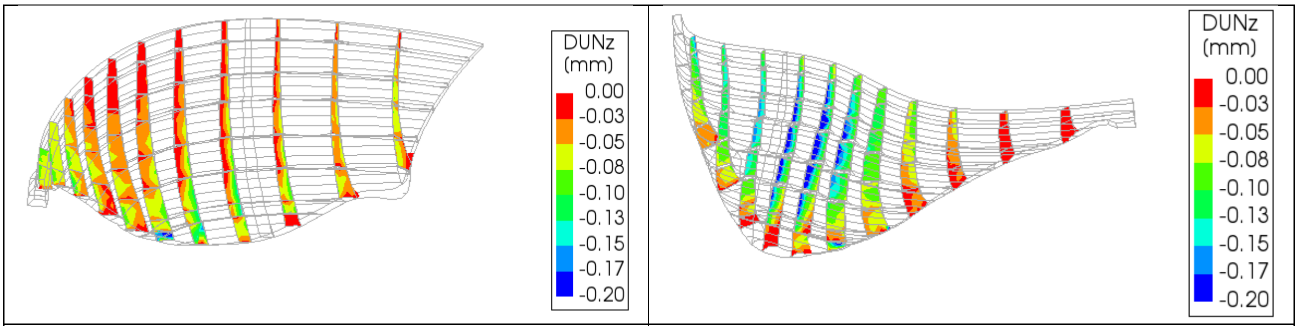
The typical seasonal operation cycle could be described as follows:

- Winter: water level decreases typically from December to January, depending on the year and reaches its minimum by the end of the winter.
- Spring: filling of the reservoir.
- Summer: continue filling of the reservoir, eventually reaching the maximum water level.
- Autumn: water level in the reservoir remains at its maximum level, either start to reduce approaching the beginning of the winter.

During these cycles the radial displacements fluctuate from upstream to downstream direction producing tension zones in the dam body. Typically, the dam leans upstream during warm period and shrinks in downstream direction during cold period [1]. Such a behavior holds for quasi- constant water level, while hydrostatic pressure itself acts in the downstream direction.

As stated in the description document, the water level could drop below the heel of the dam leaving the upstream surface exposed to the ambient temperature and direct solar radiation. Already validated in the past [1], cracks are more likely to originate during cold season when the concrete contracts (shrinks), thus developing tensile stresses. On the one hand, horizontal cracks can potentially develop due to tensile stresses acting in the vertical direction. These cracks can be particularly dangerous for the operation, depending on their location, whether on the upstream or downstream zone of the dam. For instance, the development of cracks on the downstream face is considered less critical than damages of the upstream face. On the other hand, tensile stresses acting in the horizontal direction could be accommodated by the vertical contraction joints.

FE analysis demonstrates that there is a development of the horizontal tensile stresses in the upstream face of the dam, while vertical component remains in compression state. On the other side, it could be the case that accumulated tension in the contraction joints develop damages there, and with time it propagates deeper towards downstream. In the adopted finite element model, joints are modelled elastically, therefore, the obtained results could be used rather quantitative than qualitative. FE model results shows the joints that are more likely subjected to opening in the middle of the dam during cold period as illustrated in Figure 6-5.



Aug-2006	Jan-2008

Figure 6-5 Indication of the contraction joints opening

In this context, it is suggested that the opening of the joints in the upstream face could be a possible reason of the exceptional lowering of the reservoir water level. For better prediction of the joints opening and its influence on the stability of the dam, more sophisticated material model (e.g. nonlinear elastic model, friction material model) should be used.

7 CONCLUSIONS

The present paper has focused on the benchmark problem Theme A ‘‘*Behaviour prediction of a concrete arch dam*’’ of the 16th International Benchmark Workshop on Numerical Analysis of Dams, Organized by ICOLD Committee on Computational Aspects of Analysis and Design of Dams.
The paper aimed at the calibration of a statistical regression model and a Finite Element model both capable to predict the expected future behavior of the dam under examination. In particular, predictions have been provided for the radial displacements of both pendulums (CB_236_196, CB_195_161), by comparatively implementing both models. The obtained results have been investigated for the interpretation of dam’s behavior.
A training period of 13 years (January 1st 2000 to December 31st 2012) has been considered for the calibration, whereby temperature and water level data have been used as regressors. Two prediction periods have been considered for the prediction, namely short-term (01/01/2013-30/06/2013) and long-term (01/07/2013-31/12/2017) periods.

The main results can be synthesized as follows.

- The hydrostatic-seasonal-time statistical model have estimated the two separate components of displacements (due to water level and temperature), while the irreversible effects not relevant. The out of phase nature of the two separate components has been observed for both pendulums.
- Overall, a good agreement has been demonstrated between time series of measured and statistically estimated displacements, with determination coefficients R^2 equal to 0.932 and 0.964 for high and low pendulum, respectively.
- In the long-term period, the statistical model has been capable estimating displacements which are compatible with the recent scenario of exceptional drastic decrease of the measured water level.
- FEM has shown stress distribution and direction and zones subjected to cracks. These zones are mainly concentrated along the foundation of the dam, perpendicular to the rock surface. The observed crack pattern is rather typical and does not compromise the stability of the dam.

- On the one hand, vertical stresses assessment indicated the tension zone on the downstream face of the dam. However, no cracks have been originated during computations, probably due to assumption of the relatively high tensile strength (2MPa). On the other hand, the upstream face remains under compression in vertical direction, which is crucial to prevent the horizontal cracks development.
- More detailed analysis revealed rather high horizontal tensile stresses on the upstream surface during cold periods of the year, when dam tends to shrink. Usually, these stresses are absorbed by contraction joints.
- Considering the low reservoir water level for the significant part of the cold period, originated tensile stresses could have provoked damages of the joints. It was suggested that the propagation of the damages could have caused lowering of the reservoir water level.

In can be concluded that, the opening of the joints in the upstream face of the dam could be a possible reason of the exceptional lowering of the reservoir water level in the last two years of the monitoring period.

More advanced modeling strategies, e.g. sophisticated material model (nonlinear elastic model, friction material model), could provide better insights and a more accurate prediction of the joints opening and its influence on the stability of the dam.

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