Finite Element Models in the Analysis of Thermomechanical Problems – Application to an Arch Dam

Summary of Dissertation for the degree of Master in Civil Engineering

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Abstract

This article describes the numerical modeling of an arch dam under strong seasonal thermal loading. The model is based on a transient physical model describing the seasonal temperature variation of the structure and a mechanical model, which combines the effects of the temperature variation with the mechanical loading. Transient thermal analyses are performed to establish temperature distributions for the subsequent mechanical analysis. The main focus of the study has been to evaluate the deformations of the structure. The linear numerical simulation using the Finite Element Method was carried out in the *Code Aster* software. The analysis reveals that the thermal expansion caused the dam to deflect upstream during the summer and downstream during the winter. The concrete arch dam used in this study has been proposed for the 14th ICOLD International Benchmark Workshop on Numerical Analysis (theme A).

Keywords: Thermomechanical; Arch Dam; *Code Aster*; Finite Element Method.

1. Introduction

The durability of concrete structures such as bridges and dams is an increasingly relevant topic in civil engineering. For example, arch dams are subjected to seasonal temperature variations and as a consequence thermal stress leading to concrete cracking. The design and maintenance of dams in cold regions, therefore, presents a substantial challenge for the engineering community. It is usual to carry out routine deformation monitoring in the maintenance period of a dam to anticipate problems and allow preventive actions. However, with the advances in computational mechanics, it is highly convenient to use numerical methods in dams' analyses, as they help understand the behavior of the structure from the design period to the end of its service life (E. Castilho 2013), (N. S. Leitão 2012) and (Sheibany and Ghaemian 2004).

The aim of the paper is to analyze the eventuality of cracking of the concrete arch dam subjected to a load combination of self-weight, hydrostatic pressure and seasonal temperature variations.

The current analyses were performed following the requirements and using the data provided within the framework of the 14th ICOLD Benchmark Workshop on numerical analysis of dams This dam was selected because simulations carried out by several authors have been published in the proceedings of the 14th ICOLD. This allows us to establish a direct comparison between our results and the ones obtained by other researchers.

The modeling and the computations are carried out by means of the finite element method (FEM) computer program *Code Aster.*

The FEM transient thermal analysis based on temperature data from the dam site was performed and the resulting temperature distribution was used in the mechanical analyses. Transient thermal analyses were then used to generate temperature distributions over a period of two years, (R. Malm 2016). The subsequent mechanical analysis allowed to assess the response of the structure due to the effects of gravity loads, water pressure and enforced deformations due to temperature variations.

The paper is structured as follows: details regarding the materials and numerical model are presented in section 2 (Methodology); results are presented in section 3, and lastly, in section 5, conclusions to the study are presented.

2. Methodology

2.1 Geometry description

A schematic 3D view of the dam is shown in Fig.1. The dam has a height of approximately 40 meters and an upper arch length of 170 meters. The upper arch has a radius of 110 meters. The boundaries of the foundation measure approximately 193 meters by 225 meters, with a maximum height of 60 meters. The thickness of the dam is about 2.5 meters at the crest and 5 meters at the base (central cross-section).

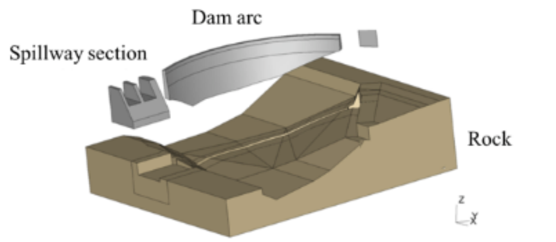

Figure 1. Three-dimensional schematic diagram of the dam used in this study.

2.2 Material Parameters

Material parameters were provided by the formulators of Theme A (14th ICOLD) and are listed in Tables I and II.

Table I. Material parameters

Material parameters	Concrete	Rock
Density (kg/m^3)	2300	2700
Thermal expansion (K^{-1})	10^{-5}	10^{-5}
Poisson´s ratio	0.2	0.15
Youngs-modulus (GPa)	33	40
Uniaxial tensile strength (MPa)	2.9	-
Biaxial compressive strength (MPa)	38	-
Properties	**Concrete**	**Rock**
Thermal conductivity (*W/m*K*)	2	3
Specific heat capacity (*J/kg*)**K*	900	850

2.3 Mesh

The finite element model mesh was prepared using the Salome-Meca platform. A mesh with distinct elements was created. Hexahedral elements were used for the spillway section, the dam arch, and the abutment. For the foundation, tetrahedral elements were used.

The number of elements and their dimensions are described in Table III. Fig. 2 illustrates the spatial distribution of the elements in the dam.

Table III. Summary of mesh characteristics used for thermomechanical dam analysis.

Mesh details				
	Spillway	Dam body	Support	Rock
El. type (dimension)	HEXA (1 m)	HEXA (1 m)	HEXA (1 m)	TETRA (5 m)
nº nodes	23690	42592	3471	22 861
nº elements	150 266	205 078	16 907	93 969

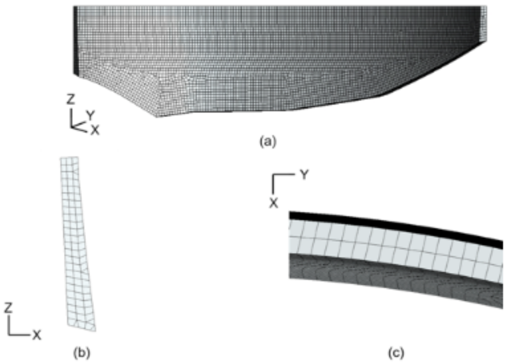

Figure 2. Finite element mesh of the dam body. (a) front view arc, (b) cross section and (c) top view.

3. Results

3.1 Thermal analysis

Thermal analysis was carried out using the values of the environmental thermal variations (air and water) provided by the ICOLD organizers and which are represented in Table III. Two consecutive years were considered, an exceptionally hot year (summer) followed by an exceptionally cold year (winter). The requirements imposed by ICOLD organizers required that two combinations of these periods be simulated, namely (i) a warm year, followed by a cold year and (ii) a cold year followed by a warm year. Fig. 3 shows the location of the 4 nodes where temperatures were calculated.

The values of the thermal properties of materials, namely the thermal conductivity (*k*) and specific heat (*C*) used in the simulation are shown in Table II.

The temperature in the concrete structure is estimated at 4 different nodes. Fig. 3 (a) shows a cross-section of the arch dam where the relative positions of the four nodes are depicted. Fig. 3. (b) shows the estimated four-node temperature variation over a period of two years, a warm year followed by a cold year.

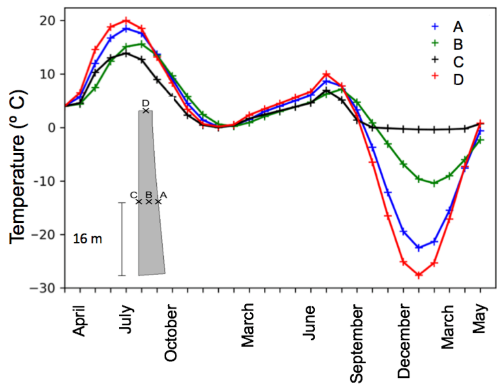

Figure 3. Evolution of the temperature over two years. The default is a warm year followed by a cold year. The inset shows a cross section of the dam showing the position of the nodes where temperature variations were calculated.

Table III. Ambient air and water temperature used in the simulation of the displacements.

Month	Maximum temperature		Minimum temperature	
	Air (°C)	Water (°C)	Air (°C)	Water (°C)
January	-0.2	0	-25.8	0
February	0.6	0.4	-23.6	0
March	2.4	1.7	-15.7	0
April	6.5	4.6	-6.5	0
May	14.8	10.4	1.1	0.8
June	18.5	13	6.6	4.6
July	19.7	13.8	10	7
August	18	12.6	7.3	5.1
September	12.6	8.8	1.9	1.3
October	8	5.6	-6.4	0
November	3.1	2.2	-15.9	0
December	0.6	0.4	-23.8	0

3.2 Thermomechanical analysis

The thermomechanical analysis of the dam was done in static mode. The loads considered were; (i) self-weight, (ii) hydrostatic pressure and (ii) temperature. The dam foundation was simulated as being fixed (rigid foundation) i.e. all displacements were blocked.

The horizontal displacement studies were calculated in three distinct lines as illustrated in Fig. 4.

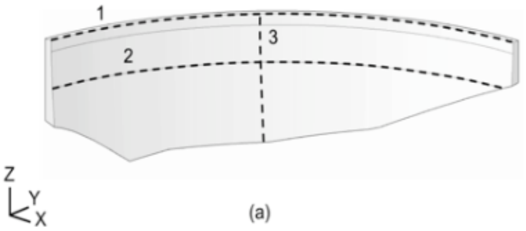

Figure 4. Schematic diagram of the position in the arch of the lines where temperatures were evaluated.

3.3 Displacements analysis

Figure 5(a) represents the horizontal displacements of the crest (line 1 in Fig. 4) for initial time, summer and winter. Displacements are considered positive in the downstream direction and negative when they occur in the upstream direction. The displacements are null on the abutment and the spillway.

The central green line represents the displacement caused only by the dam's own weight and hydrostatic pressure. The dashed red line shows the displacements for July in the first year of the study (summer). The average temperature considered was 19.7 ° C for air and 13.8 ° C for water. Finally, the blue dotted line represents the displacement during January of the second year (cold year). In this case the assumed average temperature was -25.8 ° C for air and 0 ° C for water. The displacement is not uniform and reaches the maximum value at a distance of 40 meters from the spillway (starting point).

Hydrostatic pressure causes a downstream displacement that reaches a maximum of 15 mm. In the summer the high temperatures cause a displacement in the opposite direction to the displacement caused by hydrostatic pressure. This balance due to the combined action of water temperature and pressure produces a relatively small displacement. This displacement reaches only 7 mm upstream, about half of what is caused exclusively by hydrostatic pressure.

During winter, negative temperatures do not counteract the effect of hydrostatic pressure but, rather, both effects contribute to displacements in the same direction (downstream). During winter, displacements due to the combined effect of temperature and pressure reach 48 mm, 34 mm more than the displacement due only to hydrostatic pressure (14 mm).

The global displacement during the summer of the hot year is in the opposite direction to the displacement caused by hydrostatic pressure so the overall result is beneficial to the dam because the stress in the concrete structure is reduced. Fig. 5 (b) shows displacements for the same conditions as described above, but now estimated 14 meters below the crest line (line 2 in Fig. 4). As expected the lower the height, the smaller are the displacements. The maximum displacement in line 2 did not reach 30 mm, while at the crest the maximum displacement was close to 50 mm.

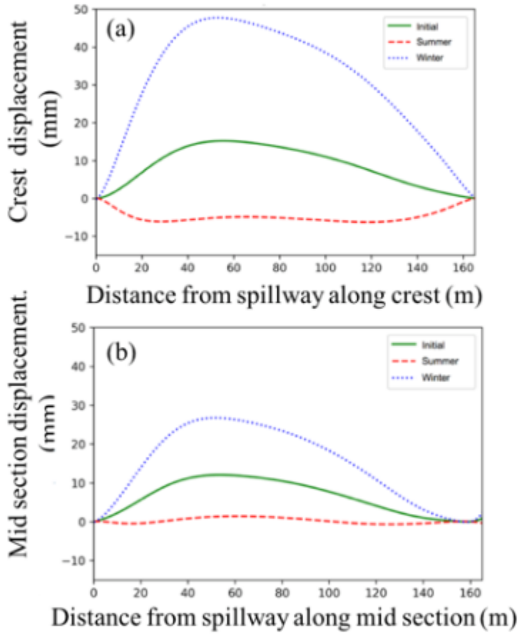

Figure 5. Horizontal displacements along the crest of the dam. The green solid line represents the static situation due only to hydrostatic forces. The dotted blue line and the red dashed line show the combined effect of hydrostatic pressure and temperature. The dashed red line represents the displacement during summer and the blue dotted line represents the displacement during winter. (a) horizontal displacements at the crest of the dam (line 1 in Fig.4). (b) horizontal displacements in the dam arch located 14 meters below the crest line (line 2 in Fig. 4).

Fig. 6 shows the variation of the displacement along section 3 (line 3 of Fig. 4) from the dam base (0 meters) to the crest (40 meters high). The red dashed line represents the displacement during winter and the blue dotted line represents the displacement during summer. The displacement represented by the green line is the displacement caused only by hydrostatic pressure. This graph clearly shows that the dam bends further as the height increases.

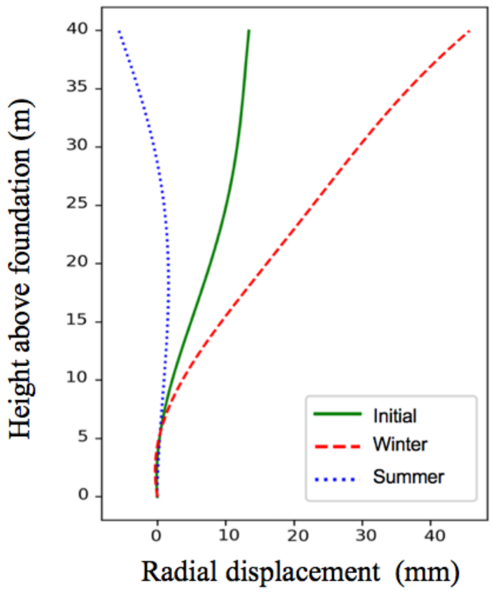

Figure 6. Displacement along a vertical line (line 3 of Fig. 4) from the dam base (0 meters) to the crown (40 meters high).

3.4 Stress analysis

In this section the stress analysis is made for three particular cases: the first case only takes into account the self-weight and the hydrostatic pressure; in the second case the effect of the temperature during the summer (hot year); finally, in the third case, the effect of temperature during winter (cold year) is considered. Stress analysis allows us to determine at which zones of the dam structure the highest tensile tensions occur. Maximum tensile regions are considered critical because concrete has low tensile strength. Bellow we explain the analysis of the three cases.

- **Case 1 - Analysis of stresses caused by self-weight and hydrostatic pressure.**

In this analysis we considered only the mechanical actions, more specifically, the self-weight and the hydrostatic pressure. The seasonal variation in temperature was not taken into account. Fig. 7 shows the stress distribution in the upstream face. The blue color corresponds to compression stresses, and the red color represents tensile stresses. The base of the dam is traceable to an approximate value for the stress of 0.9 MPa. This value is relatively far from the critical tensile strength of the concrete (2.4 MPa). The remaining areas of the dam are in compression. The maximum compression of 3.7 MPa occurs at the crest height in the upstream part.

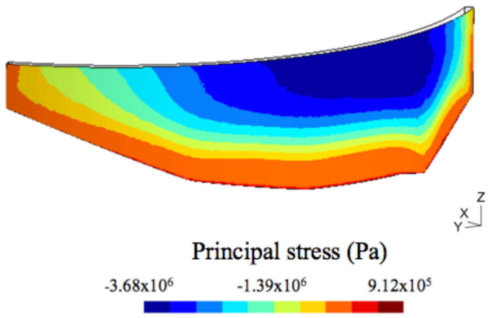

Figure 7. Principal stress (σ_I) on the upstream face.

Fig. 8 shows the distribution of stresses in the downstream face. As expected, the downstream side is compressed. The maximum compression value occurs at the base of the dam and reaches the value of 9.6 MPa (Fig. 8).

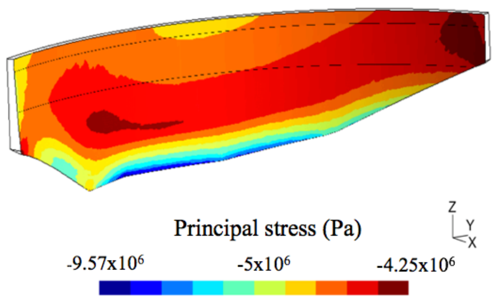

Figure 8. Principal stress (σ_I) on the downstream face.

- **Case 2 - Analysis considering self-weight, hydrostatic pressure and thermal action during the summer.**

During summer the concrete expands and both sides are compressed. Comparison with the identical load case without regard to thermal effects is interesting in that it highlights the benefits of compression due to concrete expansion. This effect is illustrated in Fig. 9

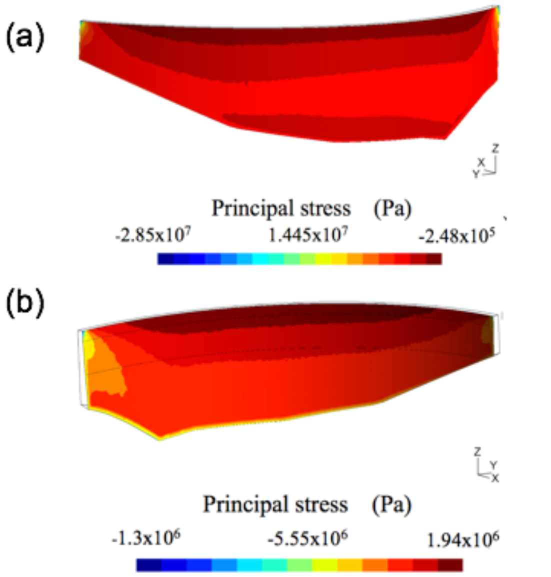

Figure 9. Principal stress (σ_I) in July (summer). (a) for the upstream side and (b) for the downstream side.

- **Case 3 - Analysis considering the combined action of self-weight, hydrostatic pressure and thermal action during winter.**

The combined analysis of self-weight and hydrostatic pressure and thermal action for the cold months reveals that tensile stresses occur mainly in the crest of the structure.

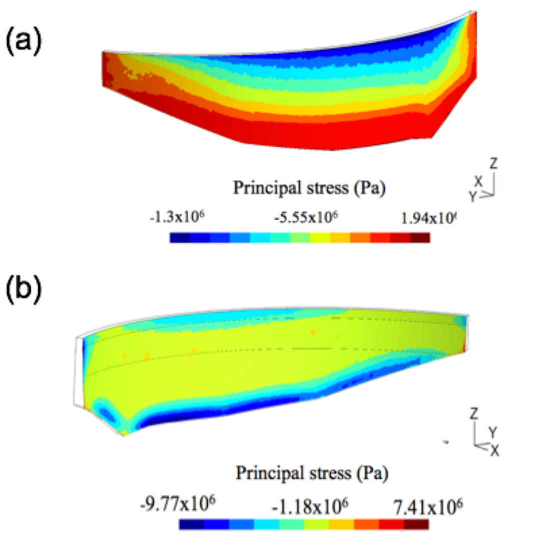

Figure 10. Principal stress (σ_I) in January (winter). (a) for the upstream side and (b) for the downstream side

This effect is particularly noticeable in the upstream face as illustrated in Fig. 10 The estimated maximum traction value reaches 1.94 MPa. This value is significantly lower than the maximum tensile strength of the concrete which is approximately 2.4 MPa.

In the downstream side the stresses are essentially compressions. This case is depicted in Fig. 10. The maximum estimated value for the compressed regions is 9.8 MPa, which is much lower than the tolerable value for concrete which is approximately 24 MPa.

Validation of results by comparing them to others available in the literature

In order to validate the model adopted in this study the simulations were compared with the results obtained by the participants at the 14th ICOLD. Only linear analysis was considered. Fig. 9 compares the results of the present work with the results of two teams, team 13 and team 16. These teams assumed, as in our study, a fixed constraint to model the interaction between the foundation and the dam.

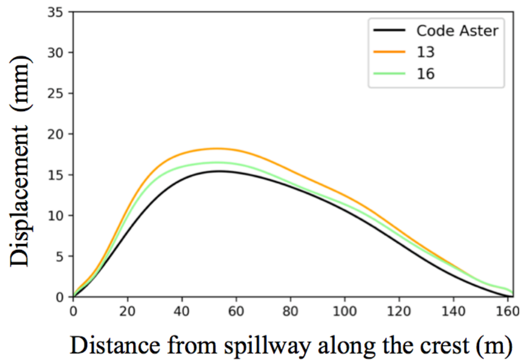

Figure 11. Comparison between the results of this study and the results obtained by teams 13 and 16. The curves describe the horizontal displacements along the dam top arch at the initial instant.

The simulated curve in this work has the same shape as presented by teams 16 and 13 but has slightly lower displacements. The curve obtained in this work is very close to the curve obtained by team 16. There is only a discrepancy of about 3 mm, located between 20 and 40 meters. This difference corresponds approximately to a 13% difference. For the remaining length of the arch the curves practically coincide.
Fig. 11 compares the results of the simulation made in this work with the results of team 11 and team 12. For distances greater than 100 meters the curve obtained in this work is very close to the curves obtained by teams 11 and 12. For distances between 20 and 80 meters along the arch of the dam the displacements

obtained in this work predict an upstream deformation about 3 mm away from the curve simulated by team 11.

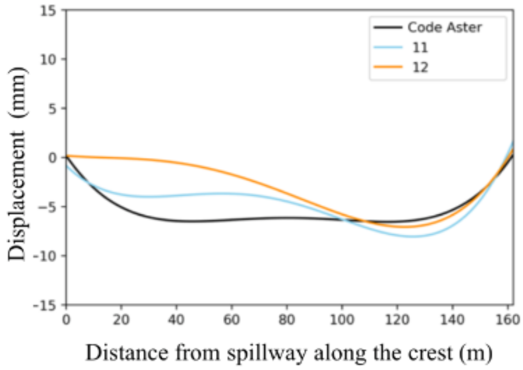

Figure 12. Comparison between the results of this study and the results obtained by teams 11 and 12. The curves represent the horizontal displacements along the dam crest during the summer.

Fig. 13 compares the displacements obtained in this study with the observed values estimated from the temperatures measured in the winters of 1996 and 2011. Our simulation estimates peak values identical to the ones of the winter of 1996. However, our curve has a maximum that is shifted by approximately 20 meters to the left (towards the spillway) in respect to what should be expected.

All simulated displacement curves have a much more rounded shape and predict near the extremities of the dam a larger displacement than those experimentally expected.

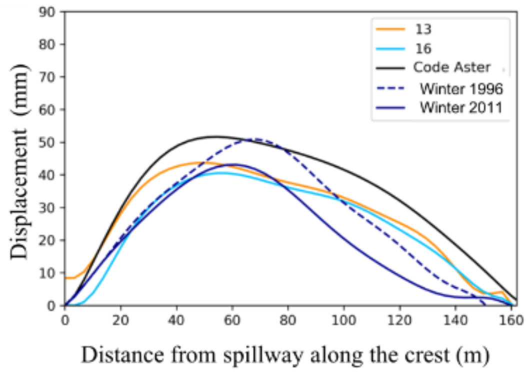

Figure 13. Comparison between the results obtained by *Code Aster* and the results obtained by teams 13 and 16. The graph also includes the curves calculated using real data for the temperatures in the winters of 1996 and 2011.

Fig.14 compares our results obtained in *Code Aster* with the horizontal displacement along the elevation of the central section of the dam obtained by the participating teams at ICOLD. Teams 13 and 16 used a rigid dam/foundation interface, identical to the one used in this study. The curve obtained in this work has an identical shape and is almost parallel to the curves obtained by the other researchers. The displacements obtained in this study are only about 2 mm smaller than those estimated by team 16 and approximately 3 mm smaller (20%) than those of team 13.

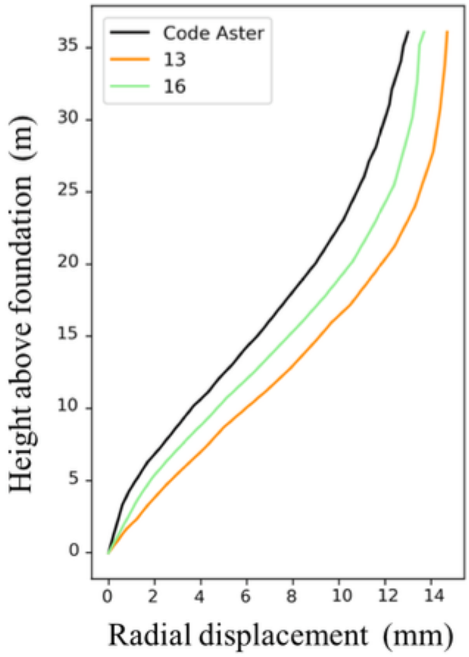

Figure 14. Horizontal displacement along the elevation of the central section of the dam. The curve predicted in this study (Code Aster) is compared with those obtained by teams 13 and 16 of the ICOLD benchmark workshop.

4. Conclusions

This study presented a numerical simulation of an arch dam using FEM. The code used to solve the problem was *Code Aster*, an open-source software which implements the FEM.

The thermal analyses were carried out in transient hypothesis for the coldest (January) and warmest (July) months of the year in Sweden. A sequence of two years was considered starting with the cold season.

The analyses pointed out that the dam displacements produced by temperature variations are higher than those produced by the combination of gravity load and hydrostatic pressure.

The areas within risk of cracking as stresses there approach the maximum tensile strength are located in the central zone - downstream face at the toe and at the crest of the dam. This is due to a load combination of gravity, hydrostatic pressure and temperature in the winter.

During winter the concrete is subjected to the maximum tensile stress. It is important to note that the displacement during summer is in the opposite direction to the displacement caused by hydrostatic pressure so the overall result is beneficial to the dam structure. This is because it reduces the tensile stresses in the concrete. In the cold months, however, the concrete retracts. During winter the displacements are in the same direction as those caused by hydrostatic pressure. The global horizontal displacement during winter reaches a value of 50 mm downstream.

The displacements of the structure cause tensile forces to appear near the base and, thus, increase the likelihood of cracking (R. Malm 2016).

This study does not predict cracking patterns. However, it is obvious that the regions with the highest probability of cracking are located in the regions subjected to the highest tensile stresses. The numerical model developed in this study can be improved so as to obtain the cracking patterns.

Ideally, to achieve the highest performance, the model presented here should be calibrated using experimental data. In order to obtain this data it is important to install in the dams instrumentation for temperature and displacements/deformation measurements. For example, fiber optics based distributed sensors and strain gauges to measure deformations (Zhou et al. 2018).

The numerical simulations presented here were performed for a Nordic climate using a typical dam of a Nordic country (Sweden). The dam selected is a very slender one. This type of dam is very sensible to temperature variations compared to thick dams.

The model selected for analysis allowed us to compare the results obtained in *Code Aster* with the results obtained with other researchers using other programs thus validating our work. There is now enough confidence to apply the same procedure to other types of dams and climates.

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