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SIMULATION OF TEMPERATURES AND STRESSES DURING CONSTRUCTION OF AN RCC DAM

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SUMMARY

The curing of concrete is an exothermic process. The heat of hydration generated induces temperature increases in the concrete, which will disappear in the long term by heat conduction in the concrete mass and thermal exchanges with the environment. The problem is of particularly interest for large concrete masses, as is the case of dams, because the time involved in the heat diffusion process grows with the square of the dimensions and a hotter dam interior implies the possibility of cracking the exposed surfaces of the dam.

The Cuira dam, currently being built in Venezuela using roller compacted concrete, is a 134 m high, arch-gravity dam. In support of the design, different strategies were analysed, including various combinations of cooling of the water and the aggregate in order to achieve acceptable results. The calculations were conducted with Abaqus, taking into account all the necessary mechanical and thermal characteristics, as well as the relevant non-linearities. The analyses led to the conclusion that no cooling was required, even taking into account the stress state imposed by an early and rapid filling of the reservoir.

1. INTRODUCTION

Whether or not roller compacted, the curing of concrete is an exothermic process. The heat of hydration generated induces temperature increases in the concrete, which will disappear in the long term by heat conduction and thermal exchanges through the thermal boundary conditions. This process is widely known and has been studied by different authors, e.g., Schindler et al. ([1] and [2]), Pane et al. [3], Lin et al. [4] and, also, from a numerical point of view by Cervera et al. [5]

The problem is of particularly interest when dealing with large concrete masses, as is the case of dams, since a hotter dam interior implies the possibility of producing cracks in the exterior faces of the dam. It therefore becomes necessary to study the effects of parameters such as the rate at which the concrete can be poured and the spacing between joints in the dam

2. DESCRIPTION OF THE PROBLEM

2.1. THE DAM AND ITS CONSTRUCTION SEQUENCE

The Cuira dam is a relatively large structure, 134 m high, currently being built with roller compacted concrete on the river Cuira in the state of Miranda (Venezuela). Fig. 1 presents a plan view and a cross-section of the dam.

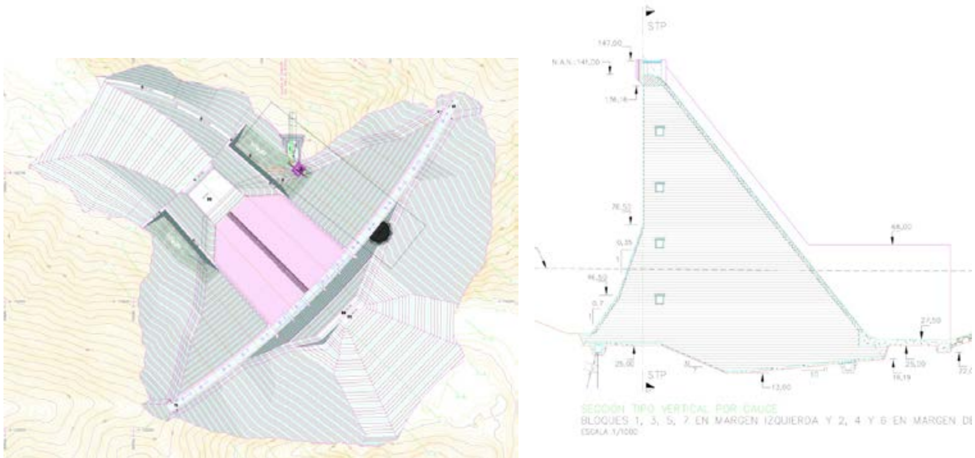

Fig. 1
Plan view and cross section of the dam

The characteristics of the concrete evolve during the curing process. For the concrete being used at the dam, the evolution of the stiffness and strengths is that shown in Table 1. The Poisson's ratio was assumed to remain equal to 0.2 throughout the process. Shrinkage was neglected because of the relatively high local humidity. The concrete data were taken from Fosce [6].

Table 1
Evolution of Stiffness and Strengths of the Concrete

Age (days)	Young's modulus (GPa)	Compress. strength (MPa)	Tensile strength (MPa)
7	13.0	8.0	0.32
28	18.0	15.0	0.60
90	22.0	22.0	0.88
180	24.0	26.0	1.04
365	25.0	28.5	1.14

As already mentioned earlier, the curing is an exothermic process. The heat generated has been represented by the two-parameter law given below:

$$Q(t) = Q_\infty \frac{1 - \exp(-t/\tau)}{1 + \exp(-t/\tau)} \qquad [1]$$

where $Q(t)$ is the heat generated per unit mass up to age t, Q_∞ is the heat generated at infinite time, and τ is a characteristic of the specific reaction.

The two constants were determined on the basis of data for the specific concrete being used at the dam and their values are Q_∞=21.36 kJ/kg and τ=3.44 days. Also of interest from a thermal point of view, the heat conduction coefficient of the concrete is 1.957 W/mK, the specific heat is 921.1 J/kgK, and the coefficient of thermal expansion is 10^{-5} K^{-1}. It is a relatively dense concrete, with 2550 kg/m^3.

The ground on which the dam is placed is mafic and ultramafic rocks of the Villa de Cura group. They have been characterised with a Young's modulus of 20 GPa and a Poisson's ratio of 0.25. The thermal properties of the ground were assumed to be similar to those of the concrete of the dam. To ensure that the results are conservative in relation with possible concrete cracking, it has been assumed that the ground will not experience any cracking and that the no relative movements take place across the dam-rock interface.

The construction sequence planned appears in Table 2. It includes 3-day interruptions when reaching elevations 67 m and 70 m, 4-day interruptions at 91 m and 94 m, and 5-day interruptions at 115 m and 118 m.

Table 2
Construction Sequence

Month Year	Elevation reached (m)
Jun 2013	28.0
Jul 2013	32.8
Aug 2013	38.8
Sep 2013	45.7
Oct 2013	54.7
Nov 2013	64.9
Dec 2013	70.0
Jan 2014	75.4
Feb 2014	89.8
Mar 2014	101.2
Apr 2014	115.6
May 2014	129.1
Jun 2014	136.0
Jul 2014	146.6

The success criteria considered in the analyses cover several aspects. On the one hand, it is not acceptable that tensile cracking develops in the outer surfaces of the dam as a consequence of thermal effects. Also, the longitudinal behaviour of the dam must be studied to establish whether the distance between vertical joints is adequate. Finally, the construction must follow the sequence planned, it must be possible to proceed to an early filling of the reservoir, and the construction process should be as simple and inexpensive as possible.

2.2. CONSTRUCTION STRATEGIES AND THERMAL EXCHANGES

The ambient temperatures at the site are relatively high, averaging 25ºC, which is the temperature adopted as baseline for the analyses. In case the thermal expansion taking place inside the dam happened to be too large and hence cracking was predicted in the exposed surfaces, several alternative strategies will be analysed in order to decrease the temperatures:

a) Scenario A: Curing starts at 18ºC as a result of having cooled the aggregate and the water, and adding ice chips to the water.

b) Scenario B: Curing starts at 23ºC as a result of having cooled the water, and adding ice chips.

c) Scenario C: Curing starts at 28ºC, which is a conservative upper bound if no special measures are taken to cool the aggregate or the water.

Heat exchanges with the atmosphere are associated with an atmospheric temperature of 25ºC and a film coefficient of 10 W/m^{2}K. The emissivity coefficient of the outer surfaces of the dam was taken as 0.9.

Alternative hypotheses have been studied for possible heat sinks at the galleries. At one extreme, an assumed air velocity of 10 km/h gives rise to a film coefficient of 5 W/m^{2}K; at the other, adiabatic boundaries were conservatively introduced, thus assuming that the galleries would not constitute a heat sink.

3. ANALYSIS OF THE PROBLEM

3.1. NUMERICAL MODELS

Two different models were used to represent the dam: a plane strain model for studying the cracking (see Fig. 2) and a three-dimensional model for the longitudinal tensile strains (Fig. 3), which spans from a joint to a symmetry plane between contiguous joints. The 2-D model has 14,000 elements and the 3-D one about 180,000.

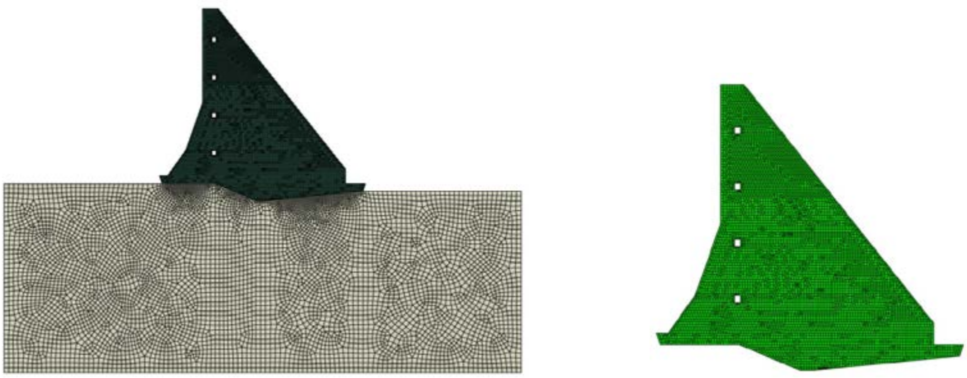

Fig. 2
Global and detail views of the plane strain mesh

Fig. 3
Three-dimensional mesh

Elements are activated as construction progresses; the construction of the dam is assumed to take place between May 2013 and June 2013, although the analyses span an additional year after construction finishes. The elements acquire their constitutive properties and dissipate heat as a function of the time elapsed since pouring their concrete.

All the various strategies of initial cooling, as well as the different hypotheses for heat losses through the galleries were studied in the corresponding combinations although, for reasons of space, only some selected results are presented here.

Finally, one year after completing the construction, a rapid filling of the reservoir is assumed to take place and the corresponding hydrostatic pressures are applied at the upstream face of the dam.

3.2. RESULTS AND DISCUSSION

Fig. 4 describes the evolution of temperatures in the three scenarios given in section 2.2 in four-month intervals, as well as that one year after the end of construction. As could be expected the highest temperatures develop in scenario c) in which no cooling is provided.

The associated cracking is presented at those same times in Fig. 5. The cracks near the foundation should not be taken into account, they are simply a consequence of the conservatively stiff conditions assumed at that interface. Those arising near the galleries are caused by the unrealistically large heat sinks assumed there, which would not develop without forced convection; indeed, although not shown here, that cracking can be seen to disappear when, more realistically, the galleries are assumed to introduce adiabatic boundaries.

More important, it can be observed that no cracking is expected to appear in the upstream and downstream faces of the dam, which indicates that all three

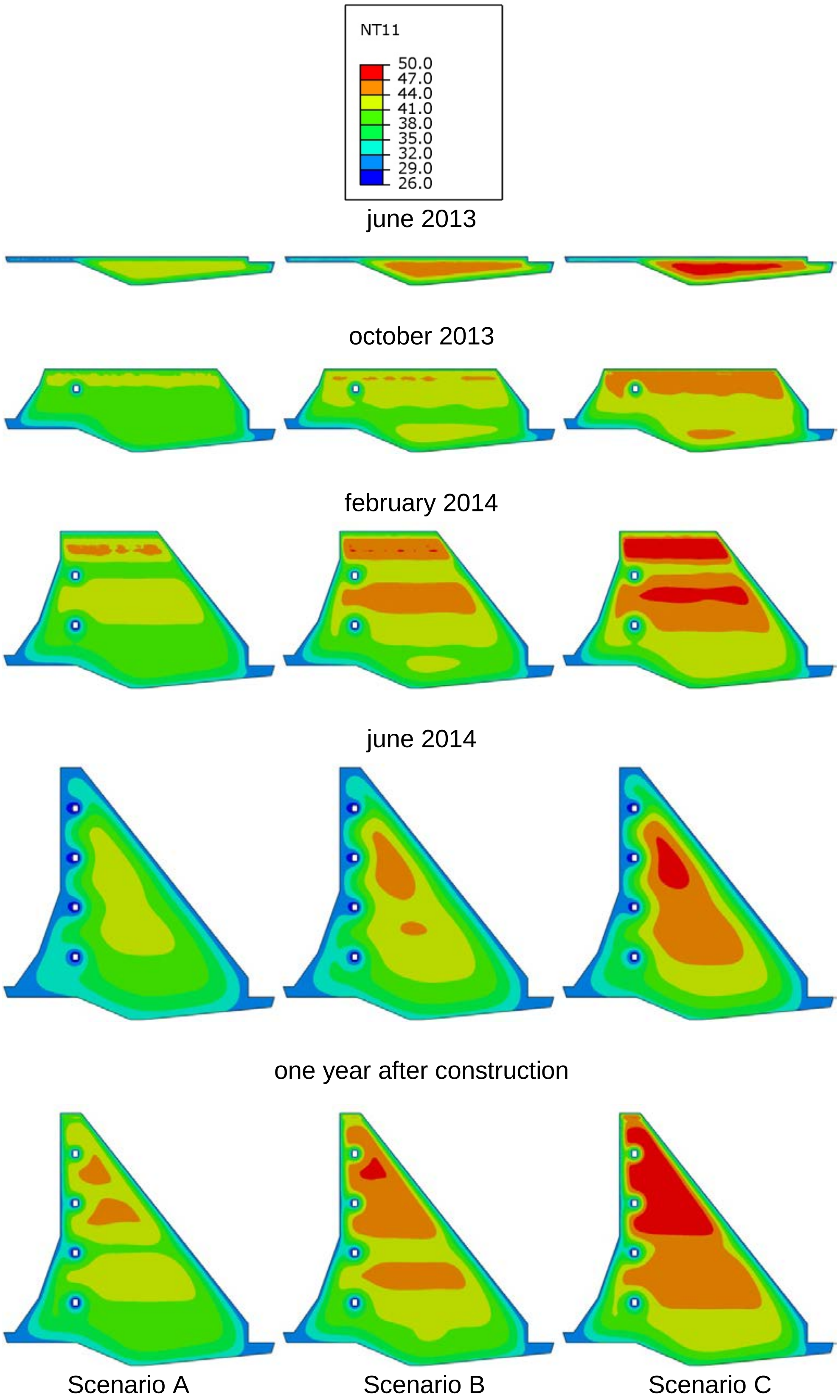

Fig. 4
Temperature distributions (ºC)

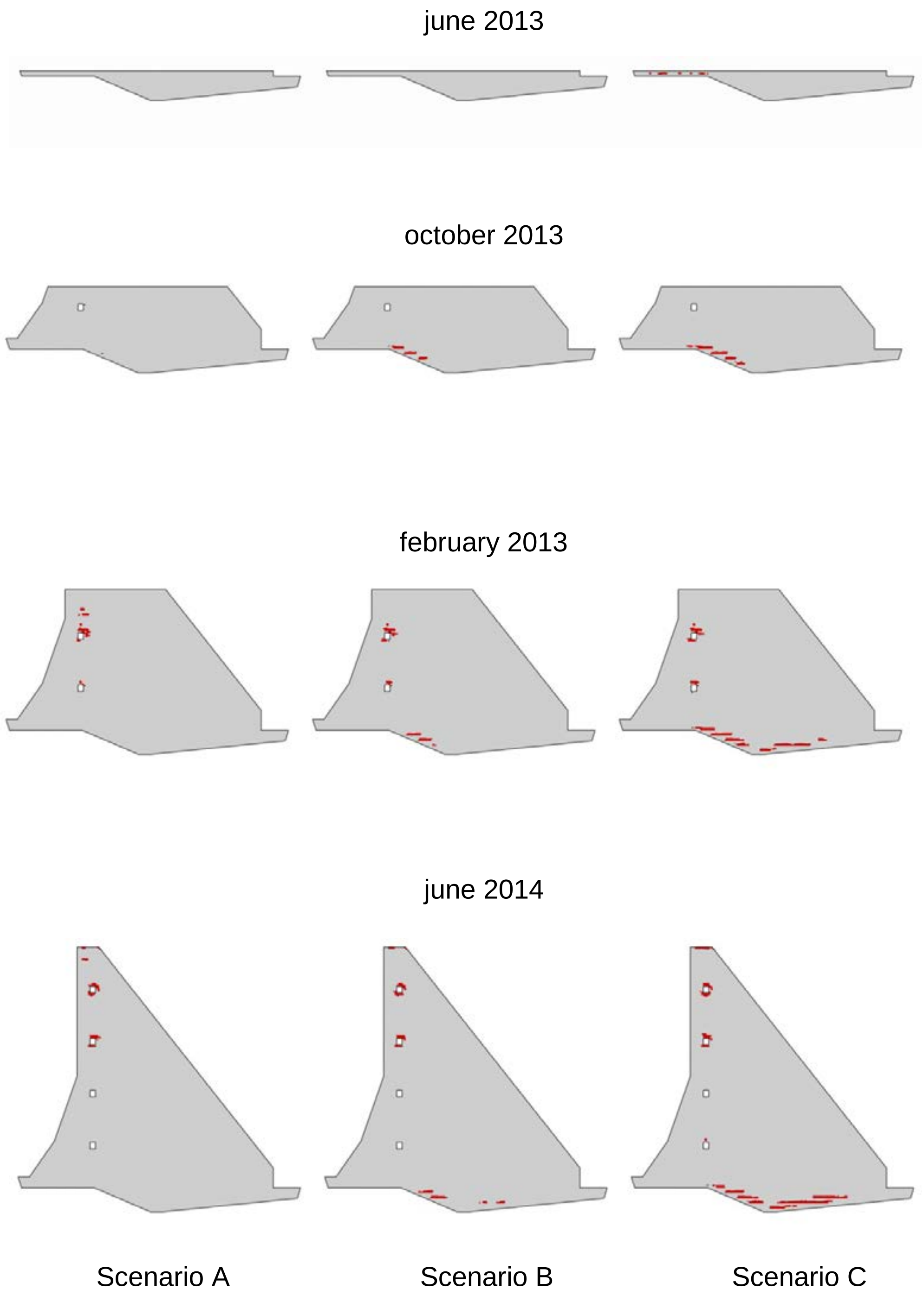

Fig. 5
Cracking developed with heat sinking galleries

scenarios are satisfactory from that viewpoint and no cooling is therefore necessary.

The tensile stresses associated with the filling of the reservoir one year after construction are shown in Fig. 6. With the exception of the local peaks caused by the contact with the foundation, the highest values are around 0.7 MPa and occur in the upper part of the upstream face. Fig. 7 presents the principal stresses in those conditions.

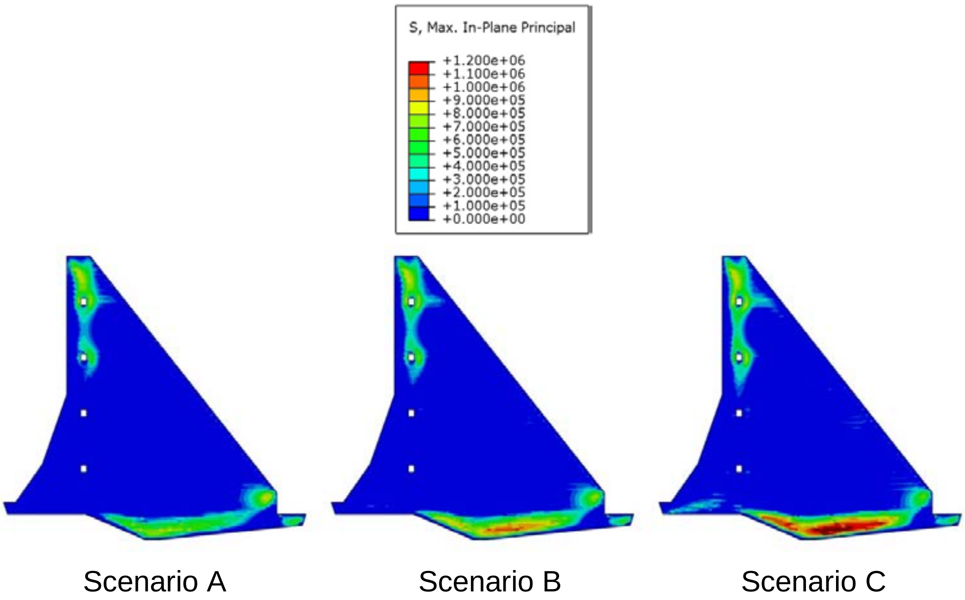

Fig. 6
Tensile stresses after filling the reservoir (Pa)

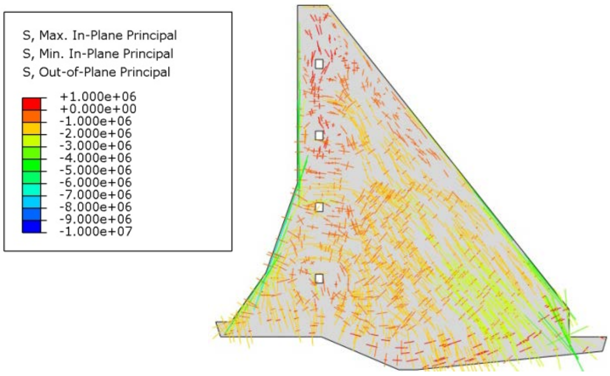

Fig. 7
Principal stresses after filling the reservoir for scenario C (Pa)

Finally, using the three-dimensional model, the various analyses were again conducted, specifically with a view to determining the longitudinal stresses developed in the dam. Fig. 8 presents those stresses for scenario C, both in the plane of symmetry and in that of the joint, after filling the reservoir. The peak tensile stresses developed remain below 1.2 MPa.

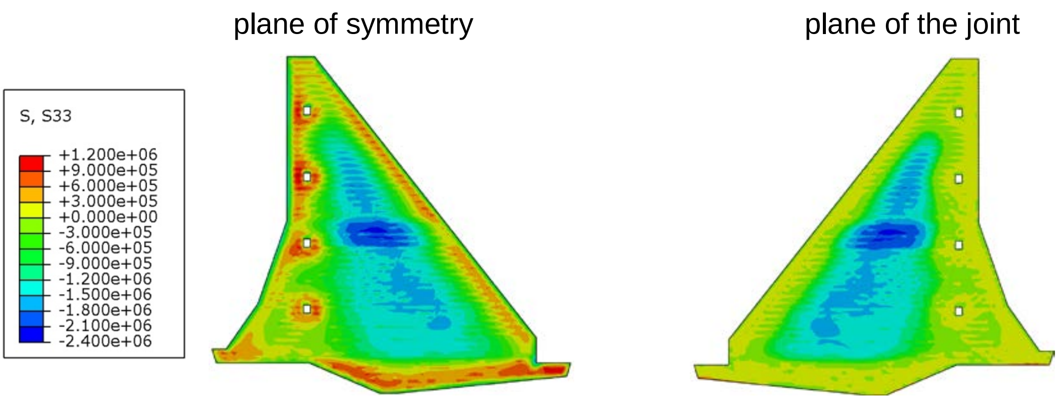

Fig. 8
Longitudinal stresses with hydrostatic pressures for scenario C (Pa)

4. CONCLUSIONS

Analyses have been presented spanning the construction and one additional year of the Cuira dam, to be built with roller compacted concrete. The calculations are particularly concerned with the possibility of cracking the outer surfaces of the dam and the possible development of excessive tensile stresses in the longitudinal direction if the distance between vertical joints is inadequate. Different cooling strategies were considered to judge their interest. As a result of the analyses conducted the following conclusions were reached:

a) The no cooling strategy obviously results in the highest temperatures in the dam. Still, no cracking of the outer surfaces is expected to develop under any of the three scenarios considered.

b) Excessive heat removal through the galleries could lead to cracks developing in their surroundings, but such cooling however would not take place without forced convection. Indeed, the assumption of adiabatic galleries leads to perfectly admissible results. The minor cracks predicted near the foundation interface are considered unrealistic and simply a consequence of the conservative boundary conditions applied.

c) An early filling of the reservoir, just one year after the end of construction, generates tensile stresses limited to 0.7 MPa in the upper part of the upstream face, which are acceptable.

d) Finally, the tensile stresses developed in the longitudinal direction are also acceptable, thus confirming that the 20 m distance between vertical joints is adequate.

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